An exploration into aphantasia: the inability to form voluntary mental imagery

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Abstract

Congenital aphantasia is a variation of the human experience, characterised by a life-long inability to generate voluntary mental imagery, and so far, has been examined in the visual domain. In a series of 10 experiments, this thesis took an experimental approach to examine the possible explanations of congenital aphantasia and the nature of the experience in the visual and non-visual domains, using objective measures and matched samples. Chapter 2 examines the findings of the early published studies within larger experimental designs, and the results confirmed self-reported differences in object imagery but not spatial imagery. Chapter 3 investigates whether aphantasia may be associated with differences in personality or deficits in broader cognitive functions. The results showed no evidence of a difference between individuals with aphantasia and neurotypical imagers on personality or selected neuropsychological measures. Aphantasic participants were slower in a task during trials that had greater working memory load, however, individual differences in performance were apparent and four aphantasic subgroups identified. Chapter 4 showed no difference in accuracy or response time in complex visuospatial working memory tasks requiring allocentric and egocentric transformations. However, aphantasic participants exhibited greater variability in their response times for front/back orientations within an egocentric task. In Chapter 5, a task that attempted to isolate 'visual' from spatial imagery showed no difference in performance across visual and spatial features. Nevertheless, self-reports of nonvisual sensory imagery showed variability in the range of imagery experience across the other senses. Chapter 6 extended exploration of mental imagery in aphantasia beyond the visual modality by examining behavioural performance in two auditory imagery tasks, in which no differences in accuracy or reaction time were evident. Taken together, this research shows that despite the differences in self-reported experience, limited group differences are found between aphantasic and neurotypical participants on a range of imagery and visuospatial working memory tasks. Nevertheless, individual differences in performance were apparent. Further research should investigate the processes adopted by these subgroups, or whether (or not) individuals with aphantasia have unconscious mental imagery.

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*Awarded first place award for best speaker

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Outreach presentations

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Authors declaration

I declare that all the material contained in this thesis is my own work.

Zoë I E Pounder, November 2020

Definitions

Term	Definitions
Mental imagery	Representations and the accompanying experience of sensory information in the absence of direct external stimulus (Pearson, Thomas, Holmes & Kosslyn, 2015).
Visual mental imagery	Often abbreviated to the term 'visual imagery,' it can be defined as "seeing in the mind's eye" in the absence of relevant sensory input (Kosslyn, 1994). It is a type of mental representation which comprises visual features (e.g. pictorial aspects such as colour). Shape/form and texture are often considered a visual features, however, shape can also comprise of spatial information as objects can be processed spatially through structural components (Biederman, 1987). Similarly, texture can be both visual and tactile (Eardley & Pring, 2014). In this thesis, visual properties such as texture and shape are not assumed to be 'visual' features, even if the information can be acquired through vision.
Object imagery	It concerns the pictorial visual appearances of objects or scenes e.g. colour, brightness, texture and shape (Kozhevnikov, Kosslyn & Shephard, 2005), i.e. the visual aspect of visual imagery without the spatial component. In this thesis, shape is not considered to be a feature of object imagery as it comprises spatial components. The term object imagery is arguably often used interchangeably with visual imagery.
Spatial imagery	Relating to spatial relations and movements of objects and their parts, and spatial transformations. (Kozhevnikov et al. 2005). Visual imagery is not necessarily compulsory for the creation of spatial imagery (e.g. Carpenter & Eisenberg, 1978; Marmor & Zaback, 1976).
Propositional representation	Relating to imagery experience, an abstract code that also incorporates semantic knowledge, beliefs, and goals (Pylyshyn, 1973, 2003).

Visuospatial working memory	Visuospatial Working Memory: A working memory subsystem assumed to be responsible for maintaining visual and spatial information (Shah & Miyake, 1996), with the assumption that both types of information are linked. The visuospatial sketchpad comprises of the visual cache, which stores passive static visual perceptual information (i.e. memory for shape and colour), and also the inner scribe (the equivalent spatial component), which actively rehearses information regarding movements and spatial locations (Logie, 1995).

List of abbreviations

ANOVA	Analysis of Variance
BAIS-C	Bucknell Auditory Imagery Scale - Control
BAIS-V	Bucknell Auditory Imagery Scale - Vividness
BFI	Big Five Inventory
BKB	Bamford-Kowal-Bench sentences
BOLD	Blood-oxygen level dependent
CANTAB	Cambridge Neuropsychological Test Automated Battery
fMRI	Functional Magnetic Resonance Imaging
FSIQ	Full-Scale IQ
Gold-MSI	Goldsmiths Musical Sophistication Index
HD	High-Definition
IM	Imagery
M	Mean
MATLAB	The MathWorks Inc., Natick, MA, USA
MDS	Multidimensional Scaling
MOT	Motor Screening
MRT	Mental Rotation Task
O1/O2	Order 1/ Order 2
OBT	Own Body Transformation
OSIQ	Object Spatial Imagery Questionnaire
OTS	One Touch Stocking of Cambridge
PIAT	Pitch Imagery Arrow Task
pg	Page

PRM	Pattern Recognition Memory
Psi-Q	Plymouth Sensory Imagery Questionnaire
QMI	Questionnaire Upon Mental Imagery
RMS	Root-Mean-Square
RPS	Research Participation Scheme
rTMS	Repetitive transcranial magnetic stimulation
SG	Subgroup
SD	Standard Deviation
SMA	Supplementary Motor Area
SSP	Spatial Span
STRAIGHT	Speech Transformation and Representation by Adaptive Interpolation of weiGHTed spectrogram
t	Test statistic
tDCS	Transcranial Direct Current Stimulation
VOSP	Visual Object and Space Perception Battery
VRM	Verbal Recognition Memory
VSWM	Visuospatial Working Memory
VVIQ	Vividness of Visual Imagery Questionnaire
WTAR	Weschler Test of Adult Reading

Chapter 1: Introduction to mental imagery

Overview

For decades, the study of visual imagery has remained a complex and sometimes controversial field of study, mainly owing to the long-standing visual imagery debate that started in the 1970s. For most people when asked to form '*an image*' of a person they are familiar with, or of the house in that they lived, most people will respond that they '*can see it*' within their mind, or that it feels like '*looking'* at a picture. In other words, the subjective experience feels depictive to many, and the question as to whether visual imagery was depictive in nature was at the heart of this long-standing imagery debate. Kosslyn sought evidence to show that visual imagery had depictive qualities, even using an analogy that we have a '*screen'* from which images are displayed within our mind. However, Pylyshyn disagreed with Kosslyn's notion of depictive imagery and argued that visual imagery is symbolic in nature and described it as a thought process represented through abstract code. The behavioural similarities between visual imagery and perception favoured the depictive theory. However, the invention of neuroimaging techniques has re-stimulated interest not only in visual imagery but mental imagery across all sensory domains. The debate regarding the format and neural basis of visual imagery is ongoing. Our understanding of visual imagery has been further enhanced through the examination of imagery performance in patients who have brain lesions and in individuals who are congenitally blind. Furthermore, there has been a recent shift in the literature to examine (and acknowledge) the influence of individual differences. The field of visual imagery has once again gained interest following the formal identification of a subset of the population who consistently report an inability to voluntarily conjure visual images, while perceptual performance remains unimpaired. The phenomenon is known as *aphantasia* and is thought to be experienced by 2-5% of the population. Investigating aphantasia is a new way to understand imagery experience, not only in the visual domain but across all sensory modalities.

1.1. Mental imagery

For most people, mental imagery is an everyday cognitive process that enables one to generate an instantaneous range of fictitious or previously experienced sensory scenarios, free from the constraints of reality. Aristotle (384 – 322 BC) was the first to suggest the pivotal role of mental images, famously claiming that mental images were vital for thought: *'The soul never thinks without phantasma'* (Aristotle, 1984; MacKisack et al., 2016). Despite the familiarity of the subjective imagery experience, historically the nature of imagery has been under much debate and heavily influenced by researchers' own beliefs with regards to the underlying processes (Reisberg, Pearson, & Kosslyn, 2003). As a result of this, there have been a number of variations in the definitions produced to describe this imagery experience; however, most of them share the idea that imagery is a quasi-perceptual experience in the absence of perceptual stimuli. Pearson, Naselaris, Holmes & Kosslyn (2015) pg. 590, refer to mental imagery as '*representations and the accompanying experience of sensory information without direct external stimulus.'* Definitions such as this one, predominantly imply that these representations are conscious and require conscious effort (Thomas, 1999) for subsequent inspection. However, more recent studies have suggested that these representations may also be unconscious (Brogaard & Gatzia, 2017; Nanay, 2018). The '*sensory information*' within the above definition also extends to imagery across all sensory modalities: visual, audition, olfaction, gustation, kinaesthetic, and tactile. Numerous neuroimaging imagery studies have documented similar patterns of brain activation in sensory areas, which are also activated during corresponding perception tasks (e.g. Auvray & Spence, 2008; Bensafi et al., 2003; Ganis, Thompson, & Kosslyn, 2004; Halpern, Zatorre, Bouffard, & Johnson, 2004; Olivetti Belardinelli et al., 2009; Sathian & Zangaladze, 2001). It is acknowledged that perception and imagery are not synonymous. Although it is thought they do share partially common neural mechanisms, the extent and the exact brain networks involved are still debated (see Spagna, Hajhajate, Liu, & Bartolomeo, *submitted*). Despite the range of sensory modalities imagery experiences manifest, the majority of studies and debates undertaken in the field of mental imagery are predominantly in reference to the visual domain. As a result of this, many of the theories established in relation to mental imagery have been based on the findings within the visual domain. To date, visual imagery has remained the most studied modality and shall be discussed from this point forward.

Visual imagery or as it is colloquially referred to '*seeing with the mind's eye*' enables us to perceive an object or scene within the mind, without the object or scene physically present within the visual field (e.g. Kosslyn, Ganis, & Thompson, 2001). The generation of visual imagery arises through the recall of previously perceived information, stored in long-term memory, which can be combined, reinterpreted and modified (Kosslyn et al., 2001). This enables us to create new images using the foundations of stored knowledge (Bartolomeo, 2008). In this way, information can be extracted, and visual images can be reassembled to depict and revisit aspects or scenarios of a visual object or future event (Finke, 1989). Generated visual images are described by some as '*a weaker version of perception*' (Pearson et al., 2015), but the phenomenological experience of the visual image is largely influenced by individual differences in imagery vividness (Faw, 2009; Fulford et al., 2018). The ability to form and manipulate visual imagery is suggested to be key in a wide array of processes (which can also be undertaken non-visually), such as the ability to solve problems, episodic memory, future-think, language comprehension, creativity, and the ability to solve problems and daydream (e.g. Eardley & Pring, 2006; Just, Newman, Keller, McEleney, & Carpenter, 2004; Kosslyn, Thompson, & Ganis, 2006; LeBoutillier & Marks, 2003; Szpunar, Watson, & McDermott, 2007; Zeman, Dewar, & Della-Sala, 2015).

1.1.1. The imagery debate and the role of the primary visual cortex

Having originated primarily in the 1970s and spanning several decades, the infamous imagery debate, or analogue-propositional debate has concerned the representational format of visual images. On the one side of the argument, there were analogue or depictive theories based on the hypothesis that visual imagery was depictive (i.e. pictorial) and that it shared processes to visual perception (Kosslyn, 1973, 1975; Kosslyn et al., 2006; Shepard & Cooper, 1982). This theory relied on the existence of a *visual buffer* (within the primary visual cortex) which was suggested to preserve the same spatial structure as the retina and function similar to a computer array (Kosslyn, 1975, 1981; see also Kosslyn's Computational Model, section 1.2.1). On the other side of the argument, however, non-depictive or propositional theories claimed that visual imagery was derived from abstract code, like language (i.e. non-pictorial) and did not utilise the same mechanisms as visual perception (Pylyshyn, 1973, 2003). Depictive theorists did not deny the existence of propositional properties within imagery; however, the propositional theorists strongly argued that only propositional representations could exist in imagery (Kosslyn et al., 2006; Pearson & Kosslyn, 2015). In brief, a few examples of the seminal studies undertaken during this time involved asking participants to mentally visualise two animals and determine aspects of a shared anatomical feature (Kosslyn, 1975), as well as mental scanning between two points on a map (Kosslyn, 1973) and mental rotation (Shepard & Metzler, 1971). Kosslyn (1975) argued that visual images retain spatial information, such as the spatial relations between objects and their parts and distance. This was reflected as a linear relationship between time and distance the further apart two landmarks were on a map, and also a linear relationship between time and angle of rotation. Kosslyn (1975) proposed that this pattern of performance was indicative that participants were forming visual images within the task, and such images could be viewed from a particular perspective and manipulated much like actual objects. Nevertheless, these interpretations were challenged by Pylyshyn (1973, 1981), who claimed that Kosslyn's findings were due to participants' expectations or 'tactic knowledge,' which suggested that participants used existing knowledge, and their performance in the tasks was influenced by their own beliefs, goals and experimenter demand characteristics.

Moreover, behavioural performance within such tasks during this time could not conclusively conclude the nature of visual images (Anderson, 1978). However, the application of neuroimaging techniques provided compelling evidence to support depictive theories, specifically the idea that visual imagery and visual perception shared common neural mechanisms i.e. topographical visual cortices (Kosslyn et al., 2006; Kosslyn 1994). For instance, in healthy sighted participants, visual imagery was shown to activate the primary visual cortex retinotopically (Slotnick, Thompson, & Kosslyn, 2005). In a repetitive transcranial stimulation study (rTMS), participants exhibited impaired performance on a visual imagery task when stimulation was applied to area V1 (Kosslyn et al., 1999). The authors concluded that this showed the functional role of the primary visual cortex for visual imagery. Perhaps the most compelling evidence for the shared mechanisms in V1 stem from studies that adopt a voxel-wise modelling and decoding approach (Thirion et al., 2006). This models activity and representations created during visual perception and uses the model to decode visual images from brain activity using functional Magnetic Resonance Imaging (fMRI) (Thirion et al., 2006). During this study, the authors developed a voxel-wise model of tuning to retinotopic location, which was subsequently used to decode visual images of high-contrast blobs. These stimuli, however, are not comparable to the complex visual images that one generates of scenes or objects, as these contain rich information, for example, low-level visual features, such as, orientation and position (of objects), which are key in visual perception (Naselaris, Olman, Stansbury, Ugurbil, & Gallant, 2015). Such a voxel-wise modelling and decoding approach was used to show that low-level visual features were encoded in early visual cortical areas (V1 and V2) (Naselaris et al., 2015). The model, which was attuned to detecting only variations in activity in relation to low-level visual features, and could identify visual images associated with this specific pattern of activity across a range of complex images (Naselaris et al., 2015). This decoding supported the claim that these low-level depictive features were present within visual images.

Studies that employ fMRI, specifically blood-oxygen level dependent (BOLD) responses have shown during an imagery task a positive correlation between the self-reported vividness of visual imagery and BOLD activity within the visual cortex (Cui, Jeter, Yang, Montague, & Eagleman, 2007). Likewise, individuals who self-reported high imagery vividness showed greater neural overlap between imagery and perception conditions in the visual cortex compared to participants who self-reported low imagery vividness (Dijkstra, Bosch, & van Gerven, 2017). Anatomically, studies have shown the size of area V1 positively correlated to precision within visual perception and imagery tasks (which examined orientation and location - spatial features of an image) (Bergmann, Genc, Kohler, Singer, & Pearson, 2016). Furthermore, a negative correlation was evident between the size of V1 and imagery strength, a measure that was defined as the effect of priming of visual imagery on visual perception (Bergmann et al., 2016). It should also be noted; the authors showed that subjective vividness ratings of visual imagery correlated to prefrontal cortex volume, rather than the size of V1 (Bergmann et al., 2016). This anatomical variation of V1 has been suggested to be one way to account for possible individual differences within visual imagery (Kosslyn et al., 2001). Collectively, these studies not only support the idea of retinotopic organisation in visual imagery (Slotnick et al., 2005) but also they strongly support of depictive theories of visual imagery.

1.1.2. Evidence questioning the role of the primary visual cortex in visual imagery

Earlier brain imaging research on the relationship between visual perception and visual imagery was presented in terms of an overlap in brain mechanisms. However, there is a growing body of evidence questioning the extent of this overlap within the primary visual cortex. For instance, activation in the primary visual cortex is evident to a lesser extent, with a greater overlap in fronto-parietal areas (Ganis, Thompson, & Kosslyn, 2004). This suggests that larger brain networks are involved in the generation of visual imagery, with visual areas activated by top-down processes from fronto-parietal regions (Ishai, Ungerleider, & Haxby, 2000; Yomogida et al., 2004). Activity within these areas also reflects shared cognitive control processes required for both visual imagery and perception, such as attention or retrieval of information from memory (e.g. Cabeza et al., 2003; Kosslyn, 1994), while activity in regions (other than fronto-parietal areas) has been influenced by the content of the visual image, for instance, differences in activation for imagery of faces compared to imagery of places (O’Craven & Kanwisher, 2000). Specifically, in terms of primary visual cortex, discrepancies in activation during visual imagery tasks have been documented for V1, with several studies showing activation during visual imagery (e.g. Amedi, Malach, & Pascual-Leone, 2005; Mazard, Laou, Joliot, & Mellet, 2005), whereas other studies have not documented activation of this nature in V1 during visual imagery (e.g. Ishai et al., 2000; Yomogida et al., 2004). Discrepancies in activation have been suggested to be caused by individual differences in image vividness, or to be the result of the nature of the high-level resolution details required to be generated within a task (Cui et al., 2007; Kosslyn & Thompson, 2003; Winlove et al., 2018).

Further evidence which contradicts the hypothesis of visual perception and visual imagery showing shared activity in the primary visual cortex (i.e. this similarity is at a lesser extent) stems from studies of patients with brain lesions. There exist some patient studies that document parallel impairments in visual imagery and visual perception; for instance, patients with unilateral visual neglect who ignore objects on one side of their bodies in both visual imagery and visual perception tasks (Bisiach & Luzzatti, 1978). Other studies of patients with brain damage show that they cannot distinguish colours (DeVreese, 1991) or faces (Young, 1994) perceptually, or in visual imagery. However, there are also a number of patient studies (based on patients with achromatopsia, cortical blindness and brain lesions) who show impairments in one process (e.g. visual imagery) but not impairments in another (e.g. visual perception - and vice versa). Patient studies[1] have shown individuals to have a deficit in visual recognition of objects, while they remain unaffected in the ability to conjure a mental image of such an object (Bartolomeo et al., 1998; Bridge, Harrold, Holmes, Stokes, & Kennard, 2012; Chatterjee & Southwood, 1995; Shuren, Brott, Schefft, & Houston, 1996) whereas some have been shown to display normal performance on imagery tasks (Servos & Goodale, 1995).

[1] While collectively these studies provide evidence for a dissociation between visual perception and visual imagery, it should be noted that the imagery tasks used within these case studies differ greatly in nature, for instance, in terms of the task requirements and demands.

Conversely, other case studies have shown that some individuals are unable to form visual imagery; however, they have intact perceptual abilities (Charcot & Bernard, 1883; Farah, 1984; Moro, Berlucchi, Lerch, Tomaiuolo, & Aglioti, 2008; Sirigu & Duhamel, 2001; Zeman et al., 2010). Hence, these studies suggest a double dissociation between visual imagery and visual perception. More recent studies within healthy individuals have shown that visual imagery and visual perception have differing temporal dynamics (Dijkstra, Mostert, de Lange, Bosch, & van Gerven, 2018). The authors showed that when examined in 'real-time,' temporal processing in perception was characterised by distinct stages in temporal processes, which was not evident in visual imagery (Dijkstra et al., 2018). Collectively, these studies suggest that both visual perception and imagery do not share common mechanisms, specifically in the primary visual cortex in the way previously thought, and there is an ongoing debate with regards to these exact brain networks.

Controversially, the authors of a recent meta-analysis (reviewing 52 fMRI studies) have proposed the involvement of the left fusiform gyrus (termed the Fusiform Imagery Node) as the 'hub' for retrieving visual information from long-term memory (from the anterior temporal lobe) and visual information from the occipital cortex (from the ventral pathway) (Spagna et al., *submitted*). The authors suggest that structures in the medial temporal lobe and the fronto-parietal attention networks contribute to the phenomenological experience (the vividness) of visual images (Spagna et al., *submitted*). The role of the frontal areas, specifically the volume of the prefrontal cortex was found to correlate to the subjective vividness ratings of visual imagery within another study (Bergmann et al., 2016). The authors state that this model better accounts for the double dissociation in visual imagery and visual perception evident within patient studies. In these studies, patients who have impaired visual imagery often exhibit damage to the left temporal lobe rather than to occipital areas (Spagna et al., *submitted*). The findings of this meta-analysis are in stark contrast to the majority of the long-standing literature in the field of visual imagery, which reports the dominant role of the primary visual cortex in the generation of visual imagery.

1.1.3. 'Anti-representational' theories of visual imagery

While the imagery debate is claimed to be resolved in favour of the depictive theory, the general consensus is that representations can also be propositional in nature (Kosslyn, 1996; Pearson & Kosslyn, 2015). In view of this, a number of theories following this debate still allude to the notion that visual imagery is not necessarily associated with a pictorial representation, but depends on the body and its interactions (e.g. O'Regan & Noë, 2001). Such theories are described by some as taking an *'anti-representationalist'* viewpoint (Nanay, 2014). One such theory is the enactive approach, which refers to the concept that imagery depends on the action and also on the way the body interacts with the environment (Varela, Thompson, & Rosch, 1991). According to this view, perception is a form of action because perception is deemed to be active in the ongoing exploration of the surrounding environment (Thomas, 1999). It follows that visual imagery is proposed to stem from the re-enactment of visual perception - one must go through the motions of wanting to see an object or item, for instance, a cat, in order to have to *'see'* it. In this way, there is only the action of imagining and its associated eye movements (rather than the experience of a visual representation) which occur as if the item (e.g. the cat) was present in front of us (Johansson, Holsanova, Dewhurst, & Holmqvist, 2012; Laeng & Teodorescu, 2002). However, one of the main objections to this theory is the lack of visual representation when undertaking complex tasks. For instance, Foglolia and

O'Regan (2016) have argued that the re-enactment of visual perception is insufficient to explain the processes needed to perform in complex tasks, such as a mental rotation. Foglolia and O'Regan (2016) state that a mental representation of some description must be involved in this type of complex task.

Likewise, the sensorimotor approach suggests that perception depends on sensorimotor knowledge, that is, a set of conscious rules and possibilities '*of what movements bring about*' (Noë, 2010; O'Regan & Noë, 2001; O'Regan, 2011). For example, if we see an object such as a cup, we use sensorimotor knowledge to know what it looks like if it were to be seen from a different point of view. Unlike the enactive theory, which postulates that in order to see an object we have to engage in the activity of wanting to see it, the sensorimotor theory proposes that we exist in a state of '*attunement*' to sensorimotor laws, which enables us to 'know' how sensory input would change depending on the type of movement (motor output). The notion that visual perception and visual imagery share neural overlaps accounts for the sensorimotor approach. Foglolia and O'Regan (2016) suggest that when one imagines a coffee-cup, the activation corresponds to the knowledge and laws associated with that sensation (or object). Conversely, the lack of overlap between perception and imagery could depend on the lack of body movements that are involved with the interaction with the environment during the process of imagining (Degenaar & O'Regan, 2015). The main criticism of this theory is the way these laws are stored and consciously accessed, especially if they are to support visual imagery (Di Paolo, Buhrmann, & Barandiaran, 2017). In a neuroimaging study, similar cortical activations were evident when participants generated visual images from verbal descriptions and from visual items; this was not to be expected if different types of sensorimotor knowledge systems were involved (Kosslyn, 2005). Kosslyn (2005) suggested that this showed information with regards to objects was retrieved from long-term memory, and not from differing knowledge systems.

More recent theories have integrated elements of the enactive and the sensorimotor approaches to form an embodied representational approach (Palmiero et al., 2019). This approach acknowledges that a mental representation comprises of perceptual, motor, as well as, cognitive (semantic) components, which are all related to a specific experience. These components are stored in long-term memory and retrieved together to form a representation (Palmiero et al., 2019). For instance, a visual image will involve the act of seeing an item (the motor component), the perceptual details of an item (the perceptual component), and the conceptual semantic information about the image (the cognitive component), which together form a '*dynamic embodied representation*.' This view also takes into consideration the variation in individual differences, such as, imagery ability (i.e. imagery vividness), which may influence the different characteristics of the consequent mental imagery (Palmiero et al., 2019). The authors suggest that individuals with high imagery ability are likely to generate detailed visuospatial images (e.g. colour and shape), as well as corresponding motor representations with regards to the act of seeing and handling the object, and semantic information with regards to the conceptual attributes of the object. Whereas, individuals with low imagery vividness will have few visuospatial details, and the representations will comprise of mostly motor and semantic conceptual components (Palmiero et al., 2019). This is still a relatively new theory, but it has potential because it can be applied to other sensory modalities, for instance, to olfactory images, which are associated with perceptual (olfactory expertise), motor (the act of sniffing) and cognitive components (ability to name odours and traits) (Royet, Delon-Martin, & Plailly, 2013).

1.2 Visual and spatial imagery distinctions

Challenging the notion that visual imagery is a unitary construct (Hollenberg, 1970; Paivio & Harshman, 1983), 'visual' imagery is proposed to consist of two distinct subsystems: visual imagery and spatial imagery (Farah, Hammond, Levine & Calvanio 1988; Levine, Warach, & Farah, 1985). Such a distinction is defined within Kosslyn's theory of mental imagery and has been supported by a range of neuropsychological case studies and from individual differences investigations within neurotypical populations (e.g. Bisiach & Luzzatti, 1978; Blajenkova, Kozhevnikov & Motes, 2006; Farah, Levine, & Calvanio, 1988; Kosslyn et al., 2006; Kozhevnikov, Kosslyn, & Shephard, 2005; Levine et al., 1985). Visual imagery (also referred to synonymously as object imagery, see Kozhevnikov et al., 2005) depicts details of texture, colour and brightness[2]. Visual imagery and object imagery are often synonymous because they both refer to visual aspects or 'object' characteristics of an object. Contrastively, spatial imagery depicts the spatial layout; hence spatial relations between or among objects or parts of an object, the object location, its orientation and its corresponding movements through space.

While distinctions have been made between visual and spatial imagery, Kosslyn's theory of mental imagery considers both sub-types as separate yet inextricably linked to each other (Kosslyn et al., 2006). More generally, research into visual imagery generally examines both constructs, e.g. visuospatial imagery. However, in individuals who are congenitally blind (no vision from birth), research suggests that in the absence of visual input, they utilise non-visual sensory systems, such as, touch (through perceptual

[2] In the visual imagery literature, aspects such as shape and texture are often considered characteristics of visual imagery (e.g. Farah et al., 1988; Kozhevnikov et al., 2005). However, shape can also comprise of spatial information as objects can be processed spatially through structural components, such as spatial relations between parts of an object (Biederman, 1987). Similarly, texture can be both visual and tactile (Eardley & Pring, 2014). Thus in this context and thesis, texture and shape are not assumed to be 'visual' features, even though the information can be acquired through vision.

exploration), audition and proprioception modalities to form internal spatial representations (Occelli, Spence, & Zampini, 2008). This indicates that spatial imagery can exist in the absence of a 'visual' component (see section 1.2.4 for a discussion).

1.2.1. Kosslyn's Theory of Mental Imagery

The most prominent theory of visual imagery in neurotypical sighted individuals is Kosslyn's Theory of Mental Imagery, which had been developed from the depictive (Computational Model) theory. Briefly, Kosslyn's Computational model (Kosslyn, 1981; Kosslyn, 2005) is based on the analogy that visual images are displayed on an internal visual display system akin to a computer screen known as the '*visual buffer*,' a topographically organised area of the visual cortex (Kosslyn, 2005). It was the role of the '*attentional window*' to shift and scan across an image within the visual buffer, through which the properties of the image, such as the shape, size or spatial location can be consciously inspected (Kosslyn, 1981; Kosslyn, 2005). Kosslyn (1981) postulated that the visual buffer received information from long-term memory, which originated in the visual system. Although the Computational Model focused on the visual domain, Kosslyn (1994) stated that there would be a corresponding process in the other sensory modalities, but provided no other details.

Building on the Computational Model, Kosslyn developed his theory of mental imagery, which made a distinction between visual and spatial images (Kosslyn, 1994; Kosslyn et al., 2006; Kosslyn, 2005). Both visual and spatial images differ in their content, but it was viewed that both types of imagery have a spatio-analogical structure (Kosslyn et al., 2006). According to this theory, spatial images comprise of information with regards to location, size, the relations among objects and their orientation; these are processed partially within the parietal lobe, an area which is viewed to be topographically organised (Sereno, Pitzalis, & Martinez, 2001). Kosslyn et al. (2006) suggested that spatial imagery uses similar processes needed to processes spatial information during visual perception.

In contrast, visual images are constructed in the visual buffer within area V1, and they comprise of information relating to shape, colour and texture; thus they are depictive in nature (Kosslyn et al., 2006). Both of these imagery sub-types undergo four processes: generation, inspection, maintenance and manipulation. According to Kosslyn et al. (2006), visual and spatial images are generated from the retrieval of information from long-term memory. Visual information can be presented in the visual buffer for inspection. However, the visual buffer is not needed for spatial imagery, and it is unclear from the model how or even if spatial information is presented or inspected. The authors state that the 'visualised' part of a visual image is only the part which is present in the visual buffer (and must match the stored representations in long-term memory) – this visual image is a small part of a spatial image (Kosslyn et al., 2006). The processing of both spatial and visual images occurs in parallel (Kosslyn et al., 2006). The construction of a visual image (e.g. an object) also requires information about its spatial properties (e.g. location), information that is found in the content of spatial images (Kosslyn et al., 2006). The manipulation of an image alters the spatial image, which underlies the visual image. For example, the manipulating and alteration of the size of an object in spatial imagery changes the overall presentation of the visual image of that object (presented in the visual buffer) (Kosslyn et al., 2006; Kosslyn, 2005).

While a distinction is made between visual and spatial images which comprise of different types of information, the theory relies heavily on the notion that the areas that are active in visual perception are also active in visual imagery. Furthermore, it depends on the idea that there exists a medium, i.e. the visual buffer, a topographically organised area of the primary visual cortex, which possesses a functional role in forming the depictive phenomenological experience of visual imagery.

1.2.2. Visual and spatial imagery dissociation in neuropsychological case studies

One of the most prominent patient studies that identified the dissociation between visual and spatial imagery was undertaken by Farah et al. (1988). The authors described patient *LH,* who in the aftermath of an automobile accident, exhibited difficulties in performance within a range of visual imagery tasks. These included tasks requiring the ability to distinguish the colour of common household objects, and mental size comparisons of the size of animals' tails (Farah et al., 1988). However, in spatial imagery tasks, such as mental scanning and mental rotation, patient *LH* performed just as well as neurotypical controls (Corballis, 1997). A similar case study involved patient *LE* who suffered systemic lupus erythematosus (resulting in vast damage to white matter) and was unable to generate visual images and exhibited poor performance in visual short-term memory and recognition tasks (Morris, Abrahams, Baddeley, & Polkey, 1995). Despite this, however, patient *LE* showed unimpaired performance in spatial imagery tasks and was able to draw figures from short-term memory (Della Sala, Gray, Baddeley, & Wilson, 1997).

Bisiach and Luzzatti (1978) reported the case of an individual with intact visual imagery but with spatial imagery impairment. The authors presented the case study of patient *EP* who suffered from slowly progressive deterioration of the brain and atrophy of the anterior right temporal lobe. Although patient *EP* performed accurately on visual imagery tasks that included making accurate colour distinctions of household objects, patient *EP* performed poorly on tasks that involved making judgements with regards to the spatial locations of such objects (Bisiach & Luzzatti, 1978). A similar pattern of performance was evident in the case of patient *MV,* who following an ischemic stroke, displayed impairments in spatial imagery tasks, such as mental rotation (Carlesimo, Perri, Turriziani, Tomaiuolo, & Caltagirone, 2001). Nevertheless, patient *MV* was able to perform within a normal range in visual imagery tasks (Carlesimo et al., 2001). Overall, these observations suggest that visual imagery and spatial imagery are dissociated and that each of these subtypes of imagery is served by different brain networks (Carlesimo et al., 2001; Levine et al., 1985).

Although the case studies discussed suggest a distinction between visual and spatial imagery by showing an impairment in one construct but not in the other (and vice versa), nonetheless, the two processes remain intimately associated with one another. For instance, tasks that involve the ability to distinguish the colour of common objects, at least to some extent, require the recall of integrated spatial information with regards to the shape and the form of the object. Biederman (1987) postulated that in neurotypical sighted individuals, shapes or object stimuli are recognised and processed spatially by means of their structural components (Biederman, 1987). Therefore, visual and spatial imagery remain linked to one another, although tasks tend to load more heavily on one of them (i.e. visual imagery) than the other (i.e. spatial imagery), and vice-versa.

1.2.3. Imagery distinctions in neurotypical populations

Neuroimaging studies have documented differences in brain activation during visual and spatial image tasks in healthy populations (e.g. Kosslyn & Thompson, 2003; McCarthy et al., 1996; Smith et al., 1995; Zacks, 2008). It should be noted that distinctions between visual (object) and spatial subsystems are also evident within visuospatial working memory, shown within behavioural and neuroimaging studies (e.g. Klauer & Zhao, 2004; Mazard, Tzourio-Mazoyer, Crivello, Mazoyer, & Mellet, 2004). These subsystems are underpinned by functionally and anatomically separate processing pathways: the 'where' or 'how' pathway in the dorsal system (from the occipital lobe to the posterior parietal lobe), which processes spatial information with regards to the location of the object and its movements. Contrastively, the 'what' or ventral system (from the occipital lobe to the inferior temporal lobe) processes information about the visual characteristics of an object, such as, colour and shape (Borst, Thompson, & Kosslyn, 2011; Goodale & Milner, 1992; Kozhevnikov, Blazhenkova, & Becker, 2010).

A number of studies examining individual differences have also provided evidence for visual and spatial distinctions (Blajenkova et al., 2006; Kozhevnikov, Hegarty, & Mayer, 2002; Kozhevnikov et al., 2005). Kozhevnikov et al. (2005) demonstrated that individuals who were visualisers (i.e. who interpret information visually, rather than verbally), could be divided into two distinct groups: object imagers and spatial imagers. Hence object imagers used imagery to generate pictorial, colourful high-resolution visual images of scenes and objects, while spatial imagers used imagery to assess the spatial relationships between or among objects to undertake difficult spatial transformations (Kozhevnikov et al., 2005). In behavioural tasks, object imagers outperformed spatial imagers on object imagery tasks, for instance, object imagers excelled in object recognition tasks, such as, a degraded picture task, which entailed the generation of high-resolution visual images (Kozhevnikov et al., 2005) Contrastively, spatial imagers outperformed object imagers on spatial imagery tasks, such as mental rotation, which required spatial transformations of objects (Kozhevnikov et al., 2005). Object imagers were suggested to process images globally, whereas spatial imagers process images segment-by-segment in a sequential manner (Kozhevnikov et al., 2005).

Individual preferences for object and spatial imagery can also be assessed through self-report measures (Blajenkova et al., 2006). Although few studies have examined the neural underpinnings for these individual differences, nevertheless, Kozhevnikov et al. (2010) postulate that there is a 'bottleneck trade-off' during the development of visual-processing resources. However, the authors provided no other details of how this could occur. Additionally, Kozhevnikov et al. (2010) claim that this developmental trade-off is the reason why visualisers show either visual or spatial preferences; hence this is not the result of the individual preference of one ability over the other. Of the few neuroimaging studies to explore individual differences of these imagery subtypes, studies have shown that spatial and object imagers have efficient neural resources in regions associated respectively with spatial and object processing pathways (Lamm, Bauer, Vitouch, & Gstättner, 1999; Motes, Malach, & Kozhevnikov, 2008).

1.2.4. Imagery in the blind: Imagery without visual experience

In conjunction with research in mental imagery in sighted individuals, it is also worth considering mental imagery in individuals who are totally congenitally blind, and those who have lost their sight in early infancy. The review of research of individuals who are totally congenitally blind provides further insight into the relationship between visual and spatial imagery. This focuses on the issue of whether visual input is essential for either construct or whether one can exist (e.g. spatial imagery) in the absence of the other (e.g. visual imagery). If it is assumed that vision is crucial to imagery, then one could hypothesise that totally blind individuals with no visual memory experience mental imagery that is propositional in nature. For instance, they possess mental imagery that comprises of abstract and semantic representations. In view of this statement, it could be assumed that this propositional format of imagery would result in differences in performance in tasks that are analogical in nature (i.e. pictorial or depictive). Nevertheless, substantive evidence shows that individuals who are congenitally or early blind in life are able to perform similarly to sighted individuals on 'visual' imagery tasks, such as, mental rotation and haptic versions of Kosslyn's mental scanning paradigm (Carpenter & Eisenberg, 1978; Kerr, 1983; Marmor & Zaback, 1976; Zimler & Keenan, 1983). A number of studies have shown that blind individuals take longer to rotate a stimulus or to scan mentally in comparison with sighted individuals (Kerr, 1983; Marmor & Zaback, 1976). Hence Marmor and Zaback (1976) have argued that differences in reaction time were not because congenitally blind participants used propositional strategies, but because mental rotations were '*easier to perform upon visual representations than non-visual ones*' (Marmor & Zaback 1976, pg. 520). Despite the lack of vision, congenitally blind individuals were able to perform in these 'visual' imagery tasks, and they created analogue spatial representations from sensory information acquired through non-visual perceptual or through verbal means (Aleman, van Lee, Mantione, Verkoijen, & de Haan, 2001; Kaski, 2002; Vecchi, Tinti, & Cornoldi, 2004). Therefore, the performance of congenitally blind individuals demonstrates that these tasks can be undertaken and performed without a 'visual' component.

Furthermore, Kerr (1983) claimed that a 'visual' imagery task is best described as a 'spatial' imagery task. In view of this, numerous tasks cited in the literature can be referred to as spatial imagery tasks. For example, mental rotation and mental scanning can be classified as spatial tasks because they involve either the movement of stimuli/an object through space or the approximation of a distance. What is more, other types of tasks described as 'visual' arguably are 'spatial'; for instance, they include tasks which involve comparisons of sizes of animals, or other features, such as, their tails (Farah et al., 1988; Kosslyn, 1975). In their case study, Farah et al. (1998) documented the performance of patient LH who performed at 65% accuracy in an animal tails task compared to neurotypical controls who performed at 96%. While LH's accuracy was significantly lower than the neurotypical controls, LH's performance was above chance. It may be the case that such comparisons can be answered with spatial imagery, however, greater accuracy in the task is achieved if one can also visualise (i.e. form a visual representation) the animals in question. Therefore, these tasks could be considered spatial tasks as neurotypical sighted individuals can recognise objects (i.e. features of animals) spatially through their structural components (Biederman, 1987). Although Kerr (1983) viewed 'visual' images as 'spatial' because individuals who are congenitally blind were not reliant on the 'visual' component, the term 'visual imagery' in sighted individuals is viewed to comprise of imagery combining both visual and spatial features (Kosslyn et al., 2006). These are assumed to be closely associated with one another and potentially difficult to separate. While it is assumed that both constructs cannot be fully dissociated (but may load more heavily on one than the other), evidence from congenitally blind populations suggest that spatial imagery can exist in the absence of vision.

Where visual information is not available, mental imagery is forcibly generated from non-visual sensory modalities: touch (via haptic exploration), audition, olfaction and proprioception (Goldreich & Kanics, 2006; Roder, Rosler, & Spence, 2004; Théoret, Merabet, & Pascual-Leone, 2004; Wan, Wood, Reutens, & Wilson, 2010). It is commonly believed that if one sensory modality is impaired or absent, perceptual processing in the remaining senses (such as audition and tactile acuity) become more practised in its absence (Théoret et al., 2004). However, it should be noted that the results from studies testing this sensory compensation tend to be varied owing to individual differences of the participant sample within these studies. For example, participants' performance on tasks is influenced by factors, such as the age of the participant, aetiology and manifestation of the visual deficit, duration and age from visual deficit onset, musical and mobility ability (Thinus-Blanc & Gaunet, 1997). Nevertheless, a number of studies have shown that congenitally blind individuals perform better than their sighted counterparts in some perceptual tasks, for example, they show better sound localisation (Voss et al., 2004), and they also have enhanced verbal abilities (Occelli, Lacey, Stephens, Merabet, & Sathian, 2017). Furthermore, eye movements in congenitally blind participants (if they have eyes) have been observed in association with spatial attention of auditory information (Dufour, Després, & Candas, 2005). A similar pattern of eye movements has also been found in sighted individuals during auditory tasks (Rorden & Driver, 1999). In relation to tactile acuity, studies have shown that early blind participants perform better than sighted participants in tactile tasks that require the ability to discriminate among the textures of different surfaces (for instance smooth verses thinly grooved) (Goldreich & Kanics, 2006). Goldreich and Kanics (2003) state that blind individuals (compared to sighted individuals) have a more refined and superior capacity to decode spatial information from touch (Goldreich & Kanics, 2003). The absence of visual cues results in the enhancement of audio-tactile spatial interactions (Occelli et al., 2008).

Moreover, multisensory integration of non-visual sensory information is crucial to update the body's position within space, and it is also necessary for successful navigation of the environment (Butler, Smith, Campos, & Bulthoff, 2010; Prsa, Gale, & Blanke, 2012; Schmidt, Tinti, Fantino, Mammarella, & Cornoldi, 2013). Sighted individuals use vision, which among all the senses available, provides accurate information with regards to the layout of the surrounding space (Loomis, Klatzky, Philbeck, & Golledge, 1998). However, blind individuals gather this type of spatial information via audition and proprioception, which can jointly provide information on the range of distances within space (Kolarik, Moore, Zahorik, Cirstea, & Pardhan, 2016). A number of studies have shown that the congenitally blind find it more difficult to adopt an allocentric frame of reference compared to the sighted or the late blind individuals (Cattaneo et al., 2008; Schmidt et al., 2013; Thinus-Blanc & Gaunet, 1997). However, this observation is very task dependent, with reference frames heavily influenced by task-related variables, such as the size of the space to be explored within a task (Iachini, Ruggiero, & Ruotolo, 2014; Loomis et al., 1993). It has been claimed that the absence of visual experience affects the processing of object-to-object spatial relations; therefore somatosensation is required in order to acquire spatial information (Ruotolo, Ruggiero, Vinciguerra, & Iachini, 2012). Overall, collectively these studies show that information gathered perceptually from touch, audition and from proprioception modalities provides rich spatial mental representations and compensates for the lack of visual perceptual input.

1.3 Visuospatial working memory (VSWM)

Both visual imagery and visuospatial working memory concern the ability to represent and manipulate visual information (which comprise visual and spatial features). The main distinction between these two systems is that visuospatial working memory refers to the maintenance of recently presented images, while visual imagery concerns the generation of images that have not been presented (e.g. Albers, Kok, Toni, Dijkerman, & de Lange, 2013). Another distinction is that visual images are generated on the basis of information stored in long-term memory, which is not the case for visuospatial working memory, as it stores information from direct visual perceptual input (Borst, Ganis, Thompson, & Kosslyn, 2012). Although both visuospatial working memory and visual imagery processes involve similar types of information, the precise relationship between these two processes remains unclear (Logie & Cowan, 2015). Nevertheless, it is considered that they may share common cognitive processes, including representations which are depictive (Borst et al., 2012). Historically, the majority of research has examined these two processes separately and used different behavioural paradigms with little reference to either field (Tong, 2013). More recent studies have examined the relationship between visual imagery within visuospatial working memory paradigms (e.g. Keogh & Pearson, 2011). Other studies have claimed that cortical regions involved in perceptual processing also play a part in the maintenance of information in visuospatial working memory (Scimeca, Kiyonaga, & D'Esposito, 2018), although this is not a claim viewed by all (e.g. Harrison & Bays, 2018). The following section will briefly outline the most dominant theory of working memory, followed by a review of the recent literature comparing the similarities and differences between visuospatial working memory and visual imagery.

1.3.1. Brief overview of working memory theory

In 1974, Baddeley and Hitch proposed a multicomponent working memory model which has evolved to be the most prominent theory of working memory (although see Miyake and Shah (1999) for a review of alternative working memory models). Originally this model comprised of three components: the central executive, the phonological loop and the visuospatial sketchpad. These components exist independently of one another in that they process different types of information and have finite capacities (Baddeley & Hitch, 1974).

The central executive represents the attentional capacity for managing the two 'slave' systems: the phonological loop and the visuospatial sketchpad. The phonological loop plays a role in the storage and maintenance of auditory information, such as, verbal speech and it contains an active and a passive store for the rehearsal of auditory information (Baddeley, Eldridge, & Lewis, 1981). The visuospatial sketchpad or visuospatial working memory is responsible for the storage and maintenance of '*visual*' and '*spatial*' information. It consists, firstly, of the visual cache, which stores passive static visual perceptual information (i.e. memory for shape and colour) and, secondly, of the inner scribe (the equivalent spatial component), which actively rehearses information with regards to movement and spatial location (Logie, 1995). The inners scribe can be subdivided further to deal with dynamic or static spatial information (Mammarella, Pazzaglia, & Cornoldi, 2008). Information in the visual cache is subject to decay or interference from new information that enters the store unless the information is maintained and refreshed by the inner scribe (Logie, 1995; Logie & Pearson, 1997). Later the episodic buffer was added to the model to describe the interactions and communications between the phonological loop, the visuospatial sketchpad and long-term memory (Baddeley, 2000).

1.3.2 Ambiguities and differences: visuospatial working memory and visual imagery

During a visuospatial working memory task, perceptual information is held in the visual cache, and it is rehearsed by the spatial inner scribe (Borst, Ganis, Thompson, & Kosslyn, 2012; Logie, 1995; Pearson, Logie, & Gilhooly, 1999). Thus, in such a scenario, the visual cache acts as a visuospatial short-term memory store of perceptual information. According to Pearson (2001), the visual cache contains representations from perception, but these are not visual images. It is the information from the visual cache that can be used to create visual images; these transfer across to the '*visual buffer*' where conscious mental images are experienced (Pearson, 2001). It should be noted, however, that the attributes of the visual cache described in the literature are somewhat confusing, especially, in terms of its relationship to the '*visual buffer*' The visuospatial working memory '*visual buffer*' is claimed to be closely associated to the '*visual buffer*' described within the theory of mental imagery (Kosslyn, 2006). However, the literature is often unclear whether this is one (or the same) construct. Some studies postulate that the two buffers are 'associated' with one another (e.g. Pearson, 2001) while other studies assume they are the same constructs (Borst, Niven, & Logie, 2012).

Moreover, there are contrasting views on whether the contents of the visual cache are conscious (or not). For instance, Pearson (2001) claims that information from the visual cache passes to the *visual buffer* to be consciously experienced. It has also been claimed that (abstract) images in the visual cache can also be consciously experienced when items are actively mentally rehearsed (Logie & Cowan, 2015) presumably by the inner scribe. Nevertheless, it is viewed that the '*visual buffer*', as described by Pearson (2001) is distinct from the visual cache (Borst et al., 2012; Logie, 1995; Pearson et al., 1999). Unlike the visual buffer, the visual cache mediates the maintenance of visual information from visual perception, but it can also maintain visual representations from long-term memory (i.e. visual images) (Borst et al., 2012). Furthermore, Borst et al. (2012) suggest that visual images are not maintained in the visual buffer, but they are preserved in the visual cache, due to the likely interference from visual perceptual inputs.

If the two '*visual buffers*' described in visual imagery and in visuospatial working memory are different constructs, they are suggested to have characteristics in common

(Logie, 1995, 2003), but also differ in a number of ways. In the theory of mental imagery, the visual buffer is described as a topographically organised area of the primary visual cortex (Kosslyn, 2006). However, no such information has been provided with regards to the structure of the visual buffer in visuospatial working memory. In terms of Kosslyn's buffer, visual images are consciously experienced by an attentional window (Kosslyn, 2006), while in visuospatial working memory, the contents of the visual buffer are to some extent maintained by the central executive (Pearson, 2001). Moreover, the visual buffer in visuospatial working memory is thought to be supported by the visual cache, which acts as a passive temporary store of visual representations (that are not presented in the buffer). According to Quinn (2008), this information is held outside of conscious awareness. This information is thought to be stored at a lower resolution in an abstract format; it is protected from incoming visual perpetual interference (Quinn, 2008) because the visual cache is considered to use the posterior parietal cortex rather than the primary visual cortex (Pearson & Keogh, 2019). Compared to the visual buffer, which is described as prone to interference from visual perception due to its situation in the primary visual cortex, similar to Kosslyn's (2006) visual buffer (Borst et al., 2012; Borst, Niven, & Logie, 2012). Irrespective of whether the two visual buffers are the same, they are viewed to be functionally and structurally distinct from the visual cache (Borst et al., 2012; Logie, 1995; Pearson et al., 1999; van der Meulen, Logie, & Della Sala, 2009).

Logie (2003) suggests that both visual imagery (the visual buffer) and visuospatial working memory (specifically the visual cache) rely on partially different structures. Evidence for this stem from the results of passive interference tasks that present irrelevant visual information, such as, dynamic visual noise interference. These tasks have shown to interfere selectively with visual imagery rather than with visuospatial working memory

(Andrade, Kemps, Werniers, May, & Szmalec, 2002; van der Meulen et al., 2009). However, such interference has not been documented in all the studies conducted (Avons & Sestieri, 2011). These observations indicate that dissociations exist between the visual cache, which supports visuospatial working memory, and the visual buffer, which supports visual imagery (Andrade et al., 2002; van der Meulen et al., 2009), thus they must be based on partially different processes. The use of the visual cache and that of the visual buffer within visuospatial working memory also depends on the type of visual information that needs to be maintained. High-level visual details during a visuospatial working memory task are suggested to require repeat generation of the image, which require the use of the visual buffer, rather than the sole use of visual information in the visual cache (Darling, Della Sala, & Logie, 2009; Kosslyn & Thompson, 2003). Overall, although there are many ambiguities and differences (more so theoretically) between the way visual imagery and visuospatial working memory relate to one another, they remain closely associated with each other.

1.3.3. Does visual imagery play a role in visuospatial working memory?

Visual imagery and visuospatial working memory share common characteristics. For instance, it is suggested that both rely on representations that are depictive in nature (Borst et al., 2012). Visual noise interference that comprises a structured visual pattern (i.e. interference that shares characteristics with objects or stimuli used in tasks) interferes with both visual imagery and visuospatial working memory in a similar capacity (Borst et al., 2012). This may be the case because irrelevant visual input interferes with the temporary storage of detailed visual information, which may require visual imagery generation within the visual buffer (Darling et al., 2009). Borst et al. (2012) suggest that from this view if they share depictive representations, they must partially rely on some cognitive processes. Sensory recruitment accounts of working memory also propose that cortical regions involved in perceptual processing are involved in the maintenance of information in working memory (Scimeca et al., 2018).

A number of studies have suggested that the primary visual cortex (among other areas, see review D'Esposito & Postle, 2015) play a role in the maintenance of visual information within visuospatial working memory (e.g. Ester, Serences, & Awh, 2009; Harrison & Tong, 2009; Kang, Hong, Blake, & Woodman, 2011; Pearson & Keogh, 2019; Scimeca et al., 2018). If visuospatial working memory involves the primary visual cortex (where detailed visual information is suggested to be generated and maintained), this would explain why interference tasks, which use visual noise such as irrelevant pictures or perceptual stimuli, impair performance in visual imagery and visuospatial working memory tasks (Borst et al., 2012; Keogh & Pearson, 2011, 2014). This would suggest both of these processes share common mechanism (i.e. the visual buffer).

It has been documented that when visuospatial working memory tasks are undertaken, some participants self-report the experience of generating highly-detailed visual representations of task stimuli for manipulation processes to occur (Gur & Hilgard, 1975; Harrison & Tong, 2009). This suggests that individuals can use visual imagery as a possible strategy within visuospatial working memory tasks. Specifically, in the study conducted by Gur and Hilgard (1975), participants were presented with two picture cards, one after the other. After a short interval, they had to identify the features that differed in the two pictures. The authors of the study found that individuals who were 'good' imagers were quicker in reporting the features which were different. For example, they self-reported that differences between images '*popped ou*t' and the participants described the process akin to overlaying one picture over the other one. This was not the case for poor imagers who exhibited slower performance on the task (Gur & Hilgard, 1975). These observations have led to the acknowledgement that visual imagery may play a cognitive role within visuospatial working memory; they also support research previously conducted that claimed that they rely on common depictive representations (Borst et al., 2012).

As observed in the study conducted by Gur and Hilgard (1975), the use of visual imagery in visuospatial working memory is influenced by individual differences, namely, the vividness of visual imagery. In an interference study, interference was shown to be more pronounced in individuals who were more vivid imagers compared to poor imagers (Keogh & Pearson, 2014). Similarly, Keogh and Pearson (2011) showed that the strength (i.e. self-reported vividness) of visual imagery correlated with visuospatial working memory performance, in that individuals who were 'good imagers' performed better than 'poor imagers' on visuospatial working memory tasks. These findings suggest that if one has vivid visual imagery, they are more likely to use it as a strategy within visuospatial working memory tasks, but this is not the case for an individual with poor imagery who are more likely to adopt non-visual strategies (Pearson & Keogh, 2019). This would arguably involve the recruitment of differing brain areas and networks (Logie, Pernet, Buonocore, & Sala, 2011; Sanfratello et al., 2014) and may also be the reason as to why there are contrasting findings in interference paradigms (as denoted in section 1.3.2), whereby interference (with visual noise) is evident in some studies but not all. It may be the case that these participants differed in the vividness of their visual imagery, although this cannot be confirmed as no indication of imagery vividness is provided in these studies.

Neuroimaging studies have also shown that when visual imagery is used as a strategy within visuospatial working memory tasks, there is considerable overlap in activity (Albers et al., 2013; Harrison & Tong, 2009; Kosslyn et al., 2001). This suggests that visuospatial working memory and visual imagery share similar cognitive (Borst et al., 2012) and neural representations (Albers et al., 2013; Slotnick, Thompson, & Kosslyn, 2012). In the case of individuals with poor imagery, Keogh & Pearson (2019) have claimed that non-imagery-based strategies, such as, propositional semantic information can be adopted in visuospatial working memory tasks, which can also result in good performance within the task.

1.4. Extremes of imagery experience

Sir Francis Galton (1880) was the first to observe that individuals experienced a wide range of imagery vividness (Galton, 1880). However, it had been assumed that although there were individual differences, imagery was a part of everyday cognition for most neurologically intact people. Identified in 2015, *aphantasia* (Keogh & Pearson, 2017; Zeman et al., 2015) is characterised by the lack of visual imagery experienced by an estimated 2-5% of the population (Faw, 2009). Historically in the literature, there exist few case studies documenting the lack of visual imagery. The majority of these case studies report an acquired sudden inability to generate visual imagery caused by brain trauma (e.g. Botez, Olivier, Vezina, Botez, & Kaufman, 1985). Research into aphantasia is in its infancy; it has been investigated only in six experimental studies (Dawes, Keogh, Andrillon, & Pearson, 2020; Jacobs, Schwarzkopf, & Silvanto, 2017; Keogh & Pearson, 2017; Zeman et al., 2010, 2015; Zeman et al., 2020). Additionally, several unpublished studies have been conducted (Bainbridge, Pounder, Eardley, & Baker, 2020; Wicken, Keogh, & Pearson, 2021; Milton et al., *submitted*).

This section will present, firstly, an outline of historical case studies which have documented the lack of visual imagery in the absence of trauma. Secondly, it will review the currently existing aphantasic literature. While writing this thesis, another unique variation of human experience had been identified, known as *hyperphantasia,* which is characterised by visual imagery that is as '*vivid and real as seeing*' similar to photographic imagery (Zeman et al., 2020; Milton et al., *submitted*). While the number of hyperphantasic participants within the subsequent experiments of this thesis is identified, it is not the focus, nor the intention to compare and contrast the two ends of the imagery spectrum in this thesis. However, a brief summary of hyperphantasia is included in this section.

1.4.1 Historic cases studies describing a sudden loss of visual imagery

Historically, there are relatively few case studies which document individuals self-reporting an acquired sudden inability to generate visual imagery, in the absence of trauma. One of the earliest cases of visual imagery deficits was described by Charcot and Bernard (1883, cited in Young & van de Wal 1996) who presented *Monsieur X.* This individual experienced the sudden inability to generate visual images in conjunction with a form of mild prosopagnosia. In another case study, a 38-year-old individual self-reported the inability to form visual mental images from birth but did not display other impairments in visual perception or visual memory (Botez et al., 1985). In both case studies, the authors did not document whether the impairments in visual imagery extended to other sensory modalities, and the patients were not subjected to an extensive assessment of their imagery abilities.

There are numerous case studies that present individuals, who as a result of trauma, display an acquired loss of visual imagery (e.g. Bisiach & Luzzati, 1978; Farah, 1984, see also section 1.2.2). Brain (1954) has described two cases of the inability to form visual imagery following head injury. In one such case, a builder who was involved in a car collision was suddenly unable to mentally visualise blueprints of buildings on which he worked, and he also found it difficult to navigate routes with which he had been familiar. This was in stark contrast to his visual imagery abilities prior to the accident (Brain, 1954). Despite this, however, the impairment had no effect on his ability to draw. The second case involved an individual who acquired a visual imagery deficit following a fall, and he claimed to be unable to '*see anything*' in his mind. Despite this self-report, the individual still performed well on visual imagery tasks (Brain, 1954). Unfortunately, both of these cases occurred prior to the development of neuroimaging, and these patients were not subject to any further standardised tests of visual imagery or investigation into their experience of imagery across other sensory domains.

A neuroimaging study of two patients (referred to as Patient 1 and Patient 2) both of whom experienced closed head injuries, which resulted in multiple brain lesion including lesions in the left inferior temporal gyrus (Moro et al., 2008). This is an area implicated in visual imagery (Bartolomeo, 2002; Mellet et al., 2000). Brain lesions were not evident in the primary visual cortex in either patient; nevertheless, both of them reported the absence of visual imagery, and they exhibited unimpaired visual, perceptual, language and memory abilities (Moro et al., 2008). Both patients performed worse in visual imagery tasks with regards to the characteristics and features of common objects, such as the description of road signs and everyday symbols (Moro et al., 2008). Although performance in other sensory imagery modalities was unaffected in one patient, nonetheless, the other patient experienced an imagery impairment in tactile imagery. In view of this, the authors suggested that these sensory modalities have separate neural substrates (Moro et al., 2008).

1.4.2. The identification of congenital aphantasia

The term *congenital aphantasia* (from Aristotle's *'phantasia'* meaning mind's eye, and '*a'* meaning absence), has been coined to describe a sub-set of the population who self-report the inability to generate voluntary visual imagery, while visual perception and semantic memory remain intact (Keogh & Pearson, 2017; Zeman et al., 2015). This variation in imagery experience was identified following the case study of patient *MX*, who following a coronary angioplasty procedure, self-reported the inability to generate visual images (Zeman et al., 2010). On visual imagery self-reports, such as the Vividness of Visual Imagery Questionnaire (VVIQ), he rated himself to have no imagery. Nevertheless, *MX* performed as accurately as individuals with typical imagery on several different imagery tasks; these tested the ability to perform mental rotation and to judge the length of animals' tails (Zeman et al., 2010). During the mental rotation task, however, *MX* displayed longer reaction times compared to neurotypical controls, which the authors explained in terms of *MX* adopting a different strategy in the task (Zeman et al., 2010). The strategy used was not specified, and with regard to the other imagery tasks performed, no measurements or indications of reaction time were provided (Zeman et al., 2010).

An article which described the experience of *MX* was featured in science magazine *Discover* (Zimmer, 2010); subsequently, 21 individuals contacted the author to describe their lifelong inabilities to generate visual imagery (Zeman et al., 2015). These congenital aphantasic individuals self-reported their experiences of aphantasia as stable and life-long; typically, they discovered that their imagery experience differed from those of the majority of the population during their teens or early twenties (Zeman et al., 2015). The majority of individuals included in this sample also reported experiences of involuntary '*flashes'* of visual imagery during wakefulness, at sleep onset or while dreaming (Zeman et al., 2015). Aphantasics' ability to dream and recall the visual content of their dreams has been documented in recent studies (Dawes et al., 2020; Zeman et al., 2020). This implies that aphantasia is not characterised by a total deficit in visual imagery but by 'reduced or absent' voluntary imagery (Zeman et al., 2015; Zeman, Della Sala & Dewar, 2016). Since 2015, thousands of individuals with aphantasia have contacted Zeman to describe their life-long inabilities to conjure visual imagery. In addition, a number of prominent figures such as the physicist Nick Watkins (Watkins, 2018), the neurologist Oliver Sacks and the retired president of Pixar and Walt Disney Ed Catmull (Gallagher, 2019) have also shared their personal insights and perspectives.

1.4.3. Understanding congenital aphantasia

One of the commonalities in studies investigating aphantasia is that the majority of individuals with aphantasia provide the minimum score (of 16[3]) on visual imagery self-report measures such as the VVIQ. The majority of studies have used this as a means to identify individuals with aphantasia within their sample, albeit with different cut-off criteria (Bainbridge et al., 2020; Jacobs et al., 2017; Keogh & Pearson, 2017; Wicken et al., 2021; Zeman et al., 2015; Zeman et al., 2020). Much of the earlier research investigating aphantasia involved either case studies or studies which comprised of a small number of participants and age-unmatched samples (Jacobs et al., 2017; Keogh & Pearson, 2017). For instance, the case study by Jacobs et al. (2017) compared the

[3] While the majority of aphantasic participants score 16 on the VVIQ, aphantasic participants can also score between 17-32 on the VVIQ (e.g. Zeman et al., 2015, Keogh & Pearson, 2017).

performance of one aphantasic participant (*AI*) with that of a control group consisting of eleven control participants. Although this control group were the same gender as *AI,* they were not matched in terms of IQ. The authors addressed this issue by comparing the performance of *AI,* specifically to a selected sub-set of four controls within their control sample who had matching IQ scores (Jacobs et al., 2017). However, the case study was based on the performance of one aphantasic participant within an experimental paradigm; thus, the findings may be spurious.

Likewise, the study by Keogh and Pearson (2017) compared the performance of a group of 15 aphantasic participants with that of a larger 'general population' of 209 individuals who had typical imagery. The data for this control group was acquired as apart of numerous other published and unpublished studies undertaken by Pearson's research group. Although Keogh and Pearson (2017) addressed the sample difference for their behavioural measure by randomly resampling 15 participants from the general population (a thousand times), nevertheless, the samples were not matched. For instance, the general population group comprised of a wider range of ages from 18-80 in contrast to their aphantasic sample who were between the ages of 21-68, and no mean age or standard deviation were provided for this group.

While several studies have used larger matched samples (Dawes et al., 2020; Zeman et al., 2020), these studies were primarily based on self-report measures. By definition, self-report measures are subjective, they are impacted by a number of different factors, and they are prone to a number of different biases (Hurlburt & Schwitzgebel, 2011). For example, participants may respond in a socially desirable way (McKelvie, 1995; McKelvie & Rohrberg, 1978) and their responses may be mediated by other variables, such as personality traits (e.g. Buchanan, 2015). While self-reports provide insight into an experience, these are not objective measures. What is lacking within the literature is an objective assessment within a larger sample of aphantasic individuals who are closely matched in terms of age and IQ to a sample of individuals with typical imagery in a wider range of tasks.

While the VVIQ self-report measure is the most convenient way to identify individuals with aphantasia, there are other objective ways in which this can be achieved. As an alternative to self-report measures, Keogh and Pearson (2017) have used a binocular rivalry paradigm as an objective method to measure the sensory strength of imagery. This paradigm is a behavioural technique where a different image is separately presented to each eye. Visual perception alternates between the two images - one image remains perceptually dominant, while the other image is unconsciously suppressed (Pearson, Clifford, & Tong, 2008). Previous studies which used this technique have shown that both visual imagery and weak-visual perception can bias responses within subsequent binocular rivalry trials (Pearson et al., 2008). For instance, if an individual generates a visual image of a green rivalry-display or is perceptually presented with a very faint image of a green rivalry-display, an individual is more likely to respond by claiming that they have seen a green rivalry-display image in the following trials (Pearson et al., 2008). The authors suggested that the extent of this priming reflects the measure of the sensory strength of visual imagery. In individuals with aphantasia, however, this priming effect is not evident compared to individuals with typical imagery (Keogh & Pearson, 2017). Therefore, the authors claimed this demonstrated that individuals with aphantasia experienced an absence of sensory visual imagery, and the results obtained were not caused by the lack of metacognition (i.e. their inability to introspect on their experience of visual imagery). Although the binocular rivalry paradigm provides an objective indication of sensory strength in the visual domain, no such corresponding technique exists in the case of other sensory modalities. Moreover, this task is difficult to carry out within online settings because of the adjustments which have to be made to the task with regards to the individual's differences in eye dominance (in comparison to the VVIQ, which is a quick gauge of visual imagery vividness).

Another preliminary objective difference within the aphantasic literature concerns the relationship between visual images, thoughts and emotions. Specifically, individuals with aphantasia showed flat-line physiological responses when reading fictitious fearful scenarios (Wicken et al., 2021). This is in contrast to individuals with typical imagery who displayed aroused physiological responses as is commonly expected due to such emotional content. Although no other emotions have been explored within the study, physiological responses and binocular rivalry constitute two objective measures, besides self-report measures to identify markers of aphantasia.

The study by Keogh and Pearson (2017) was the first one to incorporate different visual imagery self-report measures to the VVIQ; it introduced the Object Spatial Imagery Questionnaire (OSIQ). The authors demonstrated that aphantasic participants self-reported a preference for spatial imagery and provided spatial imagery scores that were comparable to those provided by individuals with typical imagery. However, the object imagery scores provided by aphantasic participants were significantly lower than their spatial imagery scores. This finding has since been replicated in larger samples (Bainbridge et al., 2020; Dawes et al., 2020), which indicates that individuals with aphantasia have intact spatial imagery abilities. Moreover, Keogh & Pearson (2017) have suggested that this preference may relate to the dissociation between the ventral and dorsal processing streams, and may also explain patient *MX's* accurate performance within the mental rotation task. Conversely, object imagery scores, which refer to imagery of high-resolution and pictorial in nature (see, Blajenkova et al., 2006), have been shown to correlate to VVIQ scores (Bainbridge et al., 2020), suggesting they measure similar constructs.

Although individuals with aphantasia are proposed to have intact spatial imagery, on the basis of their self-reports, the observation has yet to be objectively examined within tasks that assess visual and spatial imagery. However, previous research has indicated that it may be impossible to separate fully one construct from the other (e.g. Kosslyn, 2006; Kosslyn 1994). Evidence obtained from studies based on the congenitally blind indicates that it is possible for some tasks to be undertaken as accurately in the absence of the 'visual' component (Carpenter & Eisenberg, 1978; Marmor & Zaback, 1976; Tinti et al., 2018). Although object and spatial differences have been documented in a number of case studies of patients with brain injury (e.g. Corballis, 1997; Della Sala et al., 1997; Farah et al., 1988; Morris et al., 1995), exploration of the nature of aphantasia could provide another route to examine these differences within a population of individuals who are unaffected by brain trauma or changes in brain pathology. If visual and spatial processing differences exist between individuals with aphantasia and typical imagery, in line with their self-report measures, then it is necessary to investigate whether such differences can be objectively observed. However, presently, no study has investigated spatial and visual differences within behavioural tasks.

The relationship between visuospatial working memory and visual imagery remains unclear (Logie & Cowan, 2015). However, the examination of visuospatial working memory in a population who self-report the inability to use visual imagery could provide a unique opportunity to understand the relationship between the two processes. Until now, this relationship has been examined in a case study of an aphantasic participant, *AI*, who showed no significant difference to controls in an imagery condition. However, *AI* displayed impairments in the visuospatial working memory condition only when high precision working memory was required (Jacobs et al., 2017). The authors have speculated that *AI* may have adopted verbal or spatial propositional code (Jacobs et al., 2017). Such findings could be explained by theoretical models of visuospatial working memory that claim the visual cache and the visual buffer are distinct (Andrade et al., 2002; van der Meulen et al., 2009). This notion also supports the view that visuospatial working memory tasks can be undertaken using non-visual strategies (Pearson & Keogh, 2019). Nevertheless, the findings discussed were based exclusively on one case study. Therefore a more in-depth examination of these processes in a larger sample is necessary to confirm the relationship existing between the two.

The majority of studies have examined the imagery experience of individuals with aphantasia in the visual domain; nonetheless, few have explored such experiences across other sensory modalities. Although Zeman et al. (2015) reported that approximately half of their aphantasic sample experienced an absence of imagery in other sensory domains, no further information was provided. This has been examined more recently within larger samples, which indicate that not all individuals with aphantasia self-report a lack of visual imagery across all sensory domains (Dawes et al., 2020; Zeman et al., 2020). However, the extent of this variability still remains unclear; in particular, the extent or frequency with which aphantasic individuals experience comorbid imagery impairments in multiple sensory domains or the neural underpinnings of such variations. Moreover, differences in self-report across all sensory domains have not been empirically examined. Therefore, the examination of non-visual sensory domains could be another way to examine the differences in visual imagery and spatial imagery among individuals with aphantasia. For example, it has been proposed that auditory imagery shares numerous similarities with visual imagery, such as, it has spatial characteristics similar to the visual domain (Halpern, 1988; Zatorre, Halpern, Perry, Meyer, & Evans, 1996) and a 'what' and 'where' pathway similar to the 'what/where' pathways described within the visual domain (Clarke, Bellmann, Meuli, Assal, & Steck, 2000; Warren, Zielinski, Green, Rauschecker, & Griffiths, 2002). No studies as yet have examined the performance of individuals with aphantasia within auditory imagery tasks.

1.4.4. Hyperphantasia

At the beginning of this thesis, aphantasia was the only identified extreme in imagery experience. However, research recently conducted has drawn attention to the opposite end of the vividness spectrum – i.e. to those who self-report a hyper-vivid imagery experience. (Zeman et al., 2020; Milton et al., *submitted*). Hyperphantasia is characterised by visual imagery that is as '*vivid as real as seeing*' similar to photographic imagery (Zeman et al., 2020; Milton et al., *submitted*). It is regarded to have a prevalence of 11.2% in the general population and is identified by individuals who score between 75-80 on the VVIQ (Zeman et al., 2020). Individuals with hyperphantasia are more likely to recognise that their imagery experience is more vivid during early adulthood (which is earlier than those with aphantasia) (Zeman et al., 2020). Moreover, they are also more likely to report synaesthesia[4] and self-report visual dreams (Zeman et al., 2020). In a sample of 200 individuals with hyperphantasia presented in a study conducted by Zeman et al. (2020), almost half of the participants reported that all their senses were hyper-vivid. This variation of vivid imagery across the other senses suggests that hyperphantasia is a heterogenous experience like aphantasia (Milton et al., *submitted*), but little is known as to what these variations may entail or why such variations occur. A recent fMRI (unpublished) study has shown that there exists stronger functional connectivity between prefrontal regions and the primary visual cortex among hyperphantasic individuals than individuals with aphantasia (Milton et al., *submitted*), but at present research on the imagery extreme is limited. Furthermore, self-reports of individuals with hyperphantasia may be more questionable – this is so, because although individuals may have a vivid imagery experience, it is considerably harder to quantify the strength of the 'presence', than that of the 'absence.' While the number of individuals with hyperphantasia is specified within subsequent Chapters, this experience is not the focus of this thesis.

[4] Although it has been documented that synaesthesia can occur within individuals with aphantasia, suggesting that visual imagery is not necessary for the experience of synaesthesia (Dance et al., 2021).

1.5. The current thesis and research questions

Aphantasia is a newly identified variation of the human experience. Much of the early research establishing the existence of aphantasia has focused on the experience within the visual domain, explored primarily through case studies, or studies with unmatched samples (< 15). While more recent studies have examined the experience of aphantasia within larger samples, these studies have largely used self-report measures. Of the few studies that have examined aphantasics' objective performance within tasks, these studies employ unmatched control samples. Broadly, this thesis examines the possible causes of aphantasia and the nature of the experience in visual and non-visual domains within larger matched samples, examined by participant group and considering individual variations in performance.

This thesis will consider the following research questions:

1. **Chapter 2 research questions: interrogating the case studies in the literature**

The early published studies in aphantasia comprised of case studies or small sample sizes (n < 15). Can an experimental design replicate the findings obtained from self-reports and from objective performance within visuospatial imagery and working memory tasks?

Experiment 1 research questions: Examining self-reported imagery ability of individuals with aphantasia

1. Can an experimental design replicate the study findings of Keogh & Pearson (2017) that indicate self-reported object imagery (in the Object-Spatial Imagery Questionnaire, OSIQ) might be lower in individuals with aphantasia compared to individuals with typical imagery?

2. Can an experimental design replicate the study findings of Keogh & Pearson (2017) and show aphantasic participants' self-reported spatial imagery scores (in the OSIQ) might be similar to the spatial imagery scores provided by individuals with typical imagery?

Experiment 2 research questions: Examining objective imagery and visuospatial working memory function in an experimental design

1. Can an experimental design adopted by Jacobs et al. (2017) replicate the case study findings that suggest that individuals with aphantasia may have impaired visuospatial working memory but not imagery function?
2. Can an experimental design replicate the case study findings of Jacobs et al. (2017) that suggest that individuals with aphantasia may have reduced metacognitive accuracy than control participants with typical imagery?

2. Chapter 3 research questions: personality and cognitive profile

Can aphantasia be explained through differences in personality or cognitive profiles?

Experiment 3 research questions: Do personality differences explain aphantasia?

1. Do individuals with aphantasia have different personality profiles compared to individuals with typical imagery?
2. Is there a relationship between imagery vividness ratings and personality?

Experiment 4 research questions: Do individuals with aphantasia perform differently in cognitive tasks?

1. Do individuals with aphantasia perform differently to individuals with typical imagery in tasks exploring different aspects of cognitive function within standardised cognitive tasks? These tasks include: verbal memory (Verbal Recognition Memory, involving recall and recognition of words within short term

phonological memory), visual memory (Pattern Recognition Memory, involving the recognition of visuospatial images within short term memory), spatial working memory (Spatial Span, involving spatial representations/imagery) or executive function (One Touch Stockings of Cambridge task, a visuospatial working memory task requiring the maintenance and manipulation of both visual (colour) and spatial (location) information within working memory)?

2. Are there variations of neuropsychological performance between the two participant groups? Individual differences in performance will be explored using multidimensional scaling (MDS).

3. Chapter 4 research questions: Complex visuospatial performance in aphantasia

How do individuals with aphantasia perform within complex visuospatial working memory tasks?

Experiment 5: How do individuals with aphantasia perform within a mental rotation task?

1. Do individuals with aphantasia perform differently to individuals with typical imagery within a mental rotation task?

Experiment 6: How do individuals with aphantasia perform within a spatial perspective-taking task?

1. Do individuals with aphantasia perform differently to individuals with typical imagery within a spatial perspective-taking task - is there a difference in performance in tasks requiring egocentric spatial imagery?

4. **Chapter 5 research questions: What vs Where pathways**

Is it possible to isolate visual imagery from spatial imagery? If this is not possible within the visual domain, are there other sensory domains where this can be examined?

Experiment 7 research questions: Isolating 'visual' imagery function in the visual domain

1. If individuals with aphantasia self-report impairments in object imagery, how do they perform within an imagery task that requires responses to statements relating to visual (colour and texture) and spatial (size and location) properties of everyday objects?

Experiment 8 research questions: Non-visual self-reports in aphantasia

1. How do individuals with aphantasia self-report imagery experience across the other sensory modalities compare to controls with typical imagery?

5. **Chapter 6 research questions: Auditory imagery performance in aphantasia**

In individuals with aphantasia who self-report an absence of auditory imagery, how do they perform within auditory imagery tasks that comprise of perceptual and spatial imagery components?

Experiment 9 research questions: Pitch discrimination in imagery and perception

1. How do individuals with aphantasia, who self-report an absence of auditory imagery, perform in an auditory imagery task involving the discrimination of pitches of lyrics within familiar music?
2. How does this performance compare to a matching perceptual version of the task requiring participants to discriminate pitches perceptually?

Experiment 10 research questions: Categorical perception of voices in aphantasia

1. Can individuals with aphantasia, who self-report an absence of auditory imagery, generate and synthesise internal auditory representations of voices of different speakers similar to individuals with typical imagery?
2. Can individuals with aphantasia, who self-report an absence of auditory imagery, retrieved these internal auditory representations and use them to accurately identify the speakers of ambiguous voice syllables, similar to individuals with typical imagery?

Chapter 2: Interrogating the case studies in the literature

General Summary

The early published studies investigating aphantasia include responses from self-reports or behavioural performance within single case-studies or small samples. Further replication of the results obtained within these studies are necessary to confirm whether or not the findings are robust. Keogh & Pearson (2017) found in their aphantasic sample (n = 15) a self-reported higher scores for spatial than object imagery. Experiment 1 investigates aphantasics' self-reported object-spatial imagery preferences within a larger sample (n = 114) and replicated findings showing that aphantasic participants scored higher for spatial imagery than object imagery. In contrast, controls self-reported the reverse relationship. Together these results indicate that experiences of visual and spatial imagery within individuals with aphantasia may differ to those who have typical imagery. In this Chapter, Experiment 2 applies the experimental methodology described in the single case study by Jacobs et al. (2017), to a group of individuals with congenital aphantasia. Contrary to Jacobs et al. (2017) Experiment 2 shows no difference in accuracy within the visuospatial working memory task between aphantasic (n = 20) and control participants (n = 20) but a significant difference in accuracy in the imagery condition. The results of this Chapter replicate previous findings suggesting that in a larger sample of aphantasic participants, spatial imagery remains in intact, but object imagery does not, which could explain the performance similarities exhibited within Experiment 2. These results further demonstrate the need to establish whether the findings of previous case study reports generalise to the wider aphantasic population.

General Introduction

Although the Vividness of Visual Imagery Questionnaire (VVIQ) has been used to identify individuals with aphantasia (Appendix 2.1), other self-report measures such as the Object Spatial Imagery Questionnaires (OSIQ, Appendix 2.2) have also been incorporated within published aphantasia research studies to gain further insight into self-reported imagery experiences (e.g. Bainbridge et al., 2020, Dawes et al., 2020; Keogh & Pearson, 2017). This questionnaire challenges the notion that imagery is a unitary construct, and requires individuals to rate statements with regards to their preference of 'object' (visual) and 'spatial' imagery. A double dissociation between object and spatial imagery has been proposed and supported by numerous patient studies (see Chapter 1, section 1.2.2 for a discussion).

Individuals with aphantasia were shown to self-report a preference for spatial imagery compared to object imagery (Keogh & Pearson, 2017), and this has since been replicated within a larger sample of aphantasic participants (Dawes et al., 2020). Although the finding has been replicated within a larger sample, due to the subjective nature of self-reports, it is necessary to further investigate how robust this finding is within a differing aphantasic sample. This is necessary because higher scores for spatial imagery have been shown to correlate to more accurate performance within spatial imagery tasks, such as mental rotation (Kozhevnikov et al., 2005). In terms of patient *MX* who had acquired aphantasia following surgery, this ability to use spatial imagery may explain *MX's* accurate performance within a mental rotation task. As patient *MX* did not complete the OSIQ self-report, this correlation cannot be examined. It should also be noted that patient *MX* had acquired aphantasia following surgery, thus potentially may provide different OSIQ scores than individuals with congenital aphantasia. Nevertheless, the notion that individuals with aphantasia self-report relatively intact spatial imagery has also been shown (within a larger sample of congenital aphantasics) through other spatial sub-scales, such as, The Survey of Autobiographical Memory (Dawes et al., 2020). On this sub-scale, aphantasic participants' scores for spatial navigation and naturalistic spatial memory did not differ to controls with typical imagery, suggesting that individuals with aphantasia do self-report intact spatial abilities (Dawes et al., 2020). However, the number of items on this subscale comprise six items, thus cannot be viewed as a comprehensive assessment of spatial abilities.

It remains an open question whether self-reported object-spatial imagery discrepancy translates to an equivalent behavioural deficit measured in objective imagery tasks. These intact spatial abilities may in part explain why aphantasic participant *AI* performed as well as matched controls within an imagery task (Jacobs et al., 2017). However, *AI* performed worse during the most difficult trials of a visuospatial working memory task (Jacobs et al., 2017) and the authors suggested that this supported the idea that imagery plays a functional role within visuospatial working memory (for a discussion, see Chapter 1 section 1.3.3.) as visuospatial working memory and visual imagery have been shown to share similar cognitive (Borst et al., 2012) and neural representations (Albers et al., 2013; Slotnick et al., 2012). These preliminary findings need to be replicated in an experimental sample. If there is evidence of object-spatial imagery dissociations within the literature, further exploration of object-spatial self-reported preferences is also needed to enable greater understanding of the type of imagery deficit present within aphantasia.

Experiment 1: Examining aphantasic self-reported imagery ability

2.1.1 Introduction

Considerable research has demonstrated the existence of distinct spatial and object imagery subsystems, which are neuro-anatomically distinct (e.g. Farah et al., 1988; Goodale & Milner, 1992; Kosslyn et al., 2001; Kosslyn, 1994; Levine et al., 1985; see also Chapter 1 section 1.2). Spatial imagery refers to the representation of spatial relations among objects and their parts, location in space, object movements and spatial transformations (Blajenkova et al., 2006). On the other hand, object imagery refers to the salient visual features present within images irrespective of their location, for instance, colour, brightness and vividness (Blajenkova et al., 2006). Blajenkova et al. (2006) created a questionnaire, the Object Spatial Imagery Questionnaire (OSIQ) to explore individual preference of these two subtypes. The premise of the OSIQ is that visualisers, who are more likely to process information visually (opposed to individuals who are verbalisers), can be characterised as either spatial imagers or object imagers (Blajenkova et al., 2006). For instance, Kozhevnikov et al. (2005) showed that spatial imagers were more accurate within spatial imagery tasks such as mental rotation, and were less accurate within object imagery tasks, such as a degraded pictures task (Blajenkova et al., 2006). Likewise, object imagers were more accurate during object than spatial imagery tasks (Kozhevnikov et al., 2005). Object imagery scores correlated highly to the VVIQ (Blajenkova et al., 2006). The OSIQ self-report measure supports the notion of a dissociation between spatial imagery and visual imagery (Farah et al., 1988; Levine et al., 1985) and has been used within clinical populations, such as schizophrenia, to explore object and spatial imagery preferences (Aleman, de Haan, & Kahn, 2005).

Performance differences in object and spatial imagery tasks are evident in several case studies of patients with brain lesions (Carlesimo et al., 2001; Corballis, 1997; Farah et al., 1988; Levine et al., 1985). For instance, in a case study, Levine et al. (1985) provided details of a patient with lesions in the temporal cortex who was impaired in spatial transformation imagery tasks, however, performed normally in tasks involving the identification of colours and details of objects. While on the other hand, another case study by Farah et al. (1998) reported a patient who performed poorly on object tasks, however, was unimpaired on spatial imagery tasks such as mental rotation. If this dissociation exists in individuals with aphantasia, this may provide a new understanding of the relationship between visual and spatial imagery experiences.

Within the study undertaken by Keogh and Pearson (2017), aphantasic participants self-reported a significantly higher preference for spatial imagery rather than object imagery in the OSIQ. The object imagery scores provided by aphantasic participants were considerably lower than the object scores provided by controls and had smaller variance. Considering the dissociation between spatial and object imagery, with aphantasic individuals self-reporting intact spatial imagery on other measures (Dawes et al., 2020), it is expected that they will show similar self-report of spatial imagery to controls with typical imagery on spatial OSIQ subscales. The object subscale refers to the pictorial nature of imagery, and it is expected that individuals with aphantasia will self-report lower scores on this scale, in line with their self-reported lack of visual imagery. For individuals with typical imagery, no distinct difference is expected between the object imagery and spatial imagery subscales. The findings of this self-report will add to the growing literature with regards to the relationship between self-reported visual and spatial imagery experiences within aphantasia.

2.1.2 Methods

Defining aphantasia and typical imagery experiences

Aphantasia is typically identified through the VVIQ, although there is no defined cut-off score for typical and atypical self-reports of imagery, with different researchers varying in the ways they use the VVIQ to define aphantasia. Similarly, the VVIQ was not developed as a clinical measure, and as such, there is limited normative data for 'typical' imagery experience. In published aphantasic research, there is variability in how researchers are defining 'normal' imagery experience (e.g. Zeman et al., 2015; Keogh & Pearson, 2017). Previous studies, however, have demonstrated that there are a cluster of individuals with aphantasia who experience no imagery, with VVIQ scores of 16. However, there are also individuals who self-identify as having aphantasia and score higher than 16 on the VVIQ. The amount of 'minimal' imagery within the classification of aphantasia has varied across researchers, and cut-offs or criteria are not always reported (see Table 2.1 for an overview of VVIQ criteria used within current studies).[5]

Study/ title	VVIQ scores for aphantasic and control participants	Defined cut-offs or criteria?
Lives without imagery – congenital aphantasia Zeman, Dewar & Della-Sala (2015)*	Aphantasic participants (n =21), were split into: a) No imagery group (n = 12), VVIQ score = 16. b) Minimal imagery group (n = 9), VVIQ scores ranging = 17-30, median 26. Two control groups were combined with a median VVIQ score = 59: a) 111 psychology control students, median VVIQ score = 58. b) 10 middle-aged male architects (matching MX) median VVIQ score = 65.	No cut-off explanation provided for aphantasic participants. Control participants had similar means to the means provided in the meta-analysis by McKelvie (1995).

[5] Papers denoted with* were the only published literature at the outset of this PhD.

Visual working memory in aphantasia Jacobs, Schwarzkopf & Silvanto (2017)*	Aphantasic participant (*AI*) scored 16 on the VVIQ. Controls (n = 11), mean VVIQ score = 61.1, SD = 7.6 Control subgroup (who matched *AI* in terms of IQ, n = 4), VVIQ scores = 59.8 (no SD provided).	Single case study, *AI* scored 16 on the VVIQ. No indication of control VVIQ criteria.
The blind mind: No sensory visual imagery in aphantasia Keogh & Pearson (2017)*	Aphantasic participants (n = 15) mean VVIQ score = 19, SD = 6.78. No indication of control VVIQ scores.	No cut-offs provided to define aphantasic sample.
A cognitive profile of multisensory imagery, memory and dreaming in aphantasia Dawes, Keogh, Andrillion & Pearson (2020)	Aphantasic participants (n = 267) mean VVIQ score = 17.94, no SD provided. From the graphs, it is assumed their cut-off was 32, with individual scoring higher than 32 classified as typical imagers (controls). Controls (n = 203), mean VVIQ score = 58.79, no SD provided.	Within their criteria, the authors suggest '*weak visual imagery is typically defined by scores of 32 or less on the VVIQ*,' suggesting their cut-off for aphantasic (< 32) and controls (> 32) participants although this is not explicitly stated.
Phantasia – the psychological significance of lifelong visual	The authors grouped their participants within the following VVIQ criteria: Aphantasic participants (n = 2000), scored between 16-23, mean VVIQ score = 17.06, SD = 1.98.	Control 'mid-range' VVIQ scores are in line with the meta-analysis by McKelvie (1995).

imagery vividness extremes Zeman et al., (2020)	Controls 'mid-range' (n = 200), scores 51 – 63, mean VVIQ score = 57.49, SD = 3.52. Hyperphantasic participants (n = 200), score between 75-80, mean VVIQ score = 78.16, SD = 1.66.	The justifications for the aphantasic participant range (16-23) is not defined.
The critical role of visual imagery in human emotions Wicken, Keogh & Pearson (*unpublished*)	No descriptives provided, however, it is suggested: Aphantasic participants VVIQ scores ranged: 16-32 (although in the graphs, they suggest aphantasics' VVIQ scores < 30). Controls VVIQ scores ranged (as suggested in the histogram): 38-80.	The authors suggest that individuals with aphantasia scored VVIQ < 32 and controls > 32.
Behavioural and neural signatures of visual imagery vividness Milton et al (*unpublished*)	Aphantasic participants (n = 24) VVIQ scores ranged: 16-23, mean = 16.92, SD = 1.47. Controls (n = 20): VVIQ score ranged between 55-60, mean = 56.95, SD = 2.93. Hyperphantasic participants (n = 25) VVIQ score ranged between 75-80, mean = 77.08, SD =1.75.	The justifications for the aphantasic participant range (16-23) is not defined.

Table 2.1: Table to show a summary of VVIQ criteria for defining aphantasic and control participants, defined in the existing literature.

It is also not yet known how much 'limited' imagery should be permitted within the classification of aphantasia. Within this thesis, individuals with aphantasia were identified by VVIQ scores ≤ 26. This cut-off (VVIQ ≤ 26) is in line with more recent papers that take a more conservative approach to classify aphantasia (e.g. Zeman et al., 2020).

With regards to scores of 'typical' imagery experience, the majority of existing papers on aphantasia provide limited information on their definitions of 'typical' imagery (e.g. Keogh & Pearson 2017; see Table 2.1). In a meta-analysis of 1860 participants (who were mainly students), McKelvie (1995) calculated the mean VVIQ score as 59.2 (SD = 11.07), and also identified a 'low imagery' group with a mean VVIQ score of 49.6 (SD = 9.04). Several studies have adopted a wide 'typical imagery' VVIQ criteria, with scores ranging between 32-80 (e.g. Dawes et al., 2020, Wicken et al., *submitted*). The scores, which fall between 32-40 suggest that on the VVIQ, an individual could provide a mixture (on average) of 2s and 3s for each item, which equate to '*fairly vivid or vague visual imagery*.' This arguably comprises of a 'typical imagery' experience, and participants who fall within this VVIQ range have been included in the typical imagery populations within aphantasic studies (e.g. Dawes et al., 2020, Wicken et al., *submitted*). Thus, within this thesis, individuals with typical imagery were identified by VVIQ scores > 33. Hyperphantasia, a recently identified experience for individuals who experience highly vivid photographic-like imagery, has been suggestive for individuals who score between 75-80 on the VVIQ (Zeman et al., 2020). Within the current thesis, the number of hyperphantasic participants is identified within the participant sample. However, these individuals with hyperphantasia will be grouped within the sample of control participants given it constitutes a typical imagery experience.

2.1.2.1. Participants

All participants were over the age of 18 and in total there were, 231 completed OSIQ responses: 114 aphantasic and 117 control participants. Two controls were removed (their VVIQ scores were 33), and two aphantasic participants were removed (VVIQ scores were 29 and 30). Through the VVIQ, 112 aphantasic participants (VVIQ ≤ 26) were identified and had a VVIQ mean score of 16.81 (minimum = 16, maximum = 26, SD = 2.23). In contrast, 115 control participants (VVIQ > 33) were identified and had a mean VVIQ score of 59.54 (minimum = 34[6], maximum = 80, SD = 12.47). In the controls, 10 participants self-reported as hyperphantasic (mean = 77.9, SD = 1.85) The protocol for the data collection was in accordance with the British Psychological Society guidelines and the ethical approval provided by the Psychology Department Ethics Committee of the University of Westminster, UK.

2.1.2.2. Materials

Vividness of Visual Imagery Questionnaire

The VVIQ (Marks, 1973) comprises of 16 items and instructs participants to rate the vividness of various scenarios such as aspects of a person and several scenes (e.g. "*think of some relative or friend whom you frequently see, but who is not with you at present, and consider… the exact contour of face, head, shoulders and body"*). Participants are required to rate the vividness of their visual imagery on a scale from 1 (*"No image at all, you only "know" that you are thinking of the object"*) to 5 (*"Perfectly clear and vivid as real seeing"*). VVIQ scores are calculated by summing the scores from all the items, thus participants could score a minimum of 16 and a maximum of 80. In this thesis, the VVIQ is used as a diagnostic tool to identify aphantasic (scores: VVIQ ≤ 26) and typical imager participants (VVIQ > 33).

[6] Although this participant scored 34 on the VVIQ, it should be noted on the OSIQ, this participant scored highly on the object imagery subscale (3.13/5), and this was higher than their spatial subscale score (2.93/5). According to Blajenkova et al. (2006), this would suggest that this participant has imagery that is visual or pictorial in nature, despite providing a lower self-report for its phenomenological experience.

Object Spatial Imagery Questionnaire

The OSIQ assesses individual preferences for object or spatial visual mental imagery. Within this questionnaire, 15 questions related to object imagery, e.g. "*my images are very colourful and bright*" and 15 questions related to spatial imagery, e.g. "*I can easily sketch a blueprint of a building I am familiar with*." For all 30 questions, participants rated on a scale whether they 1 ('totally disagree') to 5 ('totally agree') and an average score (between 1-5) is calculated for each subtype.

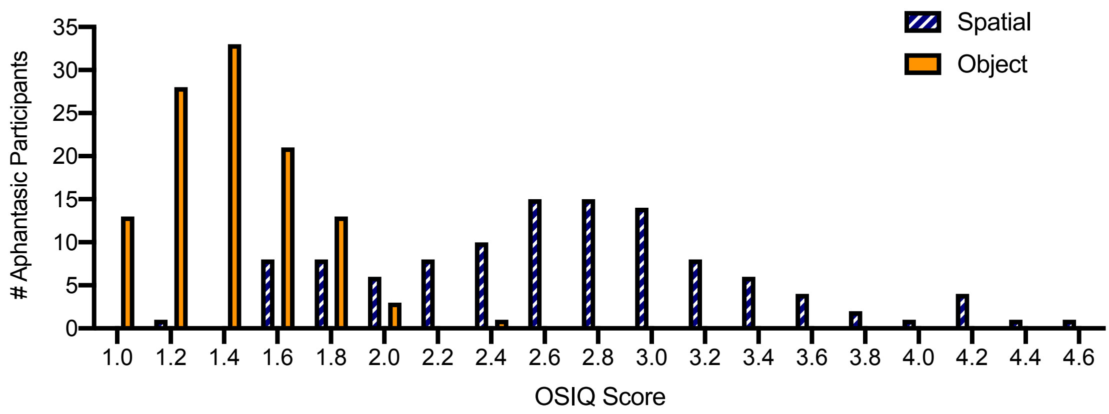
2.1.2.3. Procedure

The data collected for the OSIQ was collated across several experiments: Experiments 2, 3 and Experiment 8. For data collected in Experiment 2 and Experiment 3, aphantasic and control participants were asked to complete the OSIQ and VVIQ consecutively. For data collected in Experiment 8, aphantasic and control participants were asked to complete the OSIQ and the VVIQ as well as two other questionnaires regarding non-visual sensory imagery (discussed in Chapter 5). All OSIQ data collection (in all of these Experiments) was conducted through the online survey platform, Qualtrics. Participants were sent a URL to the Qualtrics version of the questionnaires. Subsequently, participants completed each questionnaire and all 30 questions of the OSIQ.

2.1.3. Results

2.1.3.1. Range of OSIQ responses

A) Aphantasic participant distribution of object and spatial imagery scores:



B) Control participant (individuals with typical imagery) distribution of object and spatial imagery scores:

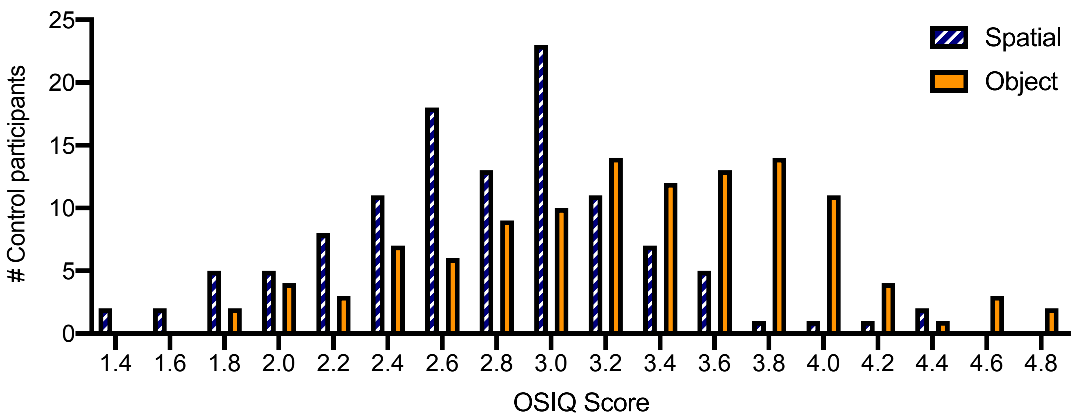


Figure 2.1: Frequency histograms to depict the number and distribution of scores for aphantasic (A) and control (B) participant in the OSIQ questionnaire.

Figure 2.1 shows the distribution of OSIQ scores for both aphantasic (A) and control participants (B). Object scores provided by aphantasic participants ranged from 1- 2.4 while spatial scores ranged from 1.2 - 4.6. Two aphantasic participants scored higher on the object scale (mean = 1.73, SD = 0) than the spatial scale (mean = 1.6, minimum =

1.53, maximum = 1.67, SD = 0.10). Another two aphantasic participants self-reported the same score for both subscales (mean = 1.97, minimum = 1.53, maximum = 2.4, SD = 0.62). The remaining 110 (96%) aphantasic participants self-reported higher spatial scores (mean = 2.75, minimum = 1.29, maximum = 4.60, SD = 0.67) than object scores (mean = 1.38, minimum = 1, maximum = 2.40, SD = 0.24). The mean difference in scores between the two subscales was 1.36 (minimum = 0.07, maximum = 3.18, SD = 0.69).

Control object scores ranged from 1.8 – 4.8, and spatial scores ranged from 1.4 – 4.4. In total, 30 controls self-reported higher scores for the spatial subscale (mean = 2.64, minimum = 2.13, maximum = 4.4, SD = 0.54) than the object subscale (mean = 2.58, minimum = 1.73, maximum = 3.73, SD = 0.49), the mean difference in scores (mean = 0.55, minimum = 0.07, maximum = 1.8, SD = 0.46). The majority of controls (n = 79, 68%) self-reported higher scores for the object subscale (mean = 3.60, minimum = 1.73, maximum = 4.73, SD = 0.45) than the spatial subscale (mean = 2.64, minimum = 1.33, maximum = 3.87, SD = 0.54), the mean difference in scores between subscales (mean = 0.95, minimum = 0.07, maximum = 3.06, SD = 0.63) The remaining 6 controls self-reported the same score for both subscales (mean = 2.84, minimum = 2.53, maximum = 3, SD = 0.18).

2.1.3.2. OSIQ Analysis

The scores provided by aphantasic and control participants for each subscale (object and spatial) were compared (see Figure 2.2) and analysed with a two-way mixed measures ANOVA.

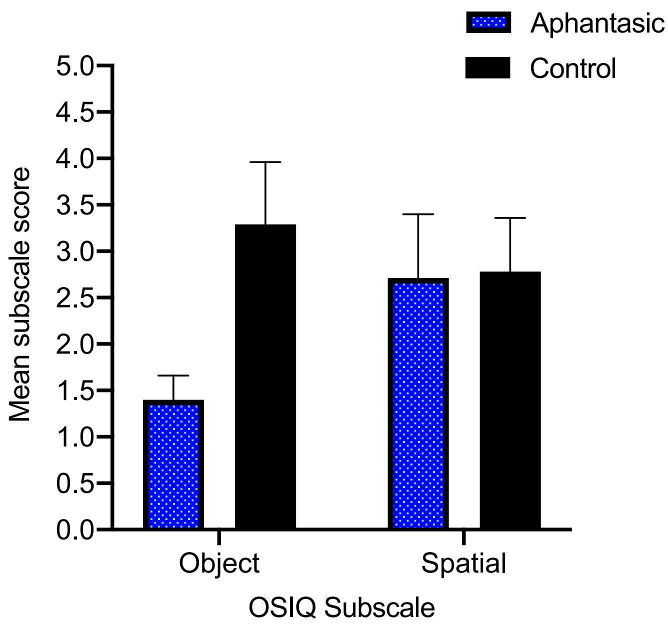


Figure 2.2: Bar chart to depict the mean and error bars (representing the standard deviation) of self-report scores of object and spatial imagery by aphantasic and control participants.

The results of a two-way mixed measures ANOVA with factors participant group (aphantasic/ control) and subscale of the OSIQ (spatial /object) showed a significant main effect of subscale ($F(1, 225) = 55.48$, $p < .001$, $\eta p^2 = .20$) with higher mean scores for the spatial than object subscale. There was also a significant main effect of participant group with controls providing higher scores than aphantasic participants ($F(1, 225) = 315.60$, $p < .001$ $\eta p^2 = .58$). There was a significant interaction between the subscales and participant group ($F(1, 225) = 293.78$, $p < .001$, $\eta p^2 = .57$).

Post-hoc independent t-test of object scores ($t(148.50) = 28.06$, $p < .001$, $d = 3.72$) indicated that the controls scored significantly higher than aphantasic participants on the object subscale, while they did not differ on the spatial scores ($t(225) = 0.75$, $p = .45$, $d = .11$). A within- subjects t-test for each participant group showed that the aphantasic participants ($t(111) = 19.09$, $p < .001$, $d = 2.51$) scored significantly higher for the spatial subscale than the object subscale, and the reverse was found in control participants ($t(114) = -6.36$, $p < .001$, $d = .81$), who scored significantly higher for the object subscale than the spatial subscale. These results show that aphantasic participants self-report higher for spatial than object imagery, while control participants scored higher for object than spatial imagery. Both participants groups provided similar spatial scores.

Self-reported object and spatial OSIQ scores for aphantasic and control participants were correlated with the VVIQ using a Spearman correlation. In controls, the results showed a significant positive correlation between the VVIQ and the object subscale ($r = .60$, $p < .001$), and no significant correlation ($r = .17$, $p = .07$) in the spatial subscale. In aphantasic participants, there was no significant correlation between the VVIQ and the object subscale ($r = .14$, $p = .14$) and the spatial subscale ($r = -.03$, $p = .78$). These results suggest the more vivid experience of visual imagery, the higher the scores provided for object imagery in the OSIQ.

2.1.4. Discussion

Consistent with the findings from previous research (Keogh & Pearson, 2017; Dawes et al., 2020), aphantasic participants scored significantly lower for object imagery compared to spatial imagery in the OSIQ. In contrast, individuals with typical imagery showed the reverse pattern. According to Blajenkova et al. (2006), the individuals with typical imagery within this Experiment are object imagers, thus construct colourful, high-resolution, picture-like images of individual objects. However, aphantasic participants show a preference for spatial, over object imagery, with very little variation in object imagery scores. The spatial scores provided by aphantasic participants were not significantly different from the spatial scores provided by individuals with typical imagery. According to Blajenkova et al. (2006), this would suggest that the majority of aphantasic participants in this sample are classified as spatial imagers, and are therefore more likely to construct schematic representations of objects, create accurate spatial relations among objects and are able to perform complex spatial transformations (Blajenkova et al., 2006).

Although the majority of controls showed a significant preference for object imagery, 30 controls within the sample rated their spatial imagery higher than object imagery. This suggests there is variation within typical imagery experiences of imagery. There was a subset of participants who scored the same score on both subscales. According to Blajenkova et al. (2006) individuals who show a preference for either object or spatial imagery in the OSIQ do so because they are visualisers and adopt a visualiser cognitive style (Blajenkova et al., 2006; Kozhevnikov et al., 2005). However, it is not clear why participants may score the same for each subscale, in other words, do not show a preference for either object/spatial imagery construct. One speculatively reason may because these participants prefer to adopt other cognitive styles (rather than visualise), such as verbal cognitive styles. However, this cannot be confirmed as it is not known how verbalisers would score on the OSIQ measure and no verbal scales were included. Alternatively, this may have been due to a sampling error. Blajenkova et al. (2006) does not state how common it is to have spatial or object imagery. However, individuals who work within scientific professions were more likely to be spatial imagers, while those in professions associated with the visual arts are more likely to be object imagers (Blajenkova et al., 2006).

The low self-reported object imagery within individuals with aphantasia may suggest a deficiency/ issue in the ‘what’ pathway or components of this pathway, such as the early visual cortex. As yet, no studies have investigated aphantasics’ performance within a purely visual imagery battery. This is potentially due to the difficulty of separating visual and spatial (see Kosslyn, 1996; and see also Chapter 1 section 1.2.1). If individuals with aphantasia self-report intact spatial abilities and show a preference for spatial imagery (over object imagery) in the OSIQ, this is suggested to be a predictor for performance within spatial tasks (Blajenkova et al., 2006; Kozhevnikov et al., 2005).

It has been suggested that imagery plays a functional role within visuospatial working memory. However, it remains to be explored whether spatial imagery alone can account for performance within visuospatial working memory tasks. If imagery does play a functional role within visuospatial working memory, then examining this role within individuals with aphantasia is of interest. If imagery does play a functional role in visuospatial working memory tasks, then differences in performance would be expected compared to individuals with typical imagery. This was found within the case study of *AI* who performed worse within the most difficult trials of a visuospatial working memory task compared to controls with typical imagery (Jacobs et al., 2017). The authors suggested that this was evidence to show that imagery is functionally involved in visuospatial working memory. However, these results were based on a single case study. Experiment 2 examines how a larger sample of individuals with aphantasia perform within the visuospatial working memory and imagery experimental paradigm, as outlined in Jacobs et al. (2017).

Experiment 2: Examining objective imagery and visuospatial working memory function in an experimental design

2.2.1 Introduction

In a case study by Jacobs et al. (2017), aphantasic participant *AI* undertook a battery of tasks including a working memory capacity battery, the Wechsler Adult Intelligence Scale-IV and a novel visual working memory and matched imagery paradigm. The authors concluded that *AI* had unimpaired working memory ability and in a novel working memory and matched imagery paradigm, they only observed impaired performance in the working memory task. These differences were most apparent at the highest level of difficulty (Jacobs et al., 2017). Moreover, *AI* had lower metacognitive accuracy in that she provided higher confidence ratings for incorrect trials compared to control participants (Jacobs et al., 2017). The authors of the case study describe their working memory task as a *visual* working memory task. While the task does involve the maintenance of visual information in the form of the location of a static shape and target dot in relation to one another, this arguably also involves the storage of spatial location within working memory, (Foster, Bsales, Jaffe, & Awh, 2017; McCants, Katus, & Eimer, 2019). Therefore, it cannot be purely *visual* despite the presentation of a static visual shape during the task. While spatial and visual working memory may be defined within the literature as separate constructs, they are often connected to the multiple-component working memory model (Baddeley & Hitch 1974; Logie 1995; 2003, see Chapter 1 section 1.3.3), which suggests there is a relationship between visual and spatial working memory. Thus, identifying tasks that assess and distinguish purely between both constructs is challenging. This is because the relationship between visual and spatial working memory remains unclear (Sima, Schultheis, & Barkowsky, 2013) and spatial and non-spatial features tend to be integrated (Foster et al., 2017; Luck & Vogel, 1997; McCants et al., 2019) thus difficult to separate through the use of behavioural paradigms (McCants et al., 2019).

Nevertheless, some tasks have been suggested to rely more heavily on either spatial or visual working memory. For instance, the Corsi Blocks task, which assesses spatial locations and the Visual Matrix Patterns, which assesses shape size and colours (Della Sala et al., 1999; Logie & Pearson, 1997). However, it is argued that rather than load more or less heavily on each construct, the difference between such tasks rather reflects differences in the attention and executive resources required (Awh, Vogel, & Oh, 2006; Owen et al., 1998). For instance, the Corsi blocks task involves more dynamic processes compared to the visual matrix, which involves static processes (Rudkin, Pearson, & Logie, 2007). On paper, tasks may be defined through the literature as either as 'visual' or 'spatial,' suggesting they load more heavily on one construct than the other. However, in practice, it is difficult to separate these tasks into uniquely visual and uniquely spatial tasks, as in real-world settings, visual and spatial information is intertwined.

Moreover, referring to a task as either 'visual' or 'spatial' does not necessarily reflect the additional executive resources recruited during working memory processes (Rudkin et al., 2007). The consideration of these additional processes is in line with other theories of working memory, such as the continuum model (Cornoldi, Rigoni, Venneri, & Vecchi, 2000). Briefly, this model suggests that tasks are defined by the level of manipulation required (along a vertical continuum) with tasks that require low levels of manipulation described as 'passive' tasks and higher levels of manipulation described as 'active' tasks

(Cornoldi et al., 2000). It is also noted within this model that visual and spatial processes are closely associated with one another (Cornoldi et al., 2000).

One way that visual working memory has been defined in the literature is the active maintenance of visual information to serve the needs of the ongoing task (e.g. Luck & Vogel 2013). This definition suggests that the information is experienced visually (i.e. manifests as visually presented within working memory) but arguably this combines both visual and spatial processes and features. The difficulty in teasing apart differences between visual and spatial working memory is further supported by evidence from individuals who are congenitally blind who perform similar to sighted individuals within adapted visuospatial working memory tasks (see Chapter 1 section 1.2.4 for a discussion). Thus, until a clear distinction can be clearly defined within the research, working memory tasks concerning visual and spatial information (that are presented visually) must be visuospatial in nature.

Luck and Vogel (2013) argued that one key concept of visuospatial working memory is that for sighted individuals, the experience of maintaining information must be *visual* in nature (as a result of the combination of both visual and spatial features). If the information is stored in a non-visual way, such as verbally, this cannot be considered visuospatial working memory (Luck & Vogel, 2013). Individuals who have more vivid visual imagery are more likely to engage in visual imagery as a cognitive tool to undertake visuospatial working memory tasks (Keogh & Pearson, 2011, 2014; Pearson & Keogh, 2019). However, forming internal visual representations is not the only strategy an individual can adopt (Berger & Gaunitz, 1979; Gur & Hilgard, 1975; Harrison & Tong, 2009) as other non-visual strategies can be used to perform within visuospatial working memory tasks (Berger & Gaunitz, 1979; Gur & Hilgard, 1975). For instance, individuals may encode the visual stimulus using either phonological or propositional strategies, and these abstract or verbal forms can be subsequently compared to the test array – this strategy does not involve the generation of an internal 'visual image'. This is in line with the view of Pearson and Keogh (2019), who argue that visual working memory should be re-defined to take into consideration the 'strategies' adopted by participants during a task, with the type of strategy adopted dependent on the demands of the task (Pearson & Keogh, 2019). These different processes within tasks explain why in some studies there is such variation of neural activity within different brain regions between participants (Miller, Donovan, Bennett, Aminoff, & Mayer, 2012; Miller et al., 2002), with some studies showing completely different neural networks activated depending on the type (i.e. visual vs verbal strategy) used (Logie, Pernet, Buonocore, & Della Sala, 2011; Sanfratello et al., 2014). In the case study by Jacobs et al. (2017), the authors did not ask *AI* what strategy she was using but inferred that it might have been a propositional or spatial strategy. Asking participants with regards to the strategies assumes that individuals have insight into their strategies. Reporting one's strategy or processes adopted within a task involves conscious introspection on one's own processes, and as such it may be difficult to provide accurate responses that reflect the true processes involved in a task.

There has been much debate with regards to the role of imagery within visuospatial working memory (see Chapter 1, section 1.3 for a discussion). Within the case study denoted by Jacobs et al., (2017), *AI* undertook a novel experimental paradigm comprising of a 'visual' working memory task and matched imagery conditions. *AI* performed worse in the 'visual' working memory condition with no differences in the imagery condition.

Based on the results of Experiment 1 whereby individuals with aphantasia self-report poor object imagery, if the working memory task described by Jacobs et al. (2017) truly is visual in nature, one would expect individuals with aphantasia to be significantly impaired in the working memory condition compared to individuals with typical imagery. Comparing the performance of individuals with aphantasia in this experimental paradigm should provide a clearer understanding of the relationship between visuospatial working memory and imagery. If visual imagery (i.e. imagery concerning the pictorial visual appearances of objects) plays a key role within the visuospatial working memory task than differences in performance are expected compared to individuals with typical imagery. However, if visual imagery does not play a functional role within visuospatial working memory, then no differences in performance are expected. By definition, individuals with aphantasia self-report the inability to generate visual imagery thus are expected to show significantly impaired performance in the imagery condition compared to individuals with typical imagery. If no differences in performance are evident within the imagery task, then it may suggest that the task can be undertaken using a different form of imagery or process.

2.2.2 Current study: Design

In the original case study by Jacobs et al. (2017), both the visuospatial working memory (VSWM) task and a matching imagery (IM) task comprised of 8 blocks each. The visuospatial working memory condition was undertaken in the first testing session and the imagery condition undertaken during the second testing session.

This experimental design was adopted by Experimenter *Z*; however, a programming error was encountered, resulting in different length blocks for each participant group (see Table

2.2). Specifically, the control task comprised of 8 blocks, while the aphantasic version comprised of 3 blocks. Thus, a new sample of control participants was recruited by an MSc student, Experimenter *E*. Experimenter *Z* supervised Experimenter *E* to ensure the same experimental procedure was adopted. This control data (collected by Experimenter *E*) was then compared to the aphantasic data (collected by Experimenter *Z*, see Table 2.2). As a result of this programming error, the paradigm is no longer identical (it has a different experimental design) to the task described in the case study by Jacobs et al. (2017).

Programming error: Number of blocks (total trials in the task)			
	Participant group	VSWM Task	Imagery Task
Case study by Jacobs et al., (2017)	Controls	8 (144)	8 (144)
	Aphantasic	8 (144)	8 (144)
Experimenter *Z*	Controls	8 (144)	8 (144)
*error in programming**	Aphantasic	3 (54) *	3 (54) *
Experimenter *E*	Controls	3 (54)	3 (54)

Table 2.2: Table to denote the programming error encountered in the VSWM and IM conditions. Experimenter *E* only collected control data, which was then compared to the aphantasic* data collected by Experimenter *Z*. Analysis within this Experiment is undertake with the aphantasic and control data highlighted in grey.

All aphantasic and control participants undertook the visuospatial working memory condition (in the first testing session) and an imagery condition (in a second session one week after undertaking the first session). The visuospatial working memory condition and imagery condition each had three levels of difficulty (that were the same in each task). The dependent variable was: accuracy and confidence of response (rating 1 = low confidence to 4 = highly confidence).

2.2.3 Methods

2.2.3.1 Participants

Twenty aphantasic participants were recruited by volunteer sampling (VVIQ ≤ 26). Of these participants, 7 were males and 13 were females, with a mean age of 40y0m (SD = 8.92y). On the VVIQ, aphantasic participants scored a mean of 16.65 (minimum = 16, maximum = 24, SD = 1.95). On the Wechsler Test of Adult Reading (WTAR, Wechsler, 2001, see Appendix 2.3), which provides a reliable estimate of intelligence (Mathias, Bowden, & Barrett-Woodbridge, 2007), aphantasic participants scored a mean of 43.35 (SD = 3.01, Full-Scale IQ (FSIQ) mean = 108, SD = 3.21, see Appendix 2.4 for a breakdown of WTAR scores and predicted FSIQ).

Twenty control participants (VVIQ < 32), 9 males and 11 females were recruited through volunteer and opportunity sampling, with a mean age of 36y3m (SD = 15.06y). On the VVIQ, the control participants scored an average of 55.35 (minimum = 34, maximum = 74, SD = 11.79). On the WTAR, control participants scored a mean of 42.80 (SD = 7.64, FSIQ mean = 108.55, SD = 8.88). A Mann Whitney test (U = 163, p = .31, r = .16) showed no significant difference in WTAR score between the aphantasic and control participants.

The Psychology Department Ethics Committee University of Westminster, UK, gave ethical approval and written informed consent for these control participants were also obtained.

2.2.3.2. Materials

Weschler Adult Reading Test (WTAR)

The Wechsler Test of Adult Reading (WTAR, see Appendix 2.3) comprises of 50 words that have atypical grapheme to phoneme translations. Participants are asked to read each word aloud. WTAR scores are calculated by counting the number of correctly pronounced spoken words.

Visuospatial working memory (VSWM) and imagery (IM) paradigm

This task drew on the same methodology as Jacobs et al. (2017). During the VSWM condition, participants were shown one of three shapes and asked to recall the shape after a short delay. This condition acted as a training session for the IM condition, which was undertaken after a delay of one week following the VSWM condition. In this IM condition, participants were not shown the shapes but had to recall the shapes from long term memory from the previous session.

In the VSWM condition, each trial began with the presentation of the name of a geometric shape (either a *diamond*, *triangle* or *parallelogram*), which was displayed for 500ms. Following the 500ms, the corresponding shape appeared in the centre of the screen for 1500ms before it disappeared. This was followed by a square of visual noise that appeared on the screen for 200ms to prevent the generation of an afterimage. After a 4000ms delay period, a small (2 x 2 pixels) black dot appeared on the screen. In both conditions, participants were instructed to indicate by button pressing (left = 'IN' and right arrow = 'OUT' keys), whether they thought the small dot appeared 'inside' or 'outside' the boundary of the original geometric shape. After each trial, participants were asked to indicate the confidence in their response on a scale of 1-4 (1 = no confidence, 4 = high confidence). Three levels of difficulty were created by presenting the target dot at three different distances from the outer contours of the original shape stimulus.

The IM condition was identical to the VSWM condition (see Figure 2.3), except participants were only shown the name of the geometric shape (not the shape itself). The name of the shape appeared within the four placeholders that marked the area of the visual field where the stimuli would have typically appeared. There were 3 blocks within the VSWM and IM condition, each block comprising of 18 trials, with a total of 54 trials within the task. The VSWM began with a 9 trial practice block prior to the experimental phase, where feedback was provided for each trial. There was no practice block in the IM condition.

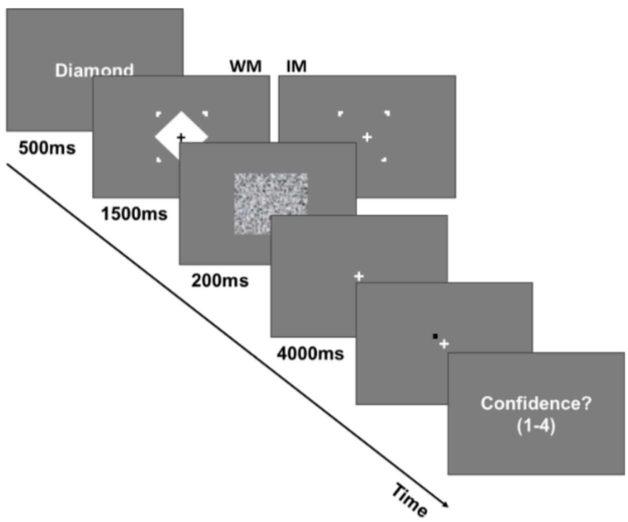


Figure 2.3: Diagram to depict the visual working memory (VSWM) and imagery (IM) conditions, from Jacobs et al. 2017.

2.2.3.3. Procedure

Participants who expressed an interest in the study were sent the information sheet, consent form and briefed by email regarding the nature of the study, and also asked to complete the VVIQ. Aphantasic data collected within this Experiment was part of a wider battery of tasks (described in Chapter 3 and Chapter 4, see Figure 3.1 for an overview). Both aphantasic and control participants were invited to undertake the first testing session, during which, participants provided written informed consent (see Appendix 2.5 and Appendix 3.3). Subsequently, participants undertook the WTAR whereby they were asked to read the words aloud; at a pace they felt comfortable. Following the WTAR, participants undertook the VSWM condition. In the VSWM condition, participants were verbally instructed that they would be presented with a shape and a dot, and would have to determine if the dot fell inside or outside the boundary of the shape, as well as indicate their confidence. Participants first undertook the practice of the task, followed by the experimental trials. The task was undertaken in the dark (lights switched off), and the experimenter stayed in the room only for the practice block and left the room for the experimental trials. Participants returned one week following their first visit and during this second session undertook the IM condition. This task was also undertaken in the dark, and the condition instructions varied slightly between participants: aphantasic individuals were asked to '*recall or retrieve the shape from memory*' whereas controls were asked to '*retrieve the shape from memory or imagine the shape*.' At the end of the second session, participants were thanked for their time and provided with a written debrief and a £20 voucher as thanks for their participation.

2.2.3.4. Data transformations

Throughout this thesis, the following data transformations are used (where stated) and this transformed data is used for subsequent statistical analysis. The mean differences provided in conjunction with post-hoc analysis reflect values from the non-transformed data. Data visualisations such as graphs and tables also depict the raw non-transformed data.

Box-cox transformation

A Box-cox transformation is a power transformation used to modify the distributional shape of continuous positive data, necessary for statistical analysis, which require normality as an assumption, such as analysis of variance (ANOVA) (Box & Cox, 1964). In this transformation, the transformation parameter lambda (λ) is estimated (in this case it is estimated on MATLAB between -5 minimum, and 5 maximum, in step sizes of .01) based on the lower and upper bound confidence intervals of the data using the formula:

$$\text{Data}(\lambda) = \frac{\text{Data}^{\lambda} - 1}{\lambda}$$

On a normality plot, the appropriate λ is one that shifts the data distribution curve to a normal distribution. In this thesis, Box-cox transformations are used to transform non-normally distributed data (e.g. reaction time data).

Rationalised Arcsine transformation

A rationalised arcsine transformation is used to transform non-normally distributed data for use in parametric statistical tests (such as ANOVA) (Studebaker, 1985). It is typically used on proportional data, whereby the range is bounded at 0 or 1. Undertaken on MATLAB, the arcsine transformation linearises the proportions and converts them to rational arcsine units (RAU). The effect of this transformation is that it 'pulls out' the ends of the distribution. Linear tests are performed on these RAU values. In this thesis, a rationalised arcsine transformation is used to transform the distribution of accuracy data that is bounded at 1.

2.2.4. Results

In instances where data is not normally distributed (e.g. Shapiro-Wilk < 0.05), data is transformed where stated. Where sphericity cannot be assumed, a Greenhouse-Geisser correction is used. All t-tests are 2-tailed. A Bonferroni-Holm correction was used where stated for multiple tests and adjusted p-values are reported.

2.2.4.1. Experimenter confounds and practice effects

To address experimenter confounds (i.e. differences between data collected due to two different experimenters, Z and *E*), control participant performance was compared between the first three blocks of the data collected by *Z* to the performance of controls collected by *E*, see Table 2.3.

	Accuracy and confidence for Experimenter: Z and E		
	Experimenter original: *Z*		**Experimenter MSc: *E***
Condition	**Z: 8 blocks**	**Z: 3 blocks**	**E: 3 blocks**
VSWM Accuracy	0.87 (0.05)	0.85 (0.05)	0.85 (0.06)
VSWM Confidence / 4	3.13 (0.32)	3.12 (0.37)	3.15 (0.46)
IM Accuracy	0.86 (0.04)	0.85 (0.07)	0.86 (0.07)
IM Confidence / 4	3.16 (0.35)	3.08 (0.40)	3.05 (0.43)

Table 2.3: Table to show the comparison of control performance and confidence (out of 4) within the first 3 blocks of the visuospatial working memory (VSWM) condition and the imagery (IM) condition between Experimenters *Z* and *E*. Average accuracy and confidence is also included for comparison for controls performance in the full 8 blocks (collected by Experimenter *Z*).

To check for experimenter bias within the two condition, 3 block performance was compared (between Experimenters *Z* and *E*). A 2 x 2 mixed ANOVA with factors condition (VSWM / IM) and experimenter (Experimenter *E* 3 blocks / Experimenter *Z* 3 blocks) showed no significant main effect of condition ($F(1, 38) = 0.43$, $p = .52$, $\eta p^2 = .01$) or experimenter ($F(1, 38) = 0.07$, $p = .78$, $\eta p^2 = .002$), and there was no significant interaction between the experimenter and condition ($F(1, 38) = .07$, $p = .79$, $\eta p^2 = .002$). This suggests that the effect of experimenter did not influence controls performance within the VSWM and IM conditions.

To explore whether controls would perform better (due to more practice in the VSWM condition) with 8 blocks compared to 3 blocks (within the control data collected by Experimenter *Z*), a repeated measures t-test showed no significant difference in accuracy ($t(19) = 2.03$, $p = .06$, $d = .40$) in controls accuracy at block 3 and block 8. This suggests that in the data collected by Experimenter *Z,* whereby controls were presented with 8 blocks within the VSWM condition, this additional practice in the task did not significantly improve accuracy.

To explore whether the effect of additional practice on the IM condition (i.e. controls who experienced 8 blocks in the VSWM condition during the first week compared to controls who experienced 3 blocks), IM accuracy was compared (8 blocks collected by Experimenter *Z* compared to the three blocks as collected by Experimenter *E*). A 2 x 2 mixed ANOVA with factors condition (VSWM / IM) and block length (Experimenter *E* 3 blocks / Experimenter *Z* 8 blocks) showed no significant main effect of condition ($F(1, 38) = 0.02$, $p = .89$, $\eta p^2 = .001$) or block length ($F(1, 38) = .31$, $p = .58$, $\eta p^2 = .01$) and no significant interaction between condition and block length ($F(1, 38) = .88$, $p = .35$, $\eta p^2 = .02$). This suggests that controls who were exposed to 8 blocks within the VSWM condition (therefore more practice within the condition), were not at an advantage during the IM condition compared those controls who only experienced 3 blocks. All further analysis of this experimental paradigm will be carried out with the control data collected by Experimenter *E*.

2.2.4.2. Accuracy

Accuracy data for the visuospatial working memory and imagery conditions were transformed using an arcsine transformation (Studebaker, 1985). Mean accuracy in the two conditions (at the different levels of difficulty) were compared between aphantasic and control participants (see Figure 2.4).

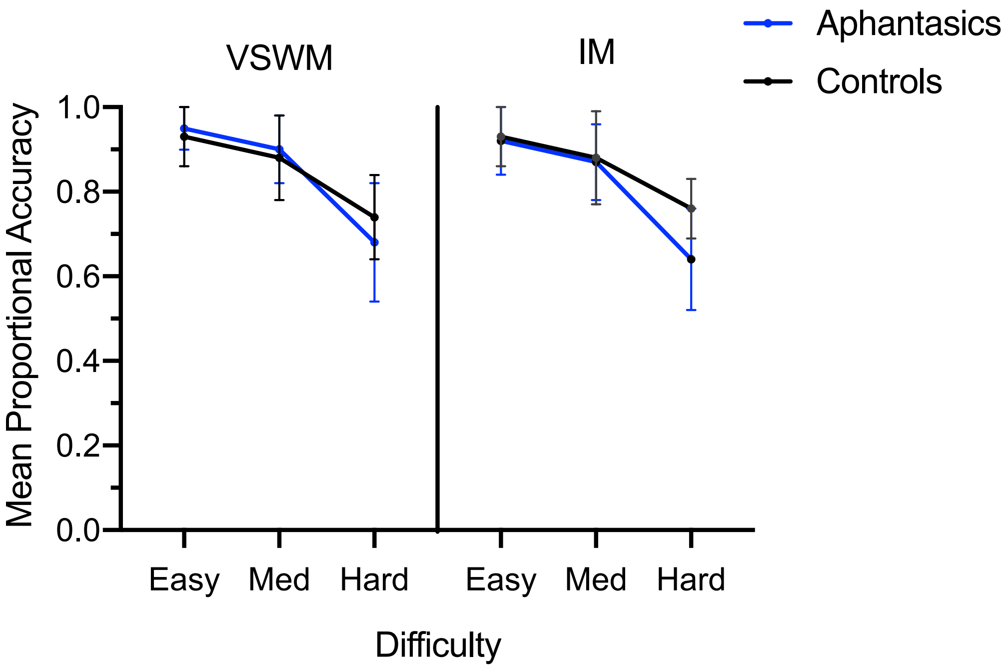


Figure 2.4: Line graph to depict the mean proportional accuracy and error bars (representing the standard deviation) of aphantasic and control participants in the visuospatial working memory (VSWM) and matched imagery (IM) condition.

A 2 x 2 x 3 mixed ANOVA with factors participant group (aphantasic/ control), condition (VSWM / IM) and difficulty (easy/ medium/ hard) showed a significant main effect of difficulty ($F(2, 76) = 114.83$, $p < .001$, $\eta p^2 = .75$), with lower accuracy with increasing level of difficulty. Post hoc tests using Bonferroni-Holm correction for multiple comparison, revealed a significant pairwise difference in accuracy between easy and medium difficulty with a mean difference in accuracy of 0.05 ($p < .001$), easy and hard difficulty with a mean difference in accuracy of 0.23 ($p < .001$) and medium and hard difficulty with a mean difference in accuracy of 0.18 ($p < .001$). There was no significant main effect of condition ($F(1, 38) = 2.36$, $p = .13$, $\eta p^2 = .32$) or group ($F(1, 38) = 0.73$, $p = .40$, $\eta p^2 = .02$). There was a significant interaction between condition and group ($F(1,38) = 4.54$, $p =.04$, $\eta p^2 = .11$), and no significant interaction between difficulty and group ($F(2,76) = 2.72$, $p = .07$, $\eta p^2 = .07$) no other interactions were significant (all $p > .89$). Breaking down the interaction between condition and group, post-hoc independent t-test of accuracy in the VSWM condition ($t(38) = .22$, $p = .82$, $d = .07$) indicated no differences in accuracy between the two participant groups, while in the IM condition ($t(38) = 2.40$, $p = .02$, $d = .76$) aphantasic participants were less accurate in the IM condition than control participants. A within-subjects t-test showed that aphantasic participants ($t(19) = 2.25$, $p = .04$, $d = .32$) performed significantly worse on the IM condition than the VSWM condition, there was no significant difference in performance between the conditions in control participants ($t(19) = -.80$, $p = .44$, $d = 0.11$). These results suggest that aphantasic participants were less accurate in the IM condition, with no differences in accuracy to controls in the VSWM condition.

2.2.4.3. Confidence ratings

Confidence data for the VSWM and IM conditions were transformed using a BoxCox transformation (Box & Cox, 1964). Confidence ratings provided in the two conditions (at the different levels of difficulty) were compared between aphantasic and control participants (see Figure 2.5).

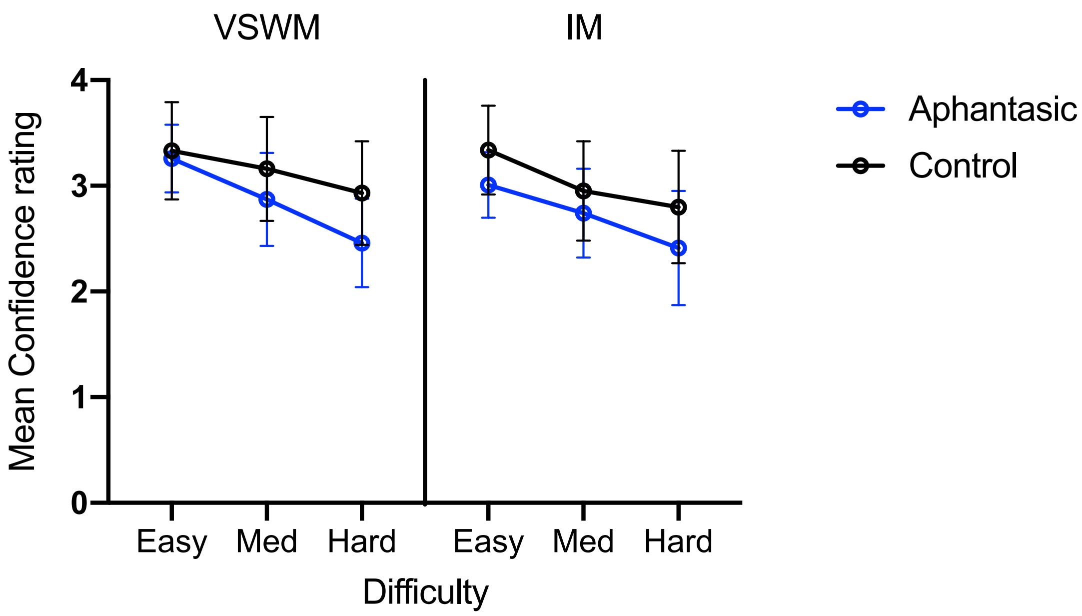


Figure 2.5: Line graph to depict the mean confidence ratings and error bars (representing the standard deviation) of aphantasic and control participants in the visuospatial working memory (VSWM) and matched imagery (IM) conditions. Confidence ratings were on a scale of 1 (low confidence) to 4 (high confidence).

A 2 x 2 x 3 mixed ANOVA with factors participant group (aphantasic/ control), condition (VSWM/IM) and difficulty (easy/ medium/ hard) showed a significant main effect of condition (F(1,38) = 11.99, p < .001, ηp^2 = .24) with both participant groups more confident of their responses in the VSWM condition than the IM condition and a significant main effect of difficulty (F(2,76) = 74.0. p < .001, ηp^2 = .66). Post hoc tests using the Bonferroni-Holm correction for multiple comparison, revealed a significant pairwise difference in confidence between easy and medium difficulty with a mean difference in confidence of 0.31 (p < .001), easy and hard difficulty with a mean difference in confidence of 0.59 (p < .001) and medium and hard difficulty with a mean difference in confidence of 0.28 (p < .001). There was a significant main effect of participant group (F(1,38) = 7.60, p = .009, ηp^2 = .17) with aphantasic participants rating lower confidence in their responses in both tasks compared to control participants. There was also a significant interaction between participant group, difficulty and condition ($F(2,76) = 6.69$, $p = .002$, $\eta p^2 = .15$). All other interactions were not significant ($p > .19$).

To explore this interaction, the confidence ratings in the VSWM and IM conditions, at each level of difficulty were compared between aphantasic and control participants. In the VSWM, independent t-tests with Bonferroni-Holm correction for multiple tests, showed a significant difference in confidence at hard ($t(38) = 3.62$, $p = .003$, $d = 1.03$) and medium difficulty ($t(38) = 2.23$, $p = .006$, $d = .70$) and no evidence of a difference at the easy difficulty level ($p > .43$), suggesting that aphantasic participants were significantly less confident in their responses with increasing difficulty (where more precision is required) compared to controls. In the IM condition, independent t-tests with Bonferroni-Holm correction showed a significant difference during the easy level of difficulty ($t(38) = 3.21$, $p = .009$, $d = .92$), and hard difficulty level ($t(38) = 2.30$, $p = 0.05$, $d = .73$) and no significant difference at medium difficulty levels ($p > .10$). These results suggest that aphantasic participants were less confident in their responses in both tasks especially during the most difficult trials, compared to control participants.

2.2.4.4. Metacognitive accuracy

Metacognitive accuracy (i.e. the mean difference in confidence ratings[7] provided during incorrect and correct trials) were calculated for both participant groups in the VSWM and IM conditions. This value shows the difference in confidence ratings when a participant is when making a correct and incorrect responses (Jacobs et al., 2017; see Figure 2.6).

[7] This is calculated by subtracting the confidence ratings provided during incorrect trials from the confidence ratings provided during correct trials.

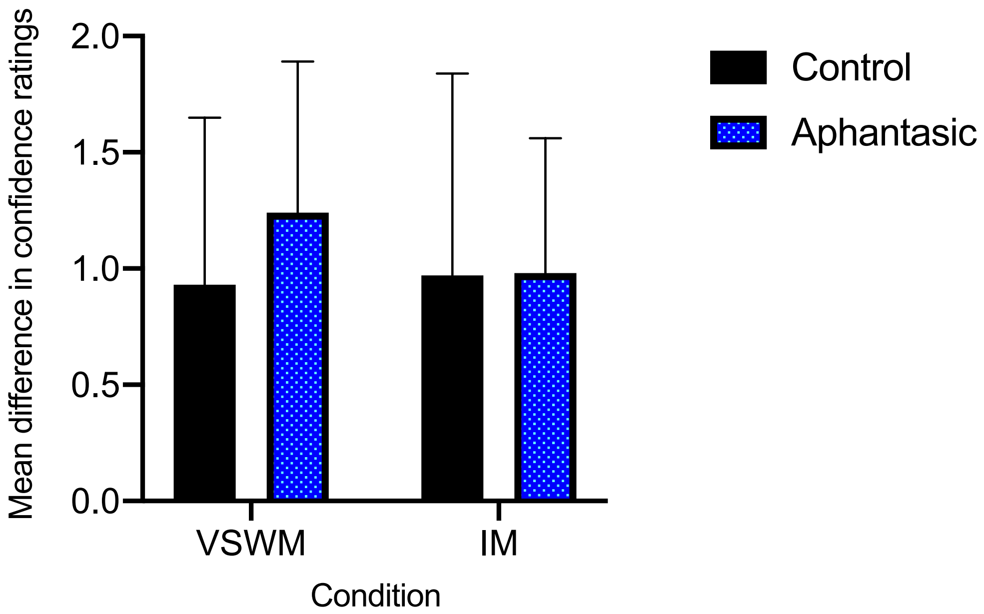


Figure 2.6: Bar chart to show aphantasic and control participants' mean metacognitive accuracy and error bars (representing the standard deviation) in the visuospatial working memory (VSWM) and matched imagery (IM) conditions.

A two-way mixed measures ANOVA with Greenhouse-Geisser correction with factors participant group (aphantasic/ control) and condition (VSWM/IM) showed no significant main effect of condition ($F(1,38) = .71$, $p = .40$, $\eta p^2 = .02$) or participant group ($F(1,38) = .74$, $p = .40$, $\eta p^2 = .03$) and no significant interaction between participant group and condition ($F(1,38) = 1.30$, $p = .26$, $\eta p^2 = .03$). This suggests there is no difference in metacognitive accuracy in aphantasic and control participants within the two conditions.

2.2.5. Discussion

Experiment 2 investigated aphantasic participants' performance within a visuospatial working memory and imagery paradigm with the purpose of understanding the relationship between the two functions. By testing individuals with aphantasia, who self-report the inability to generate visual imagery, the findings suggest that a lack of visual imagery does not impair performance within a visuospatial working memory task, contradictory to the performance of participant *AI* (Jacobs et al., 2017). The results of Experiment 2 showed that within a larger sample of aphantasic participants, no differences in performance were apparent in the visuospatial working memory condition with differences apparent in the imagery condition. Aphantasic participants reported significantly lower confidence across both conditions than participants with typical imagery. This suggests that aphantasic participants' experience of undertaking the two task conditions was different compared to controls. Furthermore, there were no differences in metacognitive accuracy, which also contradict the findings of Jacobs et al. (2017).

Although these results show the reverse effect as reported by Jacobs et al. (2017), the number of trials within the current experiment were significantly less than that reported in the case study. The number of trials that the aphantasic participants were exposed to in the visuospatial working memory condition was significantly less than the number of trials that *AI* undertook. This means that the aphantasic participants within this Experiment had less training or exposure to the shapes presented within the visuospatial working memory condition. This lack of exposure or training may have influenced performance within the imagery condition and may be a reason as to why differences in accuracy were apparent within the imagery condition. On the other hand, it should be noted that there were no differences in control participants' accuracy in the 3 block version compared to the 8 block version in either condition of the task (see Table 2.3). This might suggest that this lesser exposure during the VSWM condition (i.e. of only 3 blocks) cannot account for the less accurate performance as exhibited by the aphantasic participants in the IM condition. Similarly, this lesser exposure within the visuospatial working memory condition may explain why the aphantasic participants reported significantly lower confidence in their responses in the imagery condition (in line with lower confidence in the IM condition as provided by control participants at 3 blocks compared to 8 blocks, see Table 2.3). However, differences in block length cannot explain the reasons as to why the confidence ratings provided by aphantasics participants were also lower in the VSWM condition. Collectively, this may suggest that the design of the paradigm may influence performance to some extent in the IM condition, but it cannot fully explain the performance differences exhibited by aphantasic participants.

The authors of the experimental paradigm referred to their task as a 'visual' working memory task (Jacobs et al., 2017). It was predicted, that if the task were indeed purely visual in nature, then it would be expected that individuals with aphantasia would perform poorly. This was expected due to the lower scores provided on the object imagery scale of the OSIQ in Experiment 1, which would predict poor performance in visual tasks. However, within the current experiment, no difference in accuracy was evident within the working memory condition, suggesting that the task cannot rely purely on object imagery, but is visuospatial in nature. Experiment 1 showed that individuals with aphantasia self-reported intact spatial imagery, and this has been documented within other studies (Dawes et al., 2020). Therefore, one possible speculation is that individuals with aphantasia may be using spatial imagery within the task, in the absence of a visual component. The use of spatial imagery within the task leads to accurate performance that is comparable to individuals with typical imagery.

The visuospatial working memory task used within this experimental paradigm has a low working memory load and complexity, which may also explain why no differences in performance were apparent within this condition. During the task, participants have to hold or maintain an outline of one of three shapes for less than five seconds, which requires no further manipulation of the stored information, but a response in terms of the location of a dot in relation to the shape. In terms of the revised visuospatial working memory model, this static information would be stored within the visual cache for use in the task when required (Logie, 1995). This task could also be described as a passive working memory task whereby task information needs to be recalled in the way in that it was presented (Vecchi, Richardson, & Cavallini, 2005). Due to the low working memory load of this task, for controls, they likely engage in visual imagery to maintain the shape visually in working memory. In the absence of any additional manipulation or secondary interference and limited working memory load, aphantasic participants can use spatial imagery. If individuals with aphantasia perform similar to controls within passive tasks, specifically tasks with low working memory load, it remains to be explored how individuals with aphantasia would perform within more complex visuospatial tasks that require active maintenance and manipulation of larger amounts of visuospatial information. Such tasks would test the nature of aphantasics' internal representations, with the expectation of a difference in performance if aphantasic participants adopt different (non-imagery) processes within tasks compared to participants with typical imagery. Moreover, in terms of the multicomponent theory of working memory, it has been proposed that the maintenance of highly detailed visuospatial information may involve the repeat generation of the image within the visual buffer (Darling et al., 2009), a structure where images are thought to be consciously experienced (Pearson, 2001). As such, within tasks that require active maintenance and manipulation of larger amounts of visuospatial information performance differences may be expected between aphantasic and typical imagery individuals.

Within the imagery version of the task, there was a significant difference in performance between aphantasic and control participants, which is in contrast to the performance with participant *AI* (Jacobs et al., 2017). There are two differences between the imagery version of the task and the working memory version. Firstly, instead of being shown the image of the shape (as in the working memory version of the task), participants are shown only the name of the shape, i.e. '*triangle'* (and must recall the shape in question) and base this representation on the positioning of the dot (either inside or outside the shape). Secondly, the recall is made more difficult owing to the length of time between the two tasks, with the imagery version of the task being undertaken one week after the working memory version. Thus the shapes presented from the first testing session need to be recalled from long-term memory within the second testing session (Brady, Konkle, & Alvarez, 2011; Cowan, 2009; Schurgin, 2018). If controls are engaging in visual imagery, recall of the shape is drawn from long-term memory, and this information is held in the visual buffer for subsequent inspection and transformation (Riddoch, 1990). In this case, the transformation would include comparing the spatial location of the visual dot to the mental representation of the shape. This is a conscious visuospatial experience, and a number of studies have shown that visual long-term memory can store objects in high detail (Brady, Konkle, Alvarez, & Oliva, 2008; Konkle, Brady, Alvarez, & Olivia, 2010; Spachtholz & Kuhbandner, 2017). Within trials of the hardest level of difficulty, the judgement of the position of the dot is more difficult as it appears closest to the boundary of the shape. Although spatial imagery is one possible option available to aphantasic participants, it is not known if they used this within the imagery condition. The results of the imagery condition would suggest, however, that the processes adopted by aphantasic participants are not conducive to scenarios where information has to be held over a longer period of time. As a result, aphantasic participants perform worse in the imagery condition. Although, it should be noted that overall accuracy is high within the task (i.e. not at floor or below chance), suggesting the task can be undertaken in other ways or speculatively, they may be undertaking the task in the same way as typical imagers, but in a lesser capacity.

This difference in processes and lack of internal visual representations may also explain why aphantasic participants self-reported to be less confident in both conditions compared to controls with typical imagery. The fact that aphantasic participants report significantly lower confidence ratings than control participants would suggest that their experience of undertaking the task is different to controls, yet accuracy within the conditions is similar. In terms of the imagery condition, controls who may experience recall of the shape from long term memory as a visual experience, may as a consequence, be more confident with regards to their responses than aphantasic participants. In addition, participant *AI* showed a lower metacognitive accuracy (Jacobs et al., 2017) suggesting differences in confidence for incorrect and correct trials. However, within a large sample, there were no differences in metacognitive accuracy between aphantasic and control participants with typical imagery. This further shows the importance of replication within behavioural studies.

2.2.6. Chapter conclusion

This Chapter examined two key findings; one finding from a published case study and another finding from a study comprising of a small aphantasic participant sample, to explore whether the results obtained could be replicated. Imagery questionnaires such as the OSIQ challenge the notion that visual imagery is a unitary construct, and explores individual self-reported preferences for object and spatial imagery. Experiment 1 showed, that within a large sample, aphantasic participants self-reported higher spatial imagery scores compared to object imagery scores, suggesting their spatial imagery abilities are intact. Such a preference was not present in individuals with typical imagery, who showed a preference for object imagery (i.e. imagery that is highly pictorial and colourful) than spatial imagery. Although it should be noted there was variability within this sample, with a proportion of controls reporting a higher score for spatial imagery (than object imagery). This illustrates the variability of imagery within typical imagery experiences. Further, in control participants, a positive and significant correlation was evident between object subscale OSIQ and VVIQ scores, suggesting that these measure similar constructs.

Experiment 2 adopted the experimental design as denoted in the case study by Jacobs et al. (2017) who showed that participant *AI* had impaired performance in the visuospatial working memory task. The results of Experiment 2 contradict these findings. In a larger sample, there was no difference in accuracy in the visuospatial working memory condition compared to controls with typical imagery. However, there was a significant difference in performance in the imagery version of the task. Confidence ratings provided by aphantasic participants were significantly lower in both conditions compared to the confidence ratings provided by participants with typical imagery. This suggests that the experience of undertaking the task was different; however, it did not result in vast differences in accuracy. Reasons for these differences were discussed in terms of differences in processes adopted by both participant groups. For controls, who have access to visual imagery, they are able to encode an accurate representation of the shapes in the task that are then recalled at a later date during the imagery condition. However, for aphantasic participants, their processes are not adequate over long periods of time.

Further exploration is required within visuospatial working memory and matched imagery paradigms.

There are a number of outstanding questions remaining from these experiments. In the current experiment, individuals with aphantasia performed as well as individuals with typical imagery in the visuospatial working memory condition. However, this task comprised of a low working memory load and required little manipulation. Thus, it remains to be explored how individuals with aphantasia would perform in tasks that require the maintenance and active manipulation of large amounts of visuospatial information. In addition, if individuals with aphantasia self-report a lack of visual imagery in the VVIQ, and a preference for spatial imagery over object imagery, it also remains to be explored as to whether the reasons for such self-reports can be attributed to by variances in personality or different cognitive profile. The ability to introspect on one's experiences is prone to error (Hurlburt & Schwitzgebel, 2011). Moreover, responses provided on self-report measures may also be mediated by other variables, such as personality traits (e.g. Buchanan, 2015). Similarly, high imagers and low imagers have been shown to have different cognitive profiles (Marks, 1973; McKelvie & Demers, 1979). In the aphantasia literature, cognitive performance has only examined so far at a case study level (Zeman et al., 2010) and it is not yet understood whether congenital aphantasia is associated with a more general neuropsychological deficit. Whether individuals with aphantasia have a certain personality profile or general neuropsychological deficit that may explain their self-reported experience of a lack of visual imagery will be the focus of the following Chapter.

Chapter 3: Can aphantasia be explained through differences in personality or cognitive profiles?

General Summary

The Vividness of Visual Imagery Questionnaire (VVIQ) is typically used to identify individuals with aphantasia; however, introspection of imagery is difficult, and personality traits may modulate responses. It is also not clear whether individuals with aphantasia show broader cognitive deficits or differences within other memory domains. Similarly, no study has yet explored whether self-reported differences are linked to variances in personality or cognitive profiles (although see Milton et al., *submitted*). Experiment 3 examines the personality profiles of individuals with aphantasia (n = 20) through the Big Five Inventory (BFI), a measure for personality traits: extraversion, agreeableness, conscientiousness, neuroticism and openness. The results showed that aphantasic and control participants differed only in their levels of agreeableness, which might be accounted for by a recruitment bias. Experiment 4 explored cognitive performance within four tasks selected from the Cambridge Neuropsychological Test Automated Battery (CANTAB): Verbal Recognition Memory (VRM), Pattern Recognition Memory (PRM), Spatial Span (SSP) and One Touch Stocking of Cambridge (OTS). When compared by group, the results showed no differences in accuracy between aphantasic and typical imager participants. However, aphantasic participants took significantly longer to respond at more demanding levels of difficulty during the OTS. A secondary analysis examined individual profiles of cognitive performance and revealed four possible subgroups. In summary, these results suggest that the personality and cognitive profile of people without imagery do not greatly differ from those with typical imagery when examined by group. However, observed differences were apparent with

increased working memory load. Subgroups of aphantasia were identified, suggesting that some aphantasic individuals may experience more specific cognitive deficits.

General Introduction

The most significant findings of Chapter 2 stem from self-report measures. In the Object Spatial Imagery Questionnaire (OSIQ), aphantasic participants scored significantly lower on the object imagery than spatial imagery subscale. This finding suggests that their spatial abilities are similar to that of individuals with typical imagery, which may explain why aphantasic participants displayed normal performance within a visuospatial working memory task (Experiment 2). Although officially identified in 2015, there are still many questions about the underlying mechanisms of aphantasia. One possibility that has not yet been explored is whether the phenomena of aphantasia is linked with differences in other traits and processes that are not necessarily associated with imagery. De Vito and Bartolomeo (2016) suggested in their commentary that aphantasia had psychogenic origins, proposing a loss of visual imagery may be accompanied by psychiatric disorders such as, depression, anxiety or depersonalisation disorder. De Vito and Bartolomeo (2016) also detailed that prior to the onset of *Monsieur X's* inability to visualise, he had experienced mental alienation or stress resulting in anxiety and low mood (see Chapter 1, section 1.4.1). The current published aphantasia research studies document individuals who report a life-long inability (which is stable rather than variable) to form voluntary visual imagery, which would suggest that aphantasia is unlikely to have a psychopathological origin (e.g. Bainbridge et al., 2020; Dawes et al., 2020, Keogh & Pearson, 2017; Wicken et al., *submitted*; Zeman et al., 2016; Zeman et al., 2015).

Individuals with aphantasia self-report a difference in their conscious experience of visual imagery, but investigations have not yet established whether there is more than one aetiology that may account for this contrasting experience compared to individuals with typical imagery. This will be investigated by exploring group differences in personality and cognitive performance, as well as reviewing individual cognitive profiles. This Chapter therefore explores two possible, and so far, unexamined possibilities. The first is whether individuals with aphantasia have differing personality profiles (Experiment 3). The second, aphantasic participants may exhibit differing cognitive profiles and reveal impairments in cognitive processes (Experiment 4).

In both Experiment 1 and 2 (and typically within the aphantasic literature, see Chapter 2, Experiment 1, Table 2.1), the Vividness of Visual Imagery Questionnaire (VVIQ) was used to identify individuals with aphantasia. However, one of the main criticisms regarding the use of the VVIQ within studies is with regards to its validity, for example, participants may respond with the vividness that is most socially desirable instead of report their true ability (McKelvie, 1995; McKelvie & Rohrberg, 1978). Similarly, the process of introspection is prone to error (Hurlburt & Schwitzgebel, 2011), and it is highly subjective. Its subjectivity gives rise to the fact that responses may be mediated by other variables, such as personality traits. For instance, self-reported ‘problems’ correlate with the trait neuroticism (Buchanan, 2015). Similarly, many studies have suggested a correlation between vivid imagery and the trait extraversion (Gralton, Hayes, & Richardson, 1979; McDougall & Pfeifer, 2012; McLean, 1969; Morris & Gale, 1974; Riding & Dyer, 1980; Strelow & Davidson, 2002). Experiment 3 will examine whether individuals with aphantasia have differing personality profiles.

On the other hand, aphantasic individuals may have genuinely different visual imagery experiences because of variances in their underlying neuropsychology. Of course, it is not possible to establish a causal direction: are aphantasic individuals worse at memory tasks because they cannot hold an image in their mind? Or can they not hold an image in mind because they have impairments in their memory system? There is evidence to suggest that high imagers and low imagers have different cognitive profiles. Vivid imagers (those who have vivid imagery) are thought to have an advantage (compared to lesser vivid imagers) on visual and verbal memory recall tasks (Marks, 1973; McKelvie & Demers, 1979). So far, cognitive performance has only been examined at a case study level; for instance, with patient *MX* who performed normally on a range of executive function tasks (Zeman et al., 2010). Nevertheless, *MX* had acquired aphantasia, and his lack of imagery arose following coronary angioplasty. Thus, the origins of his loss of imagery are thought to be different from that of individuals with congenital aphantasia. It should be noted, however, that *MX's* sudden loss of ability to generate visual imagery could not be explained through neurological assessments (which were normal) or apparent differences within structural MRI scans. Although *MX* had acquired aphantasia and performed normally within executive function tasks, no studies have explored how a larger sample of individuals with congenital aphantasia perform on a battery of cognitive tasks. Moreover, it is not known whether their absence of imagery is associated with any other general neuropsychological deficits. This will be explored in Experiment 4. If neuropsychological differences are apparent, this may help to understand why the subjective imagery experiences of individuals with aphantasia differ compared to those with typical experiences.

Experiment 3: Do personality differences explain aphantasia?

3.1.1. Introduction

The standard way of measuring an individual's experience of visual imagery is through self-reports. These ask individuals to rate scenarios with regards to their own imagery experience. For instance, vividness - refers to the clarity and luminance of a mental image (Pearson, Beni, & Cornoldi, 2001) and can be measured specifically in the visual domain using the VVIQ (Marks, 1973). Although aphantasia is typically identified through the VVIQ, there is no defined cut-off score for typical and atypical self-reports of imagery (Zeman et al., 2015). There are arguably more objective methods for identifying individuals with aphantasia (Keogh & Pearson, 2017; Wicken et al., *submitted*). However, these methods are time-consuming to undertake and do not provide immediate feedback as to whether an individual has aphantasia, unlike the VVIQ. Imagery vividness as self-reported by the VVIQ has been shown to correlate with objective measures both behaviourally and through neuroimaging (Cui et al., 2007; Pearson, Rademaker, & Tong, 2011), with high and low vivid imagers showing different patterns of brain activation (Fulford et al., 2018).

While the VVIQ correlates to objective measures of visual performance (Cui et al., 2007; Fulford et al., 2018), its inherently subjective nature raises questions on its susceptibility to various mediating factors and influences. For example, participants may respond in a manner that is socially most desirable (McKelvie, 1995; McKelvie & Rohrberg, 1978). The relationship between personality and self-reported vividness has been documented in a number of studies (Gralton et al., 1979; Morris & Gale, 1974; Riding & Dyer, 1980; Strelow & Davidson, 2002). A recent study found a positive correlation between the degree of extraversion and self-reports of the vividness of visual imagery; however, this did not translate to better performance on a recall task (McDougall & Pfeifer, 2012). McDougall and Pfeifer (2012) suggested these differences in self-reported visual imagery might be due to differences in impulsion between extroverts and introverts. Previously, differences in performance between extroverts and introverts were proposed to be due to the arousal theory (Eysenck, 1967; Eysenck & Eysenck, 1985), with an enhanced cortical arousal in introverts who also scored high for the trait neuroticism (Eysenck, 1976). Neuroticism, in particular, is associated with more negative self-perceived health (Magee, Heaven, & Miller, 2013). Personality traits may thus modulate responses on self-report measures such as the VVIQ and thus influence the 'identification' of aphantasia. This is another relationship that remains to be explored. If personality traits modulate self-reports of aphantasia, then there will be differences in personality profiles between individuals with aphantasia and individuals who have a typical imagery experience.

3.1.2 Methods

3.1.2.1. Participants

Twenty aphantasic participants[8] (VVIQ ≤ 26) recruited by volunteer sampling took part in the study (these are the same aphantasic participants as described in Chapter 2, Experiment 2 section 2.2.3.1). Briefly, 7 were males, and 13 were females, with a mean age of 40y0m (SD = 8.92y). On the VVIQ they scored a mean of 16.65 (SD = 1.95, lowest score = 16, highest score = 24). On the Wechsler Test of Adult Reading (WTAR), they scored a mean of 43.35 (SD 3.01,Full-scale IQ (FSIQ) mean = 108 (SD = 3.21). See Appendix 3.1 for the full WTAR predicted equivalence to FSIQ score by participant.

[8] As documented in Chapter 2, Table 2.1 the largest sample size of aphantasic participants detailed within published studies at the outset of this data collection was 15. A sample size of 20 aphantasics was chosen on the basis that aphantasia is a niche population and the requirements of the study (the design of involving two testing sessions and lab based) made it challenging to recruit larger samples.

Twenty control participants recruited by opportunity and volunteer sampling took part in the study. Of these participants, 8 were males, and 12 were females with a mean age of 39y6m (SD 11.61). On the VVIQ, control participants (VVIQ > 33) scored an average of 63.8 (SD 12.34, lowest score = 36[9], highest score = 80). Of the controls, 4 participants were hyperphantasic (defined as VVIQ scores between 75-80, see Zeman et al., 2020). On the WTAR, control participants scored a mean of 42.3 (SD 4.12, FSIQ mean = 106.6, SD = 4.42). An independent t-test ($t(38) = -0.92$, $p = .36$, $d = .29$) confirmed no significant difference in WTAR scores between aphantasic and control participants.

The exclusion criteria for this study were two-fold; the first, if participants had a history of mental health conditions and the second if participants did not have a normal or correct-to-normal vision.

The protocol for the study was in accordance with the British Psychological Society guidelines and the ethical approval provided by the Psychology Department Ethics Committee of the University of Westminster, UK. At the end of the second session, participants were given a £20 love2shop voucher and asked to sign a declaration that they had received their payment for their participation in the study.

3.1.2.2. Materials

Big Five Inventory

The Big Five Inventory (BFI, Digman, 1990; Goldberg, 1993) is a well-adopted method to assess personality (Hendriks, Hofstee, & Raad, 1999; McCrae & John, 1992). The

[9] An additional analysis was undertaken with the removal of the control participant who scored 36 on the VVIQ. The removal of this participant did not change the significance of any of the results.

questionnaire comprises of 44 statements regarding five personality traits: extraversion, agreeableness, conscientiousness, neuroticism (emotional stability), and openness (e.g. '*tend to find fault with others*' or '*generates a lot of enthusiasm*'). For each statement, participants have to decide and rate on a scale of 1 ('*disagree strongly*') to 5 ('*strongly disagree*') with statements concerning themselves.

3.1.2.3. Procedure

Procedure overall design of the testing sessions

This experiment was part of a wider testing session (see Figure 3.1). A recruitment poster of the study (see Appendix 3.2), and Qualtrics survey of the VVIQ was posted on a number of different social media platforms to recruit aphantasic participants: the Aphantasia forum (Aphantasia Forum), two Aphantasia groups on Facebook ('*Aphantasia non-imager/mental blindness awareness group*' and '*Aphantasia!*') as well as posted on Twitter. Aphantasic participants were invited to participate if their VVIQ ≤ 26. Individuals with typical imagery who scored VVIQ > 33, were recruited from the graduate and teaching population at Westminster University, and also recruited from social media platforms such as Facebook and Twitter. Control participants were age-matched within 1-2 years of the aphantasic participants.

<u>Session One:</u> All tasks randomised	*Between testing sessions, all participants completed via Qualtrics*:	**<u>Session Two:</u>** All tasks randomised. CANTAB tasks are randomised within the battery
• Roadmap test • Mental Rotation Task (MRT Version A) • Own Body Transformation task (OBT) • Visuospatial Working Memory (VSWM) task • Wechsler Test of Adult Reading • Big 5 Inventory	• Spontaneous Use of Imagery Questionnaire (SUIS) • Object Spatial Imagery Questionnaire (OSIQ)	• Mental Rotation Task (MRT Version B) • Transpose Task • Imagery Task <u>CANTAB Battery:</u> • Pattern Recognition Memory (PRM) • One Touch Stocking of Cambridge (OTS) • Verbal Recognition Memory (VRM) • Spatial Span (SSP)

Figure 3.1: Diagram to show the overall design of data collected and described within Chapters 3, 4 and 5. Data were collected over two testing sessions, one week apart.

Data collection from the BFI originated from the wider study (as shown in Figure 3.1) undertaken over two separate testing session (two hours for each session), at the same time of day, seven days apart. At the beginning of each session, participants were verbally briefed to the rationale of the study and asked to sign consent for their participation within the study (see Appendix 3.3). The tasks within each testing session remained the same, but within each testing session, tasks were randomised using a Latin square to prevent order effects. This was except for the own body transformation task (Chapter 5, Experiment 6) and visuospatial working memory task (Chapter 2, Experiment 2) that were undertaken in the first testing session, with the corresponding transpose (a control task for the own body transformation task) and imagery task, which was always undertaken in the second session (see Figure 3.1).

Procedure: Big Five Inventory (BFI)

Participants were provided with all 44 statements of the BFI on an A4 piece paper (see Appendix 3.4). Participants were asked answer each statement regarding the five different personality traits and assign an appropriate number from 1 – 5 with regards how much they agreed or disagreed with each item. Once participants had assigned a number to each of the 44 statements, they moved onto the next task within the testing session (see Figure 3.1).

3.1.3. Results

3.1.3.1. Big Five Inventory

The Bonferroni-Holm correction was used for multiple tests and adjusted p-values are reported. The correlation between VVIQ scores and BFI personality traits was assessed using the Pearson correlation coefficient, see Table 3.1.

Personality Trait (BFI)	**Mean (SD) and *t* (test statistic)**		**Personality traits by VVIQ score**	
	Control	**Aphantasic**	**Control**	**Aphantasic**
Agreeableness	30.35 (5.93) $t = 3.91$	36.40 (3.56)	r = .13, p = .58, z = .13	r = -.31, p = .18, z =-.32
Conscientiousness	32.75 (3.84) $t = 0.32$	33.25 (5.84)	r = -.04, p = .87, z = -.04	r = .31, p = .18, z = .32
Neuroticism	24.20 (5.85) $t = 1.59$	20.9 (7.20)	r = .22, p = .36, z = .22	r = .01, p = .96, z = .01
Extroversion	29.6 (8.00) $t = 2.05$	24.9 (6.42)	r = .49, p = .03, z = .54	r = -.23, p = .32, z = -.23
Openness	36.65 (5.82) $t = 0.10$	36.45 (6.61)	r = .64, p = .003, z = .76	r = -.08, p = .74, z = -.08

Table 3.1: Table to denote the personality scores (in the BFI) of the two participant groups, including their mean scores, standard deviation and Pearson correlation of personality trait by VVIQ score.

Independent t-tests comparing participant groups for each personality trait demonstrated a difference only for agreeableness scores ($t(31.12) = 3.91$, $p = .005$, $d = 1.24$) with aphantasic participants scoring higher (M = 36.40, SD = 3.56) than control participants (M = 30.35, SD = 5.93). All other traits were not significant ($p > .18$). Self-reported VVIQ scores for individuals with aphantasia and control participants were correlated separately using a Pearson correlation with the five personality traits. In controls, the results showed a strong positive correlation for the trait extraversion and openness and self-reported vividness of visual imagery (see Table 3.1 – this was further explored in a larger sample of controls, see Appendix 3.5). This suggests that in those who scored higher for extraversion and openness on the BFI also provided higher vividness ratings on the

VVIQ. In contrast, no significant correlations were found between VVIQ scores and personality traits in individuals with aphantasia.

3.1.4. Discussion

Experiment 3 investigated whether individuals with aphantasia exhibited particular personality profiles. Our results suggest that individuals with and without aphantasia do not differ in their levels of conscientiousness, openness, extraversion or neuroticism. Aphantasic individuals did demonstrate higher levels of agreeableness. However, this could be explained by a recruitment bias. Although control and aphantasic participants were both volunteers in the study, they differed in their motivations and reasons to undertake the study. Aphantasic individuals who contacted the researcher offered their time so that researchers (and they themselves) could understand their experience and therefore potentially help not only the academic community but also other people who experience aphantasia.

In looking at the relationship between personality traits and imagery, there were no significant findings in the aphantasic group. However, in the control group, there was a positive correlation between extroversion scores and VVIQ vividness ratings (this relationship was explored in a larger sample of controls, see Appendix 3.5). Previous research examining the relationship between extraversion and imagery vividness in non-clinical populations have shown contradictory results. Several studies have documented that introverts report more vivid imagery than extroverts (Gralton et al., 1979; Riding & Dyer, 1980; Strelow & Davidson, 2002), whilst other studies have suggested that extroverts have higher levels of vivid imagery than introverts (McLean, 1969; Morris & Gale, 1974). Control participants in this experiment also showed a strong positive correlation between openness and self-reported vividness of visual imagery. Higher scores in openness to experience have been linked to the personality profiles of individuals with synaesthesia (Banissy et al., 2013; Hossain, Simner, & Ipser, 2018; Rouw & Scholte, 2016). The control sample was not asked if they experienced synaesthesia; however, four control participants were hyperphantasic (indicated through their scores on the VVIQ), which is associated with an elevated rate of synaesthesia (Zeman et al., 2020, although see also Dance et al., (2021). It is important to note that our sample size is relatively small in the context of the personality literature. However, the findings of this experiment suggest that the self-reported scores on the VVIQ by aphantasic participants are unlikely to be modulated by differences in personality traits.

If aphantasic individuals do not exhibit differences in personality traits, then a second question is whether individuals with aphantasia have any global neuropsychological deficits. In the case study of patient *MX,* who had acquired aphantasia, the authors reported no difference in executive function performance compared to individuals with typical imagery. However, as yet no studies have explored cognitive differences within a larger sample of individuals with congenital aphantasia. Earlier researchers have argued that high imagers and low imagers have different cognitive profiles (Marks, 1973; McKelvie & Demers, 1979), with vivid imagery a predictor for more accurate visual memory performance. If this pattern extends to individuals with no imagery, then we might expect to see differential cognitive profiles in aphantasic individuals compared to individuals with typical imagery. Thus, neuropsychological assessments could be used to highlight any underlying cognitive weaknesses, which may account for the lack of visual imagery as experienced by individuals with aphantasia (Experiment 4).

Experiment 4: Do aphantasic individuals perform differently in neuropsychological tasks?

3.2.1. Introduction

An open (and so far, unanswered) question regarding aphantasia is whether or not it is associated with more generalised impairments in cognitive function. This is also an important theoretical issue because it speaks to the question of what imagery is needed for – for example, for sighted individuals does visual imagery make a critical contribution to the holding and manipulation of items in working memory? Does voluntarily controlled visual mental imagery rely on executive functions? If not, what role does visual imagery play in human cognition? While cognitive performance in aphantasia has been assessed using various kinds of tasks (such as non-standardised memory tasks), the studies or case studies comprised of few participants and an unmatched control group (Keogh & Pearson 2017; Zeman et al., 2010). What is lacking within the literature is an assessment of these fundamental cognitive abilities in a large sample of aphantasic individuals using highly sensitive and standardised neuropsychological tests. This is important, both in terms of obtaining a more comprehensive picture of aphantasia and for determining whether it is associated with any specific cognitive deficits. Such deficits may reflect underlying differences in brain structure and function, although it is documented that congenital individuals with aphantasia lead full professional lives (Zeman et al., 2015).

To address this issue, a battery of neuropsychological tasks was chosen to examine the differences in cognitive performance between individuals with aphantasia and those with typical imagery, as defined by the VVIQ. The neuropsychological battery (from the Cambridge Neuropsychological Test Automated Battery, CANTAB) comprised of tasks: Verbal Recognition Memory (VRM), Pattern Recognition Memory (PRM), Spatial Span (SSP) and One Touch Stocking of Cambridge (OTS). Although this is not a large cognitive battery of tasks, these tasks are clinically sensitive to variances in core cognitive processes such as working memory, visual and verbal memory, encoding, retrieval, recall, recognition. These processes are most likely to be relevant to the experience of visual imagery. If aphantasia is associated with other cognitive impairments within one or more of these processes, then this would suggest that the inability to generate visual imagery in aphantasia may be associated with more general neuropsychological deficits. This battery would also provide a clinically standardised measure of working memory capacity, which can help to contextualise the findings from Experiment 2. Differences within these cognitive processes would manifest as differences in performance (compared to individuals with typical imagery) within these four specific tasks.

Verbal and visual memory depend on the ability to register, encode and retrieve verbal and visuospatial information (respectively), and can be assessed using CANTAB tasks such as the VRM and PRM. The VRM also comprises of a recall and recognition component, two memory processes that are suggested to be functionally dissociated (Holdstock et al., 2002; Staresina & Davachi, 2006). The tasks require the learning of either visual or verbal information, which is held in short-term memory (with no further manipulation) for immediate retrieval. The VRM and PRM tasks were chosen on the principle that if aphantasia impacts imagery without affecting other cognitive functions associated with visual or verbal memory (i.e. in encoding, retrieval, recall, or recognition) then no difference in the two tasks would be expected. If no differences in performance are evident between individuals with aphantasia and individuals with typical imagery, then it suggests that aphantasia does not impact the cognitive processes associated with these two tasks. If, however, aphantasia impacts on broader cognitive function within these processes, then a difference in performance might be expected within these two tasks.

Similarly, the Spatial Span (SSP) is a classic measure of working memory capacity (Levaux et al., 2007) and is visuospatial in nature (Kessels, van den Berg, Ruis, & Brands, 2008; Woods, Wyma, Herron, & Yund, 2016). Studies have suggested that one main strategy to perform the SSP involves the generation of mental imagery by 'making shapes' from imaginary lines (Patt et al., 2014). Spatial span performance correlates highly with executive functioning (Ridgeway, 2006) and the strength of visual imagery correlates to visual working memory capacity (Keogh & Pearson, 2014). If differences in performance arise between individuals with aphantasia and typical imagery within the SSP, then it would suggest that visual imagery plays a role determining the amount of visuospatial information that can be stored and recalled within working memory. On the other hand, no differences were apparent in a visuospatial working memory task with low working memory capacity (Experiment 2).

In contrast to the SSP, the One Touch Stocking of Cambridge (OTS) requires increasing amounts of visuospatial information to be maintained and manipulated, to calculate the minimum number of moves for each trial. Although this task assesses executive function, it also taps into processes associated with spatial planning as well as the maintenance and manipulation of increasing amounts of information within visuospatial working memory. This is arguably the most demanding of tasks within the battery, with large amounts of manipulation necessary as working memory load increases. The manipulation of information within the OTS has been shown to engage mental imagery (Hodgson, Bajwa, Owen, & Kennard, 2000). If individuals with aphantasia perform similarly to individuals with typical imagery on the OTS, this would imply their differences in imagery experience are not associated with impairments in these cognitive processes. These four neuropsychological tasks are clinically sensitive to variances within the cognitive domains that are most likely to be relevant to the experience of visual imagery. If aphantasic individuals have different underlying cognitive profiles compared to individuals who have typical imagery, then this will suggest that aphantasia is associated with more general neuropsychological deficits .

3.2.2. Methods

3.2.2.1. Participants

The participants in this study were the same as described in Experiment 3, section 3.1.2.1. The exclusion criteria and ethics are also the same as described in this section.

3.2.2.2. Materials

Cambridge Neuropsychological Test Automated Battery (CANTAB)

Cognitive function was assessed using the Cambridge Neuropsychological Test Automated Battery (CANTAB) (Cambridge Cognition, Cambridge UK). From this battery four CANTAB Eclipse version tests 5.0.0 were chosen: '*Verbal Recognition Memory* (VRM),' '*Pattern Recognition Memory* (PRM),' '*Spatial Span* (SSP),' '*One Touch Stocking of Cambridge*.' This particular battery is highly sensitive to differences in neuropsychological function, particularly working memory, visual and verbal memory, encoding, retrieval, recall, recognition and used within a diverse range of patient populations. All CANTAB tests were administered on a Windows operating system on a

15.6-inch touch-screen tablet computer by the researcher after undergoing training in the administration of CANTAB tests, and with strict adherence to version 5.0.0 (Cambridge Cognition Limited, 2012).

CANTAB Randomisation

The CANTAB battery was randomised into two different orders (O1 and O2). Prior to the battery, all participants undertook a brief Motor Screening (MOT) test, which involved participants touching the centre of a series of crosses shown in different spatial locations, to introduce participants to the concept of the touch-screen interface.

Order 1 (O1): MOT, VRM, PRM, SSP, OTS

Order 2 (O2): MOT, PRM, OTS, VRM, SSP

Participants in each group alternated in the order they undertook the battery, e.g. participant 1, 3 and 5 undertook order O1 and participant 2, 4 and 6 undertook order O2. Participants were not told the order of these tasks but were briefed with what the task would entail before each task. Once all four tasks within the battery were finished, participants moved onto the next task (see Chapter 3, Experiment 3, Figure 3.1).

3.2.2.3. Procedure

Verbal Recognition Memory (VRM)

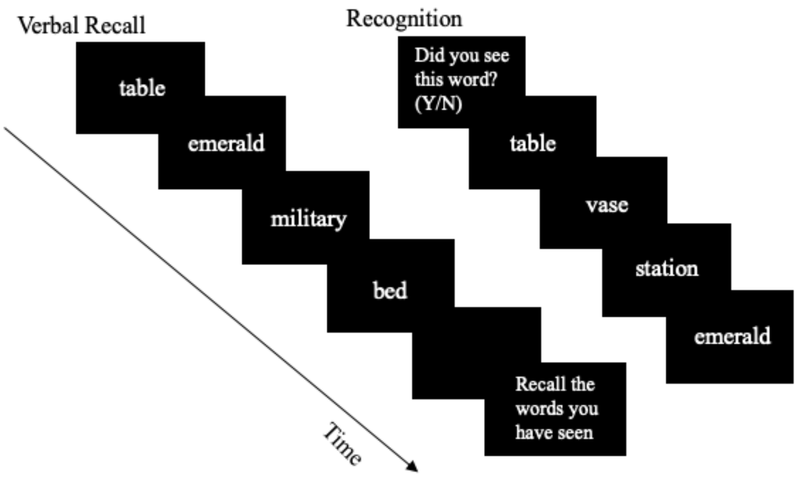


Figure 3.2: Diagram to show an example of the verbal recall condition (phase one) and recognition condition (phase two) of the Verbal Recognition Memory (VRM).

Verbal Recognition Memory (VRM; see Figure 3.2) comprised of two phases. In the first phase, participants were shown a series of 12 words that appeared for 5 seconds, one-by-one. Participants were instructed to say each word aloud verbally. Once the sequence of words had finished, participants were asked to turn 180° degrees from the screen and verbally recall as many words as possible from the list, and all words were noted. In the second phase of the task, participants were shown another sequence of (12) words. During this phase, participants had to indicate whether they recognised the word from the original list (presented in phase one). Outcome measures in the first phase were the number of correctly recalled words and in the second phase, the number of correctly recognised words.

Spatial Span (SSP)

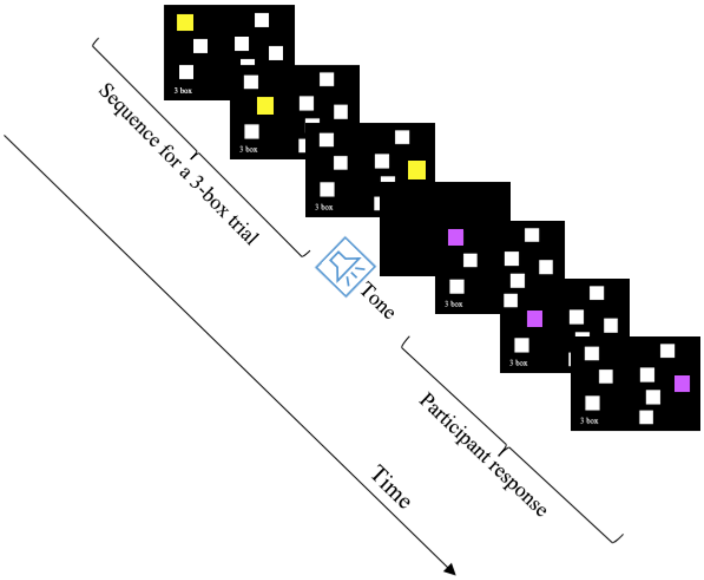


Figure 3.3: Diagram to show an example of a three-box trial in the Spatial Span (SSP). Participants were presented with a sequence of coloured boxes, and following the sound of a tone, selected the boxes as shown in the sequence.

In the Spatial Span (SSP; see Figure 3.3), participants were shown a number of white squares on a black screen. These boxes changed colour one by one, and participants were asked to remember the sequence in which the various boxes changed colour. Participants were first shown the sequence followed by the sound of a three-second monotone tone that signalled the sequence had finished. Following the sound, participants were instructed to make their response. The task increased in difficulty, with an increasing number of boxes in the sequence, from two boxes at the start to a maximum of nine. Participants had three attempts at each level of difficulty, and the task stopped when the participant was incorrect on all three attempts at a particular level. Outcome measures were the span length (the longest sequence correctly recalled), number of errors and usage errors. The number of errors denotes the total number of times a participant pressed an incorrect box. The usage errors denote the number of times an incorrect box is pressed per sequence.

Pattern Recognition Memory (PRM)

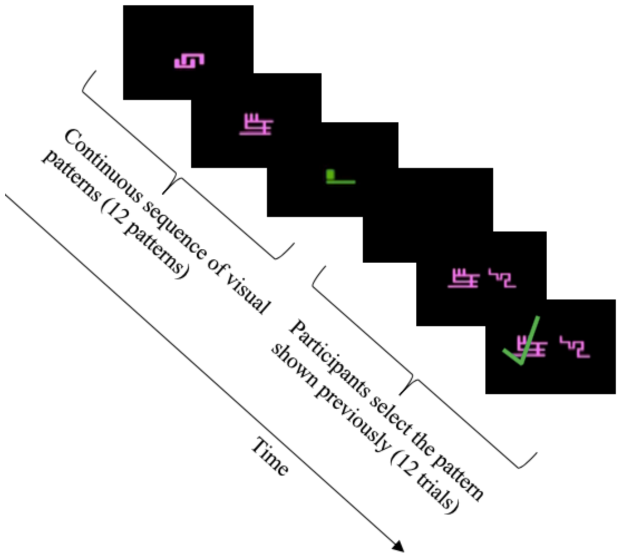


Figure 3.4: Diagram to show an example of the two phases of the Pattern Recognition Memory (PRM). A continuous stream of visual patterns was presented, following which, participants selected the pattern they recognised.

In the Pattern Recognition Memory (PRM; see Figure 3.4), participants were asked to memorise a series of 12 visual patterns, which appeared in the centre of the screen in a continuous sequence one after the other. These patterns were novel and unfamiliar and comprised of lines that were designed so that they could not be given verbal labels, nor did they look like common objects. Following the sequence, participants were shown two options: one novel pattern and one pattern that had been presented during the continuous stream of patterns and asked to indicate the pattern that had been previously presented. In the second phase, the first phase was repeated with a new set of 12 visual patterns.

Each phase comprised of 12 trials each, and outcome measures were the total number of correct trials across the two phases (i.e. accuracy across 24 trials).

One Touch Stocking of Cambridge (OTS)

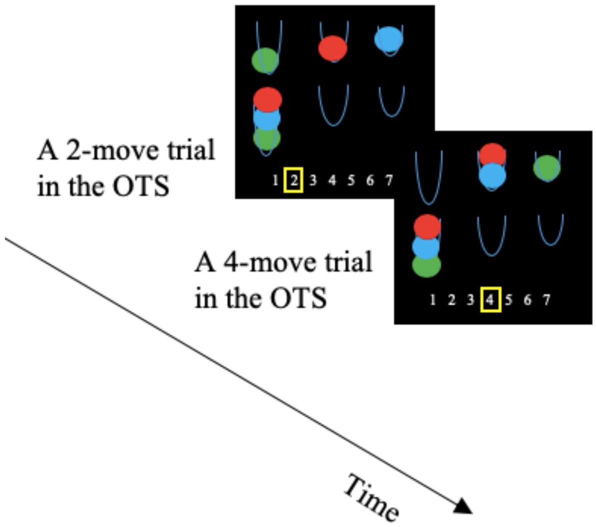


Figure 3.5: Diagram to show an example of a 2-move and 4-move trial in the One Touch Stocking of Cambridge (OTS). Participants needed to rearrange the bottom configuration of balls 'in their head' to match the top configuration and select the number referring to the minimum number of moves required.

The One Touch Stocking of Cambridge (OTS; see Figure 3.5) is based on the Tower of Hanoi. Participants were shown two arrangements of three coloured balls, one set positioned at the top, the other at the lower half of the screen. Each stocking could hold three balls. Participants had to rearrange the balls at the bottom of the screen to match the arrangement at the top of the screen and calculate the minimum number of moves '*within their head,*' and indicate their response. There were rules with regards to the way the balls could be moved. For instance, a ball would either sit at the bottom of the stocking or on top of another ball, and a ball that was beneath another ball could not be moved. Once decided on the minimum number of moves, participants had to touch the corresponding number (1 - 7) at the bottom of the screen to indicate their response. Participants were informed not to use hand or head gestures (or any part of their body) to aid calculation. This is because hand gestures have been shown to aid cognitive processing and improve performance within a range of complex visuospatial tasks (Alibali et al., 2011; Chu & Kita, 2015; Eielts et al., 2020; Logan, Lowrie, & Diezmann, 2014). These body gestures are more likely to occur in tasks that have a high working memory load (Marstaller & Burianová, 2013). In the most difficult trials, the maximum number of moves to solve the task was always 6. The results for move one were discounted in any analysis owing to the fact the test administrator was explaining instructions during this trial; thus, it increased the reaction time response for this trial. Outcome measures were the mean number of responses to correct and reaction time (latency to correct).

3.2.3. CANTAB Results

In instances when data is not normally distributed (e.g. Shapiro-Wilk < 0.05 for all variables), data is transformed. When sphericity was violated, a Greenhouse-Geisser correction is used. Where data is not normally distributed, nonparametric tests were used. All t-tests are 2-tailed. The results section will first explore group performance, followed by an individual difference examination of performance using multidimensional scaling (MDS) to explore the levels of similarity among performance.

3.2.3.1. Results by participant group

3.2.3.1.1. Verbal Recognition Memory (VRM)

In the free recall phase, aphantasic participants (M = 7.4, SD = 1.7) recalled a similar number of words to control participants (M = 7.5, SD = 1.82). An independent t-test showed no significant difference in performance in the recall phase of the task ($t(38) = 0.107$, $p = .92$, $d = .02$). In the recognition phase of the task, a Mann-Whitney test showed no difference in the number of correctly recognised words (U = 190, p = .71, *r* = .06) between aphantasic (median = 12, range: 11 – 12) and control participants (median = 12, range: 11 – 12). The results suggest there is no evidence of a difference between aphantasic and typical imager participants on the VRM.

3.2.3.1.2. Pattern Recognition Memory (PRM)

In the PRM, a Mann-Whitney test showed no significant difference in pattern recognition (U = 179.5, p = .57, *r* = .09) between aphantasic (median = 22 range: 19 – 24) and control participants (median = 22 range: 19 – 24). The results suggest there is no evidence of a difference between aphantasic and typical imager participants on the PRM.

3.2.3.1.3. Spatial Span (SSP)

In the SSP, a Mann-Whitney test showed no difference in memory spatial span (U = 170.5, p = .39, *r* = .14) between control (median = 7, range: 6 – 8) and aphantasic (median = 7, range: 5 – 8) participants. Moreover, an independent t-test showed no significant difference in the total number of errors (the number of times an incorrect box was pressed across all trials) ($t(38) = -.47$, p = .63, *d* = .16) between controls (mean total error = 13.2, SD = 6.62) and participants with aphantasia (mean total error = 14.1, SD = 4.61). For total usage error, an independent t-test showed no significant difference in the number of times a box was selected that was not in the span sequence for the trial ($t(38) = -.46$, p = .65, *d* = .15) between controls (M = 1.9, SD = 1.2) and participants with aphantasia (M = 2.1, SD = 1.41). The results suggest there is no evidence of a difference between aphantasic and typical imager participants on the SSP.

3.2.3.1.4. One Touch Stocking of Cambridge (OTS)

Both mean number of moves to correct (accuracy) and latency to correct (reaction time) responses were transformed using the Box-Cox transformation (Box & Cox, 1964) (see Chapter 2, Experiment 2, section 2.2.3.4) to permit a factorial ANOVA as the data was not normally distributed.

OTS Accuracy: Mean Moves to Correct

Mean moves to correct is defined by the number of attempts a participant takes to opt for the correct response. Accuracy for moves 2-6 of the OTS were compared between participant groups, see Figure 3.6.

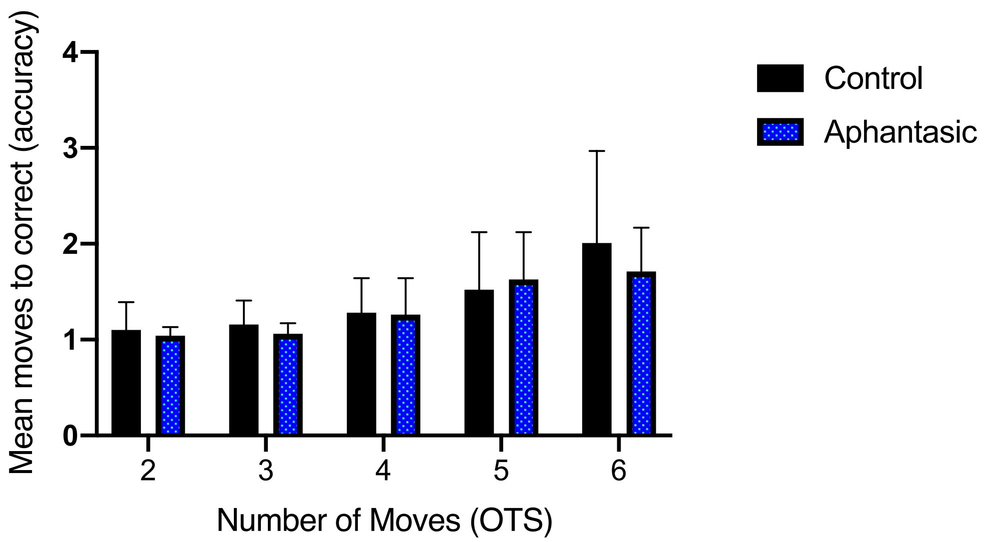


Figure 3.6: Bar chart to depict the mean number of moves to correct and standard deviation for control and aphantasic participants at each move (from move 2 – 6) in the OTS.

Accuracy in the OTS was analysed for each number of moves, from 2 moves to 6 moves using a two-way mixed measures ANOVA with factors participant group (aphantasic/control) and the number of moves (2-6). There was no significant main effect of participant group ($F(1, 38) = 0.09$, p = .76, $\eta p^2 = .002$), however, there was a significant main effect of number of moves ($F(4, 152) = 36.63$, p < .001, $\eta p^2 = .49$). Post hoc tests using the Bonferroni correction for multiple comparisons revealed a significant pairwise difference in accuracy between all moves (p < 0.01) except (moves 1-2, 2-3, and 4-5 > 0.09). There was no significant interaction between participant group and number of moves ($F(4, 152) = 0.82$, p = .52, $\eta p^2 = .02$). These results suggest that there is no evidence of a difference in accuracy between individuals with aphantasia and control participants, meaning they make the same number of responses (moves) to correct across all move trial-types.

OTS Response Time: Mean latency to correct

Mean latency to correct is defined as the amount of time taken for participants to respond correctly within each trial-type. Response time for moves 2-6 of the OTS were compared between participant groups, see Figure 3.7.

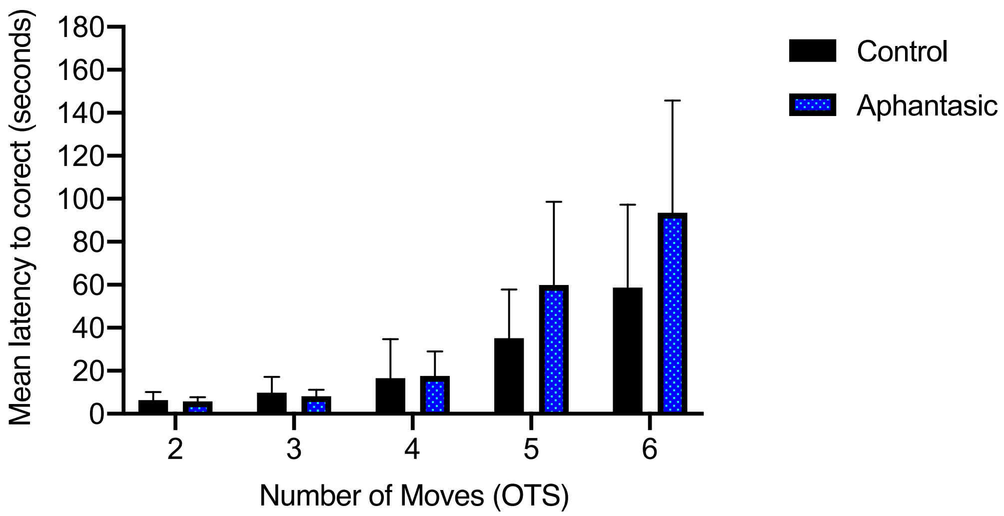


Figure 3.7: Bar chart to depict the mean latency to correct and standard deviation (represented by error bars) for each move in the OTS between control and aphantasic participants at each move (move 2 – 6).

Latency to correct was analysed using a two-way mixed ANOVA with Greenhouse-Geisser correction. The results of the two-way mixed ANOVA with factors participant group (aphantasic /control) and number of moves (2-6), showed that there no significant main effect of participant group ($F(1, 38) = 1.90$, $p = .18$, $\eta p^2 = .05$) but a significant main effect of number of moves ($F(2.80, 106.43) = 287.17$, $p < .001$, $\eta p^2 = .88$). Post hoc tests using the Bonferroni correction for multiple comparison, revealed a significant pairwise difference in latency to correct between all moves 2-6 ($p < .001$). There was a significant interaction between participant group and the time taken across moves 2-6 ($F(2.80, 106.43) = 3.40$, $p = .023$, $\eta p^2 = .08$). Subsequent independent t-tests showed a significant difference in latency at moves 5 ($t(38) = -2.65$, $p = .012$, $d = .78$) and move 6 ($t(38) = -2.62$, $p = .013$, $d = .76$). All other moves (2-4) were not significant ($p > .61$). These results indicate that differences between groups in response time to correct only emerged at levels of greater difficulty such that participants with aphantasia were slower than controls at moves 5 and 6, but not at levels 2-4.

3.2.3.1.5. Brief summary of group performance

Four tasks (PRM, VRM, SSP and OTS) were chosen from the neuropsychological CANTAB battery, with the premise that if group differences in performance were apparent within these tasks, it would suggest that aphantasia is associated with more general neuropsychological deficits. Specifically, these tasks assessed a range of cognitive processes, such as working memory, visual and verbal memory, encoding, retrieval, recall, recognition – processes relevant to the experience of visual imagery. The results of the group analysis showed that across the four tasks, aphantasic participants performed as accurately as controls with typical imagery (i.e. their performance was normal). However, during the OTS task, particularly during the most difficult trials (i.e.

moves 5 and 6), which demanded a high working memory load, aphantasic participants took significantly longer to respond. While this analysis shows virtually no group differences between individuals with aphantasia and those with typical imagery, an important possibility is that there may be individuals within the aphantasic sample who show neuropsychological abnormalities. Although aphantasic participants report a difference in their conscious experience of visual imagery, it is possible that this may reflect different aetiologies that are not recognised when performance is analysed by group. In the next step, the performance of each individual is reviewed across all four tasks to establish whether there may be a subgroup with select neuropsychological deficits, which may not have been identified by the group analysis.

3.2.3.3. Multidimensional scaling of neuropsychological performance

Calculating z-scores

For the SSP and VRM task, normative z-scores were provided by CANTAB. For the OTS and PRM task, z-scores were created by the following formula (see also, Faust, Ferraro, Balota, & Spieler, 1999).

$$\text{Z score} = \frac{(X - \mu)}{\sigma}$$

Z-scores for aphantasic participants were calculated using the mean (μ) and standard deviation (σ) from the control participants, therefore expressing the aphantasic test score (X) in relation to the control data. For the OTS and the PRM task, the data from the control sample acted as the 'normal' population from which, aphantasic participants' performance was compared. Z-scores for accuracy were compared against psychometric conversion tables, see Appendix 3.6 (i.e. scores between -3 indicating profoundly impaired performance to +3 highly superior performance). For the OTS, z-scores for accuracy and reaction time were also calculated using the above equation and were reverse-scored by multiplying the z-scores with -1. This ensured longer response times (than the mean control response time) were indicated by negative z-scores. Negative scores (in the OTS) reflected accuracy where more than one attempt was needed in a trial (i.e. the most accurate performance was if a participant selected the correct answer on the first attempt, and more than one attempt was suggestive of less accurate performance). For the SSP and VRM task, z-scores for the aphantasic and control participants were calculated using the norms obtained from CANTAB, see Appendix 3.7 for raw z-score data for each participant by participant group. Summary of the z-scores by participant group are shown in Table 3.2A and B.

A) Summary of z-scores by participant group across all CANTAB measures:

CANTAB z-score summary, Mean (SD) z-score, highest & lowest z-score: Accuracy / Reaction time (underlined)											
	VRM		OTS (Move: Move 2-Move 6, M2-M6)					SSP			PRM
Group	Recall Cor.	Recog. Cor.	M2	M3	M4	M5	M6	Spatial Span	Total error	Total use error	Total Cor.
Aph (n = 20)	-0.05 (0.93)	-0.12 (1.08)	0.22 (0.32)	0.40 (0.45)	0.03 (1.06)	-0.17 (0.82)	-0.31 (0.48)	0.25 (1.50)	0.05 (0.68)	0.09 (0.83)	0.58 (1.78)
			0.14 (0.54)	0.25 (0.49)	-0.13 (1.33)	-1.68 (2.62)	-1.42 (2.14)				
Highest z-score	1.37	0.49	0.35	0.66	0.76	0.88	1.05	1.74	1.82	1.35	2.88
			0.72	0.78	1.06	1.15	0.74				
Lowest z-score	-1.92	-1.95	-0.53	-0.35	-3.39	-1.64	-0.77	-3.22	-1.11	-1.25	-5.74
			-1.60	-1.49	-4.20	-9.77	-6.88				
Con (n = 20)	0 (1)	0 (1)	0 (1)	0 (1)	0 (1)	0 (1)	0 (1)	0 (1)	0.16 (1.03)	0.22 (0.83)	0.51 (0.97)
			0 (1)	0 (1)	0 (1)	0 (1)	0 (1)				
Highest z-score	1.37	0.49	0.35	0.66	0.76	0.88	1.05	1.74	1.53	1.44	2.88
			0.91	0.95	1.12	1.82	1.68				
Lowest z-score	-1.92	-1.95	-4.03	-2.38	-2.00	-2.90	-3.11	-1.57	-1.88	-1.25	-2.29
			-3.75	-2.94	-2.27	-1.47	-1.74				

B) Number of participants who display 'impaired to profoundly impaired' (z-scores < -2.00) in the CANTAB tasks:

Task	Aphantasic		Control	
	Accuracy	Reaction time	Accuracy	Reaction time
OTS:				
Only impaired in one move	Move 4 (n= 1)	Move 4 (n = 1) Move 5 (n = 2) Move 6 (n = 2)	Move 3 (n = 1) Move 6 (n = 1)	Move 3 (n = 1)
Impaired in two moves	0	Moves 5 & 6 (n = 5)	0	0
Impaired in three moves	0	Moves 4, 5 & 6 (n = 1)	Moves 2, 3 & 5 (n = 1)	Moves 2, 3 & 4 (n = 1)
SSP:				
Spatial Span	n = 1	-	0	-
PRM:				
Total Correct	n = 3	-	n = 1	-

Table 3.2: Summary tables to show A) Mean and range of z-scores of aphantasic (Aph) and control participants (Con) B) The number of participants who exhibit impairments in tasks (z-scores < -2.00) as determined by psychometric conversion tables (see Appendix 3.6 and 3.7). Grey and turquoise highlighted participants are the same participants.

Table 3.2A suggests that there are variations in task performance between aphantasic and typical imager participants. Specifically, aphantasic participants displayed a wider range of z-scores in tasks, such as SSP (spatial span), PRM (total correct) and OTS (reaction time for moves 4-6). Five controls displayed impaired performance, of which, four controls showed impaired performance on the OTS (as shown in Table 3.2B). Looking at this pattern, it appears likely that this is anomalous performance or measurement error as difficulties were not apparent on other tasks, arose for only one measure and most frequently during the easier levels of difficulty. In contrast, aphantasic participants displayed considerably lower or more impaired z-scores, with a larger number of aphantasic participants exhibiting a consistent pattern of impaired performance across multiple and harder levels of difficulty (i.e. moves 4-6) of the OTS. These findings could suggest that some subgroups of aphantasia exhibit different patterns of performance. It may therefore be of interest to examine the variations in these z-scores. If there are subgroups of aphantasia with differing neuropsychological profiles, this may suggest that there is more than one underlying mechanism to account for the experience of a lack of visual imagery.

Multidimensional scaling (MDS)

MDS is a data visualising technique that groups participants' performance dependent on the similarities or dissimilarities in performance across multiple tasks (Torgerson, 1952). Participants who exhibit similar performance (in the tasks) are clustered closest together within scatterplots, revealing potential clusters or subgroups of variations in performance. Aphantasic z-scores for measures: VVIQ score, recall and recognition VRM measures, average OTS accuracy across moves 2-6, OTS Move 6 reaction time, SSP Spatial Span and PRM total correct were included in the MDS model (created in MATLAB), and four subgroups were identified (as circled in Figure 3.8) from the hierarchical dendrogram.

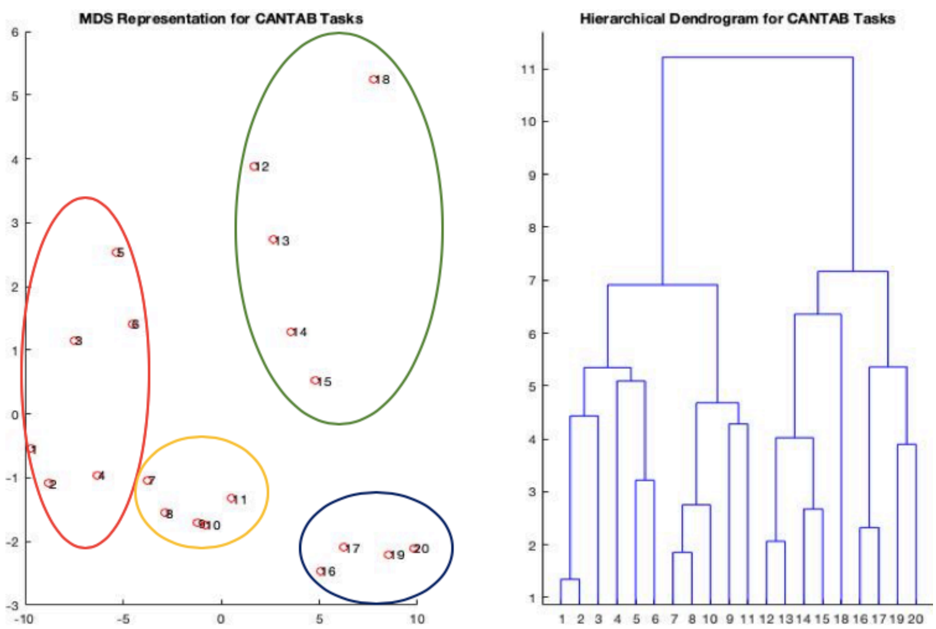


Figure 3.8: Diagrams of the multidimensional scaling representation and hierarchical dendrogram with circled clusters of task performance: Subgroup 1 (SG1 = red), Subgroup 2 (SG2 = yellow), Subgroup 3 (SG3 = green) and Subgroup 4 (SG4 = blue).

These subgroups were plotted on a radar graph (Figure 3.9) to examine the relationship between subgroups for each of the CANTAB measures, see also Table 3.3 for z-scores.

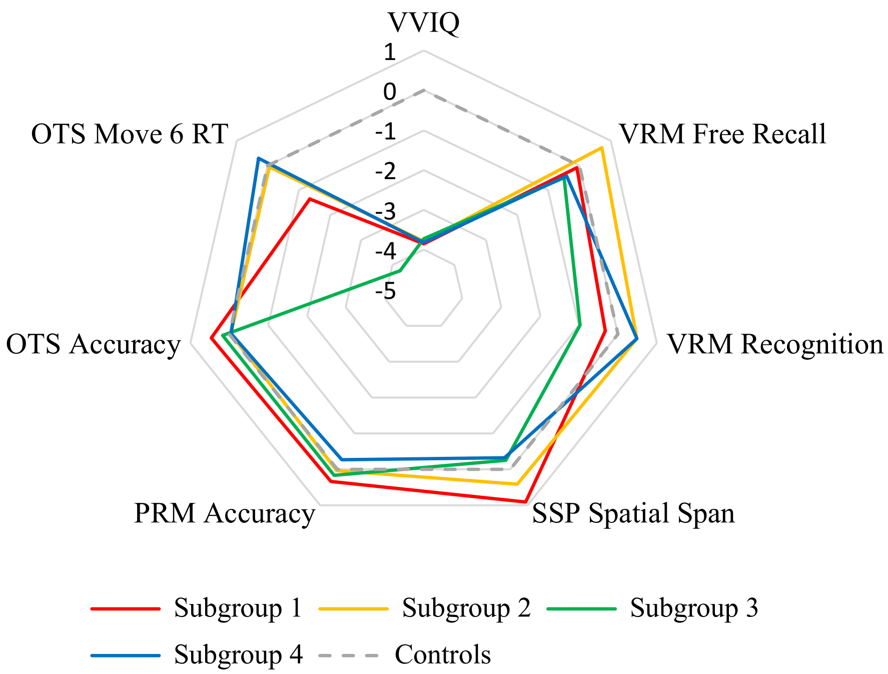


Figure 3.9: Radar graph to depict subgroups differences.

	Mean Z-scores for each identified subgroup							
Subgroup	VVIQ Score M(SD)	VVIQ z-score	VRM Free Recall	VRM Recognition	SSP Spatial Span	PRM Accuracy	OTS Accuracy	OTS Move 6
SG1 (n = 6)	16 (0)	-3.85 (0)	-0.09 (0.83)	-0.32 (1.26)	0.91 (1.38)	0.35 (1.31)	0.46 (0.24)	-1.35 (1.63)
SG2 (n = 5)	16.80 (1.79)	-3.78 (0.29)	0.71 (0.60)	0.49 (0)	0.41 (1.81)	0.03 (1.37)	-0.04 (0.62)	-0.06 (0.30)
SG3 (n = 5)	17.60 (3.58)	-3.72 (0.29)	-0.49 (0.83)	-0.97 (1.33)	-0.25 (0.74)	0.17 (0.76)	0.17 (0.14)	-4.24 (1.73)
SG4 (n = 4)	16.25 (0.50)	-3.83 (0.04)	-0.41 (1.22)	0.49 (0)	-0.33 (2.08)	-0.27 (1.48)	0.05 (0.37)	0.29 (0.33)

Table 3.3: Table to show the mean z-scores of the four subgroups for each CANTAB measure.

3.2.3.3.1. Multidimensional scaling interpretation

MDS (Figure 3.8, Figure 3.9 and Table 3.3.) shows the variation in behavioural performance by aphantasic participants, with a few tentative ‘subgroups’ proposed. MDS remains a descriptive tool used to identify variations and further research is necessary to confirm the existence of these ‘subgroups.’ Nevertheless, the greatest variation between the ‘subgroups’ arise for reaction time within the OTS task during a trial associated with complex working memory manipulations and high working memory load. Specifically, two ‘subgroups’ exhibited difficulties for reaction time on the OTS task (i.e. subgroup 3 who exhibited profoundly impaired performance for reaction time and subgroup 1, who also exhibited difficulties on the OTS task; however, at a lesser extent than subgroup 3). It should be noted that subgroup 3 also performed least accurately (compared to the remaining subgroups) on the VRM measures, however, further research would be needed to confirm whether this subset has verbal memory difficulties. While ‘subgroup’ 3 displayed the most impaired performance for reaction time on the OTS task, there were no impairments in accuracy, suggesting that this subset were potentially using different processes in the task. In comparison, ‘subgroup’ 1 were the most accurate in the OTS task potentially suggesting an accuracy-time trade-off in performance (with no other impairments evident in the other tasks). This slower response time in the OTS is in contrast to the two other subgroups (Subgroups 2 and 4) who displayed unimpaired performance and performed similar to individuals with typical imagery across all tasks. However, it should be noted that these subgroups had a wider range of variability in their spatial span measure, a spatial working memory task, which would require further investigation within a wider battery of spatial task.

3.2.4. Discussion

The results of Experiment 4 showed no group differences in performance between individuals with aphantasia and typical imagery within a range of cognitive tasks. These tasks were sensitive to variances in core cognitive processes such as working memory, visual and verbal memory, encoding, retrieval, recall and recognition. It was hypothesised, that if aphantasia were associated with more general neuropsychological deficits, then performance differences would be evident within the tasks. When examined by group, the results showed that individuals with aphantasia were as accurate as individuals with typical imagery across all four cognitive tasks. However, during the most difficult trials of the OTS task, specifically during trials associated with high working memory load and manipulation of visuospatial information (i.e. at move 5 and move 6), aphantasic participants took longer to respond within the task compared to participants with typical imagery.

In contrast, individual differences examination of the data using MDS revealed four subgroups, two of which exhibited unimpaired performance across all tasks, but displayed most variability in spatial span measures. Most notably, there was one subgroup who displayed profoundly impaired response times on the OTS task at move 6 – this was not a universal impairment shown by all aphantasic participants, with another subgroup exhibiting difficulties in the OTS but not to the extent of the profoundly impaired subgroup. This suggests that aphantasia is not a homogenous experience, and these variations warrant further cognitive exploration.

The VRM and PRM tasks are measures for verbal and visual memory respectively. They were chosen within the cognitive battery on the principle that if aphantasia impacts imagery without affecting other cognitive processes associated with visual or verbal memory, then no difference in the two tasks would be expected. The current experiment showed no differences in group performance within these two tasks between aphantasic and control participants. In terms of subgroup performance, it was suggested that there was some variability in terms of verbal memory, particularly recognition scores (i.e. subgroup 1 and 3 compared to subgroups 2 and 4) requiring a further exploration within a wider assessment of memory. Overall, however, the results from these tasks suggest that aphantasia does not impact on broader cognitive functions, specifically those associated with the recall and recognition of visual and verbal information.

Unlike the VRM and PRM tasks, the SSP task requires the maintenance of increasing amounts of visuospatial information within working memory (it does not require active manipulation). Within the current experiment, no difference in spatial span was found between participant groups, suggesting that despite a self-reported lack of visual imagery, aphantasic individuals have similar visuospatial memory capacities to those with typical imagery. However, while the group analysis suggested that aphantasic participants performed similar to individuals with typical imagery on the SSP, individual differences examination of performance offered some interesting insights. This approach revealed that there was some variation among spatial span performance (i.e. subgroup 2 and 4), with these subgroups displaying unimpaired performance on the remaining CANTAB tasks. These results should be viewed with some caution given the relatively low numbers and may simply reflect anomalies in the data. Nevertheless, it is also possible that this indicates that in some individuals, aphantasia is related to difficulties with working memory. If these subgroups have difficulties in working memory, then deficits in performance may be apparent within other working memory tasks (in Chapter 4). Spatial span performance has been shown to correlate highly with executive functioning (Ridgeway, 2006), thus suggesting for most aphantasic participants within this sample, they do not differ in terms of their executive functioning to individuals with typical imagery. This result is in line with the normal performance of *MX* within executive function tasks (Zeman et al., 2010). While visual imagery has been shown to correlate with visual working memory capacity (Keogh & Pearson, 2014), spatial imagery (thought to be intact in individuals with aphantasia, see Experiment 1 and Dawes et al., 2020) must play a role within working memory capacity limits. Patt et al. (2014) asked participants with regards to their strategy within a spatial span paradigm, and while the majority of participants self-reported the use of visual strategies, other participants reported using spatial verbal and motor strategies. This suggests that the SSP can be undertaken using different methods. The adoption of motor strategies within the task was prevented by asking participants to refrain from co-gesturing with their hands or other body parts. These movements have been shown to aid cognitive processing for complex and high cognitive load tasks (Alibali et al., 2011; Chu & Kita, 2015; Eielts et al., 2020; Logan et al., 2014; Marstaller & Burianová, 2013).

While the SSP does involve increasing amounts of visuospatial information sequentially, this differs to the OTS whereby visuospatial information needs to be both maintained and actively manipulated to calculate the minimum number of moves to respond in a trial. This active manipulation of information within the OTS involves the process of engaging mental imagery (Hodgson et al., 2000). Within trials in the OTS that have a high memory load, the group analysis suggested that aphantasic participants took significantly longer to respond compared to typical imager controls with no difference in accuracy. The significant differences in reaction time were evident during more complex trials (i.e. move 5 and move 6) associated with the manipulation of large amounts of visuospatial information. Individual difference examination of performance revealed a subgroup (subgroup 3) who showed a consistent pattern of impaired to profoundly impaired reaction times at move 6 of the OTS. On the other hand, two subgroups (subgroup 2 and 4) exhibited unimpaired performance during these difficult trials and performed similarly to individuals with typical imagery across all tasks. These differing cognitive profiles suggest that these subgroups of aphantasic participants may have differed in their approach within the OTS task.

The subgroup of aphantasic participants who exhibited significantly longer reaction times in the task show similar patterns of performance to those seen in congenitally blind participants in certain imagery tasks (Vanlierde & Wanet-Defalque, 2004). One might argue the processes adopted by this subgroup of aphantasic participants are effective to a certain level of performance but are insufficient when working memory load is increased (Cornoldi, Tinti, Mammarella, Re, & Varotto, 2009; Vecchi, 1998). In contrast, control participants in the task are more likely to have used visual imagery to solve the task (Hodgson et al., 2000), especially during the more demanding trials (move 5 and move

6). The use of visual strategies has been suggested to depend on visuospatial working memory capacities, with lower visuospatial working memory capacities corresponding to the use of more verbal strategies (Alderson-Day & Fernyhough, 2015). Within the current experiment, there was no evidence to suggest that aphantasic and control participants have different visuospatial working memory capacities. However, it could be suggested that a subgroup of aphantasic participants use different representations such as spatial imagery alone (as demonstrated by a preference for spatial imagery in the OSIQ, see Chapter 2, Experiment 1) or verbal coding within the OTS task. On the assumption that visual image representations can be held and maintained in higher detail compared to other types of mental representations, on easy trials, non-pictorial representations would provide enough detail to perform in the task adequately. However, with increased working memory load and more complex manipulation required in the difficult trials of the OTS, these other types of representations would impact performance in the task in a negative way. For instance, perform worse, or result in participants taking longer to respond in the task. Thus, within this subgroup, despite no differences in accuracy between aphantasic and control participants, the use of a different strategy within the task would explain the difference in reaction time during the more complex and difficult moves. On the other hand, two subgroups showed unimpaired performance within all tasks within the CANTAB battery, and in the OTS were as accurate and showed similar reaction times akin to individuals with typical imagery. This could imply that these individuals are using the same processes as individuals with typical imagery (despite self-reporting a lack of visual imagery), however, an examination of their performance within a wider series of tasks is necessary to draw further conclusions about this subgroup.

Together, the results of this experiment identify four potential subgroups of aphantasia. In brief, one subgroup showed significant impairments within their response times within the OTS task, despite these differences in reaction time, their accuracy in the task at the respective moves did not fall below average. Another subgroup also exhibited longer reaction times for the OTS task, but this was paired with greater accuracy, suggesting a time-accuracy trade-off. The two remaining subgroups displayed variability in their spatial span measure. However, further examination within working memory tasks is required to confirm whether these subgroups have working memory difficulties. Both of these subgroups exhibited unimpaired cognitive performance on all of the other tasks within the CANTAB battery, and they performed similarly to individuals with typical imagery.

Future research should examine these subgroups within a wider battery of cognitive tasks to provide a greater comprehensive picture of their cognitive profile. For instance, there may be other tasks that would reveal impairments in the subgroup who showed unimpaired performance in the current battery. At present, while the findings of this experiment do highlight potential differences in performance, the results do not account for the reason why individuals with aphantasia self-report a lack of visual imagery. If performance differences are apparent during complex visuospatial tasks, it remains to be investigated how individuals with aphantasia (and specifically these identified subgroups) would perform within a wider variety of visuospatial tasks. For instance, it may be the case that the impairments that arise within (some) individuals with aphantasia are evident within tasks involving complex manipulations. At present, aphantasics' performance within a wider range of complex visuospatial transformation tasks remains unexplored. Complex tasks not only comprise of tasks that have a high working memory load but also involve high active manipulation of shapes (such as mental rotation) and also those that require the transformation of perspectives. The performance of individuals with aphantasia within such complex visuospatial tasks shall be explored in the following Chapter.

3.2.5. Chapter conclusion

This Chapter examined whether the lack of self-reported visual imagery could be explained by personality variances or differences in fundamental cognitive processes. Personality profiles were explored within Experiment 3 through the BFI inventory, which examined traits: extraversion, agreeableness, conscientiousness, neuroticism (emotional stability), and openness. The results showed significant differences in the level of the trait agreeableness, which was explained as being due to a recruitment bias, with no differences within the other personality traits. Control extraversion scores correlated highly with VVIQ scores. While it seems aphantasia cannot be linked to personality influences (although this was a very small sample for personality investigations), questions remained regarding whether cognitive differences could account for their self-reported inability to generate visual imagery. Experiment 4 explored whether individuals with aphantasia have a more general cognitive deficit by examining performance within four standardised and sensitive cognitive tasks selected from CANTAB. The results of this experiment showed that at a group level, no differences were found in accuracy across all tasks. This initially suggested that the cognitive profile of aphantasic individuals does not differ to individuals with typical imagery. However, in the OTS task during difficult trials associated with high working memory load and a complex manipulation, aphantasic participants were significantly slower in responding to the task compared to controls with typical imagery.

Further examination of individual cognitive profiles revealed four potential aphantasic subgroups, two of whom showed specific and marked deficits on the OTS task. A more in-depth neuropsychological investigation is required to gain a greater understanding of individual differences in the cognitive capabilities of aphantasic individuals. Such an investigation may explain why they self-report a lack of visual imagery. One suggestion made is that the subgroup of aphantasic participants who displayed profound impaired response time in the OTS adopted different processes (such as verbal or spatial imagery) within the task. This pattern of performance (i.e. longer reaction times but no difference in accuracy) is similar to the performance of congenitally blind individuals in certain imagery tasks (Vanlierde & Wanet-Defalque, 2004). In contrast, the aphantasic subgroup who exhibited unimpaired performance on all of the tasks displayed reaction times in the OTS that were similar to that of individuals with typical imagery.

If aphantasic subgroups exist, with a large number of aphantasic participants displaying impaired performance within visuospatial task that involve the maintenance and active manipulation of large amounts of visuospatial information, then further investigation is required using a wider range of complex tasks. Moreover, investigation of their performance within a wider range of complex visuospatial tasks will also reveal whether the aphantasic subgroup who exhibited variability on the spatial span has working memory difficulties. This will be explored within the following Chapter.

Chapter 4: Complex visuospatial performance in aphantasia

General Summary

During the One Touch Stocking of Cambridge (OTS), a significant difference in response time was evident between aphantasic and control participants during trials that required the manipulation of a large amount of visuospatial information (Experiment 3). Differences in performance were not evident within a low working memory load visuospatial working memory task (Experiment 2), suggesting that differences arose within the OTS tasks due to its increased complexity. Therefore, exploring visuospatial working memory in tasks that utilise different types of manipulation in visuospatial working memory may identify why differences arose within the OTS. This Chapter will explore performance within a wider variety of complex visuospatial working memory tasks: a mental rotation task (MRT) in Experiment 5 and an egocentric spatial perspective-taking task (Blanke et al., 2005; Gardner & Potts, 2011) in Experiment 6. Twenty individuals with aphantasia and 20 individuals with typical imagery undertook the mental rotation task (Experiment 5). Results showed no significant difference in accuracy or response time between aphantasic and control participants. Similarly, in Experiment 6, no differences in accuracy or reaction time were apparent in the spatial perspective-taking task and its corresponding control task. However, aphantasic participants displayed greater variability in reaction time for front and back orientations compared to participants with typical imagery. Together, these results suggest that within tasks that require complex visuospatial manipulation and transformations, despite self-reporting a lack of visual imagery, aphantasic participants can perform just as well as individuals who have typical imagery.

General Introduction

The results from Experiment 2 (Chapter 2) showed that within a visuospatial working memory task, no differences in accuracy were apparent between aphantasic and control participants with typical imagery. A reason for this observed similarity in performance was attributed to the fact that the task required little active manipulation. Thus, it remains to be explored how individuals with aphantasia would perform in more complex visuospatial working memory tasks. In the OTS task (Experiment 3) a complex visuospatial working memory task involving high levels of manipulation, aphantasic participants were significantly slower in their responses only during the hardest/most cognitively demanding trials of the OTS (moves 5 and 6). However, they were accurate as typical imagery controls. Therefore, it is of interest to further explore aphantasics' performance within a wider variety of complex visuospatial working memory tasks that require higher levels of manipulation.

Patient *MX* performed as well as individuals with typical imagery in a mental rotation task (Zeman et al., 2010). However, it is not known how a larger sample of individuals with congenital aphantasia would perform within this task. The mental rotation task (MRT) is a classic visuospatial imagery task and measure of spatial ability (Shepard & Metzler, 1971; Xue et al., 2017). It is used to explore spatial abilities within a range of clinical syndromes and individual differences in healthy populations (e.g. Courbois, Coello, & Bouchart, 2004; Jansen, Schmelter, Quaiser-Pohl, Neuburger, & Heil, 2013; Marmor & Zaback, 1976; Peters, Lehmann, Takahira, Cortex, & 2006). In typically sighted individuals, these spatial representations are thought to be acquired by visually perceiving individual parts, such as lines, corners or angles of the stimulus piece-by-piece, to create an internal visuospatial representation of the whole stimulus from which comparisons are based (Gill, O'Boyle, & Hathaway, 1998; Larsen, 2014; Noton, American, & 1971). Eye fixation studies that track eye-movements during mental rotation further support the notion of this piece-by-piece strategy (Just & Carpenter, 1985; Xue et al., 2017), with eye movements playing a role in the acquirement of spatial information (Just & Carpenter, 1976; Xue et al., 2017). Behavioural and neuroimaging evidence proposes that mental rotation transformations occur on these visuospatial representations (e.g. Borst et al., 2011; Carpenter, Just, Keller, Eddy, & Thulborn, 1999; Shepard & Metzler, 1971; Xue et al., 2017). However, it has also been argued that the representations involved in mental rotation rely not on visual, but rather spatial representations (Liesefeld & Zimmer, 2013). This is supported by studies within the literature on individuals who are congenitally blind (i.e. in individuals who have no more than light/shade vision from birth) who perform similar to sighted individuals on adapted haptic versions of the task. This suggests that visual representation is not crucial to carry out mental rotation tasks (Cattaneo et al., 2008; Marmor & Zaback, 1976).

Spatial representations are influenced by the frame of reference adopted by an individual. A frame of reference can be defined as the "*particular perspective from which the observation of a spatial variable (position of an object, its velocity etc.) is made*" (Cattaneo & Tomaso, 2011, pg 115). The comparison of the spatial positions of objects relative to one another and independent of the subject's viewpoint (as in the MRT) is referred to an object-centred or allocentric frame of reference. Typically, a linear relationship between response time and angle is evident within MRT, which reflects longer response time with an increased level of transformation or manipulation required in the task (Borst, Kievit, Thompson & Kosslyn, 2011). Although mental rotation can be discussed in terms of an allocentric framework, studies have shown that mental rotation is also associated with embodied cognition (i.e. an egocentric framework) (Liesefeld & Zimmer, 2013; Shenton, Schwoebel, & Coslett, 2004). For instance, the mental rotation of human avatars involves a form of mental self-rotation (Deroualle, Borel, Devèze, & Lopez, 2015; Hegarty & Waller, 2004) or spatial perspective-taking (Böffel & Müsseler, 2019), an egocentric process involving the alignment of one's own body to that of an on-screen avatar. This egocentric perspective involves spatial representations in reference to the imagined movement of one's point of view or body position in relation to another object or objects (e.g. Kozhevnikov, Motes, Rasch, & Blajenkova, 2006; May, 2004; Wang & Spelke, 2000) and require kinaesthetic and somatosensory representations (Gardner & Potts, 2010; Kaltner, Riecke, & Jansen, 2014). These mental simulations stem from vestibular information, which is not necessary for object mental rotation (Deroualle et al., 2015; Falconer & Mast, 2012; Gardner, Stent, Mohr, & Golding, 2017).

Egocentric frameworks fall in line with the embodied theories of mental imagery, which suggest that mental representations are closely linked to a combination of perceptual, cognitive and motor components (see Chapter 1, section 1.1.3). In a study by Amorim, Isableu and Jarraya (2006), participants took an embodied approach within a MRT when abstract cube-like stimuli contained additional body characteristics, such as a head or hands, compared to when the stimuli were abstract cubes. The authors suggest that this facilitated the mapping of one's own body onto the abstract shape (Amorim et al., 2006). Several studies have also shown, that when an embodied approach is taken within the mental rotation task (containing body limbs), performance is faster compared to an allocentric approach (Amorim et al., 2006; Jansen, Lehmann, & Van Doren, 2012; Suggate, Lehmann, Stoeger, & Jansen, 2019). This suggests that embodied objects are processed more easily (Suggate et al., 2019), although the exact reasons for this remain unclear.

One way to explore embodied transformations is through spatial-perspective taking tasks such as the Own Body Transformation task (OBT) that require egocentric processes (Experiment 6). Although, participants have been shown to adopt an allocentric frame of reference within spatial perspective-taking transformation tasks (Martin et al., 2019). As such, the distinction between allocentric and egocentric spatial representations is difficult to distinguish, and the use of either framework is not within conscious control (Eardley & van Velzen, 2011). This is especially difficult to distinguish through behavioural tasks whereby individuals greatly differ or adopt the use of either frame of reference (Ekstrom, Arnold, & Iaria, 2014). It should be noted that while object MRT and OBT tasks have been discussed in terms of allocentric and egocentric processes, it is acknowledged that both tasks can adopt either framework, thus it is not suggested that the tasks mentioned are purely viewed in the context of either reference.

Although tasks within this Chapter both deal with spatial representations and share common processes, such as, the ability to encode or assume a visuospatial image and maintain these representations (Kosslyn, 1996), they differ in the type of spatial transformation required. These transformations are more advanced and require more active manipulation than the visuospatial task described in Experiment 2. In terms of the revised visuospatial working memory model, this information would be stored within the visual cache and its contents rehearsed by the inner scribe (spatial store), with active manipulation involving the central executive (Logie, 1995). These tasks arguably involve the processes associated with the central executive more than the visuospatial memory task described in Experiment 2. Understanding how individuals with aphantasia perform within visuospatial tasks, which are underpinned by more complex manipulation, may provide insight into whether the differences exhibited by individuals with aphantasia in the OTS were due to the level of manipulation required within the task. In addition, it will further enhance the understanding of spatial imagery abilities within aphantasia.

Experiment 5: How do individuals with aphantasia perform within a Mental Rotation Task?

4.1.1. Introduction

In a case study of acquired aphantasia (following coronary angioplasty), patient *MX* self-reported the sudden inability to generate visual imagery (Zeman et al., 2010). On standard visual imagery questionnaires, he rated himself as having no imagery. Despite this self-reported inability, patient *MX* performed as accurately as neurotypical controls in a MRT, although his performance within the task was significantly slower (Zeman et al., 2010). the authors argued that differences in response time in the mental rotation task were suggestive that *MX* was using a different strategy, although the authors do not explore the type of strategy that might have been used (Zeman et al., 2010). *MX's* apparent normal performance (in terms of accuracy) in the MRT may be interpreted as the experience of visual images is not necessary for equivalent performance within the task. This notion is supported in studies with congenitally totally blind or early blind (with no more than diffuse light/shade vison), who are able to perform similarly to sighted individuals on imagery tasks such as mental rotation (e.g. Carpenter & Eisenberg, 1978; Kerr, 1983; Zimler & Keenan, 1983). For example, in a MRT, although blind individuals were slower, the number of errors made by blind participants was similar to that of sighted participants (Carpenter & Eisenberg, 1978). This suggests that they can manipulate information that is analogous (picture-like) in nature (Afonso et al., 2010; Marmor & Zaback, 1976). Vecchi (1998) suggested that in the case of individuals who are congenitally totally blind, differences in reaction time are attributed to the fact that the blind have a lower visuospatial processing capacity compared to sighted individuals (Vecchi, 1998; Vecchi, Monticellai, & Cornoldi, 1995).

Similarly, a replication of Kosslyn's well known mental scanning study found a linear relationship between time and distances, although blind participants were slower (Kerr, 1983; Roeder & Rösler, 1998). The research suggests that the congenitally blind are able to do these tasks by accessing information through non-visual perceptual or verbal modalities (Aleman et al., 2001; Kaski, 2002; Vecchi et al., 2004). Although vision can provide a comprehensive level of spatial information from the external world, the fact that individuals who are blind lack this input yet still perform well in spatial tasks (such as mental rotation), suggest that spatial processing is also based on input from all sensory modalities such as touch, audition and proprioception (Millar, 1994). These modalities provide rich spatial representations.

Typically within MRT, the more complex and larger the angle of rotation (thus, manipulation needed within visuospatial working memory), the longer the response time (Borst, et al., 2011). MRT may also comprise more than one rotation axis (Shepard & Metzler, 1971), which further adds to the complexity of the task. In Experiment 2, the visuospatial working memory task involved little manipulation, which was one speculation as to why no differences in performance were apparent between aphantasic and control participants with typical imagery. Differences in performance were apparent in Experiment 4 in the OTS, a complex visuospatial task, but only during difficult trials involving high levels of manipulation. It should also be noted that not all aphantasic participants exhibited performance differences in the OTS, with some aphantasic participants performing similar to controls even at the harder difficulty levels. If differences in performance are apparent within a MRT, then it would suggest that aphantasics' lack of visual imagery affects their ability to manipulate a large amount of visuospatial information in working memory. If differences in reaction time are apparent between individuals with aphantasia and typical imagery, then this pattern of performance is comparable to the performance shown by congenitally blind, thus suggesting that aphantasia may be associated with a lower visuospatial processing capacity (Vecchi, 1998; Vecchi et al., 1995).

On the other hand, the results of Experiment 1 showed that within the OSIQ, a self-report measure, individuals with aphantasia did not differ in their spatial imagery scores to individuals with typical imagery, suggesting that their spatial imagery remains intact. Individuals with aphantasia have self-reported intact spatial imagery abilities (Dawes et al., 2020). Higher spatial scores reported on the OSIQ have been shown to correlate to performance in the mental rotation (Kozhevnikov et al., 2006), suggesting its close association with the ability to form spatial representations and undertake mental transformations of objects (Borst, et al., 2011).

4.1.2. Methods

4.1.2.1. Participants

Aphantasic and control participants were the same participants as outlined in Chapter 3, Experiment 3, section 3.1.2.1. The ethics are also the same as described in these sections. Participant demographic information is summarised briefly below. See Chapter 2, Experiment 1, section 2.1.2 for the aphantasia diagnostic criteria.

Twenty aphantasic participants (VVIQ ≤ 26), 7 males and 13 females with a mean age of 40y0m (SD = 8.92y) and a mean VVIQ score of 16.65 (SD = 1.95). Twenty control participants (VVIQ > 32), 8 males and 12 females with a mean age of 39y6m (SD 11.61y) and a mean VVIQ score of 63.8 (SD 12.34).

4.1.2.2. Materials

Mental Rotation Task (MRT): Creating and piloting the MRT

Adapted from the classic Shepard and Metzler mental rotation experiment, stimuli were acquired from the Mental Rotation Stimulus library (Peters & Battista, 2008). These stimuli comprised of images of 10 cubes glued together in different orientations. From the Mental Rotation Stimulus library, 138 white-cubed stimuli of angles that allowed a full view of the stimulus shape were selected, rotating around the x-axis. Each stimulus was individually super-imposed on a black background for the task.

Based on the remaining angles, 6 levels of difficulty were chosen relative to 0°: 40°, 85°, 130°, 175°, 220°, 265°). Following a pilot of 12 participants, angle rotations of 130°, 175° and 265° were excluded because the accuracy was at ceiling. As a result, three levels of difficulty were selected; these were rotation angles: 40°, 85°, and 220°. The task comprised of two blocks of 48 trials, thus 96 trials experimental trials in total (split across two testing sessions and described as MRT Version A and MRT Version B in Figure 3.1, Experiment 3, Chapter 3). One block each was included in each testing battery, carried out one week apart. The MRT was undertaken in two parts because it is a cognitively demanding task, and it was decided it was best for it not to dominate in one testing session. The two blocks were matched in terms of difficulty, with 16 trials per difficulty level in each block (see Figure 4.1 for an example of a trial). In each block of 48 trials, 24 stimuli were the same, and 24 were different. Across the two blocks of '*different*' trials, 23 were mirror images, while 25 trials comprised of different images. Data from the two blocks were combined (i.e. all 96 trials), and mean accuracy and response time was calculated for each angle of rotation. All participants also undertook a practice of 25 trials (only) on their first visit prior to starting MRT Version A (in the first testing session, i.e. there was no practice during the second session). The task was programmed on E-prime version 2 and outcome measures of performance were response time and accuracy.

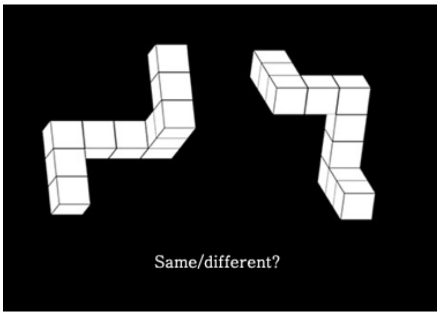


Figure 4.1: Diagram of an example trial of a '*same*' response within the MRT. Participants have to rotate one shape or the other and determine whether the two shapes are the *same* or *different*.

4.1.2.3. Procedure

Participants undertook the MRT in both of the two testing sessions. In the first testing session, all participants had to undertake a practice where they were verbally instructed to mentally rotate the shapes and determine whether the two shapes were the same or different (Shepard & Metzler, 1971). Participants were asked to respond by pressing either '1' or '2' (on a QWERTY keyboard), for 'same' or 'different' responses respectively. All participants were asked to respond as quick but as accurate as possible. Upon completion of the practice, the experimental block began (i.e. MRT Version A on the first visit and MRT Version B on the second visit). During the second visit, all participants undertook the experimental version (i.e. the practice was not repeated). Trials appeared sequentially one-by-one once participants had responded in a trial. The MRT was complete once all 48 trials (of each version) were complete.

4.1.3. Results

In this section, in instances when data is not normally distributed (e.g. Shapiro-Wilk < 0.05 for all variables), data is transformed where specified. Where sphericity cannot be assumed, a Greenhouse-Geisser correction is used. All t-tests are 2-tailed unless otherwise stated.

4.1.3.1. Mental Rotation Task: Accuracy

The accuracy of mental rotation performance was first examined across the angle of rotations and compared between aphantasic and control participants (see Figure 4.2) using a two-way mixed measures ANOVA with Greenhouse-Geisser correction.

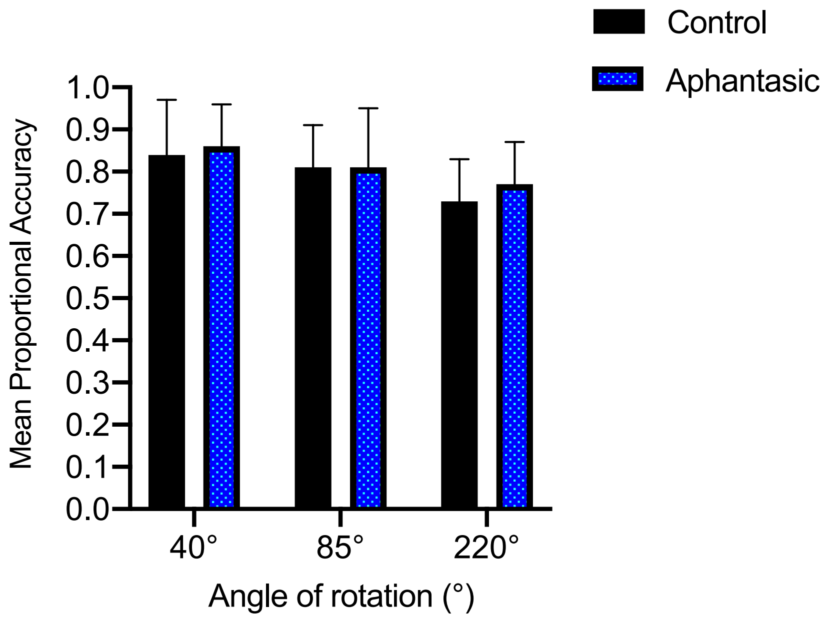


Figure 4.2: Bar chart to depict the mean proportional accuracy and error bars (representing the standard deviation) in the MRT across all angles of rotation for aphantasic and control participants.

Data was first transformed using a rationalised arcsine transformation (Studebaker, 1985), as appropriate for proportion correct data (see Chapter 2, Experiment 2, section 2.2.3.4). The results of the two-way mixed ANOVA with between-subject factor of group (aphantasic/ control) and within-subject factor of angle of rotation (40°, 85°, and 220°), showed no main effect of group ($F(1, 38) = 0.76$, $p = .39$, $\eta p^2 = .02$) but a significant main effect of angle of rotation ($F(1.70, 64.7) = 29.92$, $p < .001$, $\eta p^2 = .440$). Post hoc tests using the Bonferroni-Holm for multiple comparisons revealed a significant pairwise difference in accuracy between the angle of rotations 40° - 85° ($p = .04$) and between the angle of rotations 85° -220° ($p < .001$). There was no significant interaction between the angle of rotation and group ($F(1.70, 64.7) = .29$, $p = .72$, $\eta p^2 = .008$). These results suggest that aphantasic participants are just as accurate as individuals with typical imagery in the MRT.

4.1.3.2. Mental Rotation Task: Response Time

Response time data for the MRT was transformed using the Box-Cox transformation (Box & Cox, 1964) as the data violated normality (see Chapter 2, Experiment 2, section 2.2.3.4). Response time data was analysed across all angles of rotation (40°, 85°, and 220°) and compared between aphantasic and controls participants (see Figure 4.3). Response time data were analysed using a two-way mixed ANOVA with Greenhouse-Geisser corrections.

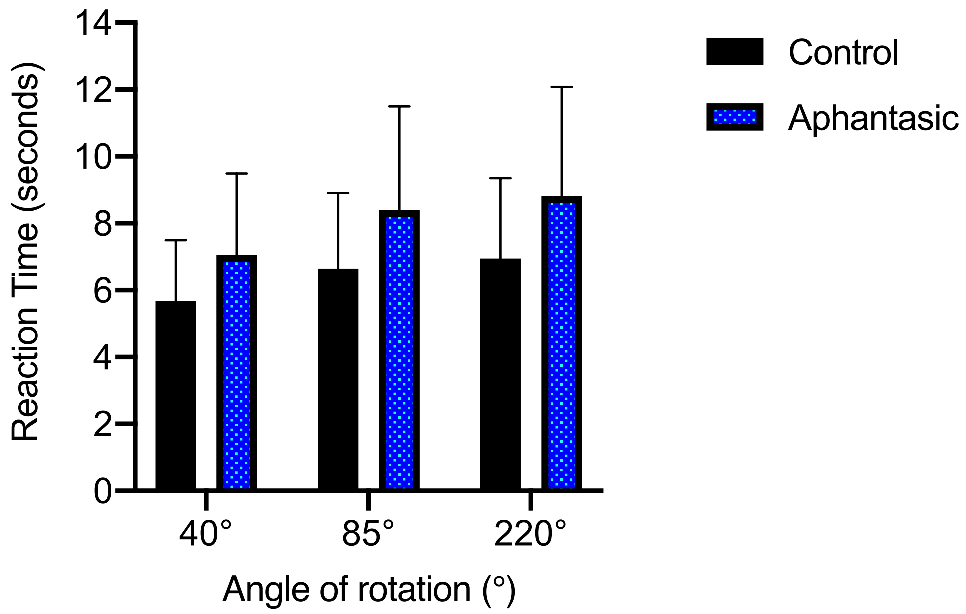


Figure 4.3: Bar chart to depict the mean MRT response time and error bars (representing the standard deviation) in seconds across all angle of rotation, for aphantasic and control participants.

The results of the two-way mixed measures ANOVA with between-subject factor group (aphantasic/control) and within-subject factor angle of rotation (40°, 85°, and 220°), showed no significant main effect of group ($F(1, 38) = 3.62$, p = .07, $\eta p^2 = .087$) but a significant main effect of angle of rotation on response time ($F(1.65, 62.86) = 66.22$, p <

.001, $\eta p^2 = .64$). Post hoc tests using Bonferroni-Holm for multiple comparisons revealed a significant pairwise difference in response time between the angle of rotation 40° - 85° ($p < .001$) and between angles 85° - 220° ($p = .008$). Overall, there was no significant interaction between angle of rotation and group ($F(1.65, 62.86) = .45$, $p = .60$, $\eta p^2 = .012$). These results suggest that despite self-reporting a lack of visual imagery, participants with aphantasia take the same amount of time to respond within the MRT across all angles of rotation similar to participants with typical imagery.

4.1.4. Discussion

This Experiment explored the performance of individuals with congenital aphantasia within a MRT. The results show that there was no significant group difference in accuracy between aphantasic and typical imagery control participants, similar to the performance of patient *MX* (Zeman et al., 2010). Further, there was also no significant group difference in response time, although the means and standard deviations for the aphantasic group were higher than the control group. This suggests there was considerable variation within task performance amongst aphantasic participants. If individuals with aphantasia display significant differences on the OTS (Experiment 4), but not the MRT, what are the differences between the two tasks? While both of these tasks involve complex manipulation, the more cognitively demanding trials of the OTS were also associated with a high working memory load of visuospatial information. The MRT may have been less cognitively demanding with one shape acting as a reference and crucially remaining on the screen for the duration of the trial, from which, the second shape was to be rotated.

A possible reason for no differences in performance between aphantasic and typical imager participants is because the MRT is viewed to load more heavily on spatial imagery, with individuals with aphantasia self-reporting intact spatial imagery abilities within self-reports (Experiment 1, see also Dawes et al., 2020). Evidence from the congenitally blind suggests that the MRT can be undertaken as accurately as sighted individuals using spatial imagery (Carpenter & Eisenberg, 1978; Marmor & Zaback, 1976). The response times of both aphantasic and control participants with typical imagery increased proportionally with the angle of rotation, which is in support of depictive theories, in particular the use of analogue mental rotation process similar to that of a physical rotation (Just & Carpenter, 1976; Kosslyn, 1994; Shepard & Metzler, 1971). While differing angles of object rotation add to the complexity of the task, the mental rotation of objects can be argued to draw on more allocentric or object-centred references frames and processes. It remains unknown how individuals with aphantasia would perform in tasks that involve egocentric process, such as spatial perspective-taking tasks. These tasks involve mental-self rotation, which has been suggested to be cognitively different from the processes involved in object rotation (Hegarty & Waller, 2004; Zacks & Michelon, 2005). This is supported by neuroimaging studies that provide further evidence for different cognitive processes involved in object rotation and spatial perspective-taking, with parietal areas associated with body schema activated during spatial perspective-taking tasks (Arzy, Thut, Mohr, Michel, & Blanke, 2006; Keehner, Guerin, Miller, Turk, & Hegarty, 2006; Zacks & Michelon, 2005). This will be explored in Experiment 6.

Experiment 6: How do individuals with aphantasia perform within a spatial perspective-taking task?

4.2.1. Introduction

Spatial perspective-taking involves making an embodied transformation that relies on internal representations of the body schema and its movements within space (Blanke et al., 2005; Kessler & Thomson, 2010; Michelon & Zacks, 2006). These representations are associated with both the motor and somatosensory system, and integration of information from the vestibular information is also key for efficient perspective-taking (e.g. Deroualle et al., 2015; Falconer & Mast, 2012; Gardner & Potts, 2010; Gardner et al., 2017; Kaltner et al., 2014). Typically, during a spatial perspective-taking task, individuals are asked to adopt or alter their perspective to that of a third party, by mentally rotating themselves to emulate the orientation of the figure (e.g. Arzy et al., 2006; Blanke et al., 2005; Kozhevnikov et al., 2006). This transformation is also argued to involve a pre-planning stage whereby individuals first need to mentally assume the starting posture from which, rotation to the target position can occur (Amorim et al., 2006). This involves more pre-planning then object rotation (such as the MRT as described in Experiment 5) and is complex given the additional need to transform perspective to a different orientation. This involves egocentric processes, and as yet it has not been examined how individuals with aphantasia would perform within such a task.

A spatial perspective-taking paradigm used widely within the literature is the OBT task (e.g. Blanke et al., 2005; Mohr, Blanke, & Brugger, 2006), which involves participants adopting the perspective of an on-screen avatar to make laterality judgements. This task should evoke a mental self-rotation, in that participants imagine their own bodies rotating to the same orientation and degree as an on-screen avatar, and subsequently respond by making '*left* or *right'* judgements. However, it has been reported that the OBT can also be undertaken through disembodied strategies, in that participants may learn to transpose their response when presented with front-facing figures (Gardner, Brazier, Edmonds, & Gronholm, 2013). The performance within this task is compared to that of the transpose task, which is a disembodied spatial control task for the OBT, where an embodied approach is not required (Gardner & Potts, 2011). The transpose task is matched to the OBT in terms of difficulty and spatial positions.

Experiment 5 demonstrated equivalent performance of aphantasic and typical imager control participants on an object-centred rotation task. This experiment will examine performance on a spatial transformation task that requires embodied or egocentric transformations. This will be compared to the performance of an equivalent control task that requires an allocentric transformation. Although spatial perspective-taking is a form of self-mental rotation, it does comprise of different cognitive processes compared to object rotation. Spatial-perspective taking is associated with internal representations relating to body schema and spatial movements (e.g. Gardner & Potts, 2010; Kaltner et al., 2014). If the task can be undertaken using spatial processes (in line with aphantasic participants' self-reported intact spatial abilities see Chapter 2, Experiment 1), no difference is expected within the task. No difference in performance is expected within the transpose task, which does not involve making an embodied transformation.

4.2.2. Methods

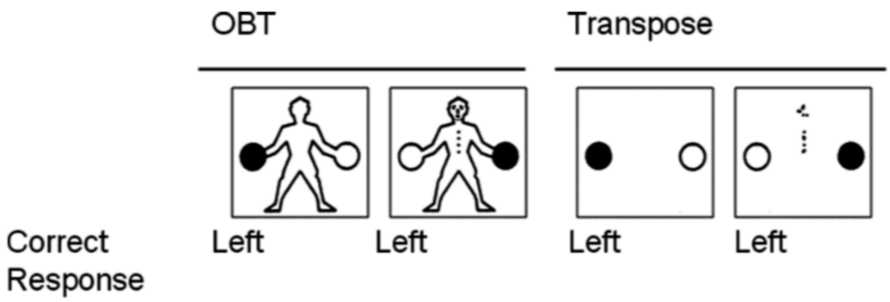
4.2.2.1. Participants

Aphantasic and control participants were the same participants as outlined in Chapter 3, Experiment 3 section 3.1.2.1 and are summarised above in Experiment 5, section 4.1.2.1. The ethics are also the same as described in these sections.

4.2.2.2. Materials

Own-Body Transformation and Transpose Task

The tasks were created using E-Prime 2.0 experiment generator software. In the OBT condition (Blanke et al., 2005; Gardner, Brazier, Edmonds, & Gronholm, 2013; Gardner & Potts, 2011), a two-dimensional (2-D) line-drawn figure or avatar was presented to participants. The avatar was holding a ball in each hand– one white and one black (see Figure 4.4) and shown in two different orientations, either front-view or back-view.



A) OBT condition B) Transpose condition

Figure 4.4: Diagram from Gardner et al. 2017 to show stimuli presented as part of the A) Own body transformation (OBT) showing 'left' as the correct response for back-view and front view stimuli B) Transpose condition showing 'left' as the correct response in each trial for cue-absent and cue-present stimuli.

The outlined shape of the avatar was identical in both back and front orientations. The way to identify the avatar was front-facing was by the presentation of simple facial features and buttons on the chest, while for back-facing orientation, there were no identifying markers. The avatar was randomly tilted at 10° increments anticlockwise or clockwise, through a range of -50° to +50°. Angles for anticlockwise or clockwise were averaged together (Kessler & Thomson, 2010; Michelon & Zacks, 2006; Preuss, Harris, & Mast, 2013) providing an overall response for front-view and back-view orientations. When the figure was presented in back-view, the on-screen location of the black ball was compatible with the location of the correct response. However, when the figure was presented in front-view, the on-screen location of the black ball was contralateral to the correct response (see Figure 4.4). Participants were informed to transform their perspective to the figure and respond to the hand that held the black ball. In the first testing session, participants undertook a practice for the OBT condition comprising of 44 trials followed by the experimental version of the OBT, which contained 132 trials split over four experimental blocks (33 trials per block). In all experimental trials, 50% were shown in the back-facing and 50% front-facing.

The transpose condition (Gardner & Potts, 2011), is a spatial control task for the OBT and was matched to the OBT condition in terms of difficulty, except for the absence of an avatar. Instead, the stimuli comprised of two balls, one black and one white, which appeared in parallel in the centre of the screen at any of the five angle orientations as in the OBT. The two balls were of the same size and angular separation as in the OBT condition and could be presented either alone (cue-absent) or with a visual cue (cue-present). This visual cue comprised of the facial features and buttons that were present in the OBT (non-embodied stimuli) presented in a fixed jumbled fashion, between the two balls. When this visual cue was presented, participants had to transpose their response (e.g. select the contralateral response to the location of the black ball). However, for cue-absent stimuli, participants had to select the ipsilateral response to the on-screen location of the black ball (see Figure 4.4). Participants undertook a practice of the transpose task, which comprised of 44 trials followed by the experimental version of the transpose condition, which comprised of 136 trials split over four experimental blocks (34 trials per block). In 50% of trials, the visual cue was present, as in the OBT. Outcome measures for both the OBT and transpose tasks were accuracy and reaction time.

4.2.2.3. Procedure

All participants undertook the OBT condition in the first testing session, and the transpose condition in the second testing session (see Chapter 3, Experiment 3, Figure 3.1). In the OBT condition, participants were verbally asked to assume the perspective of the figure on the screen by making a mental transformation and respond to '*which hand'* the figure was holding the black ball. In the transpose task, participants were verbally told to transpose their response only when presented with the visual cue. For both the OBT and transpose task, all participants were asked to rest their index fingers on top of the 'A' key (to denote left) and 'L' (to denote right) on a QWERTY keyboard and asked to respond as quickly as possible without sacrificing accuracy. In both tasks, each trial began with a black fixation cross against a white background for 1400ms. This was followed by the stimulus (either the human avatar as in the OBT or two balls as in the transpose task), which was displayed until a participant had made a response, after which the next trial appeared. For all trials in both tasks, participants were provided with visual feedback (shown for 1500ms) with regards to their response. Participants undertook the practice, followed by all four blocks of either the OBT condition (in the first testing session) and four blocks of the transpose condition (in the second testing session). The task was over when all trials had been completed.

4.2.3. Results

In this section, where sphericity is violated, a Greenhouse-Geisser correction is used. All t-tests are 2-tailed unless otherwise stated.

4.2.3.1. OBT and Transpose Tasks: Accuracy

Both aphantasic and control participants exhibited accuracy that was exceptionally high (97-99%) within both tasks (as shown in Table 4.1). Due to the near ceiling effect from both aphantasic and control participants in both tasks, no other analysis will be undertaken with this data.

	OBT task		**Transpose Task**	
Group	**Front**	**Back**	**Cue present (transpose)**	**Cue absent**
Control	0.97 (*0.37*)	0.97 (*0.04*)	0.98 (*0.04*)	0.98 (*0.02*)
Aphantasic	0.97 (*0.42*)	0.99 (*0.15*)	0.99 (*0.01*)	0.99 (*0.01*)

Table 4.1: Table to denote the mean proportional accuracy and standard deviation of aphantasic and control participants in the OBT and transpose tasks at the different orientations.

4.2.3.2. OBT and Transpose Tasks: Reaction Time

Reaction time in the OBT and transpose was examined across the two orientations and compared between aphantasic and control participants (see Figure 4.5) using a three-way mixed measures ANOVA.

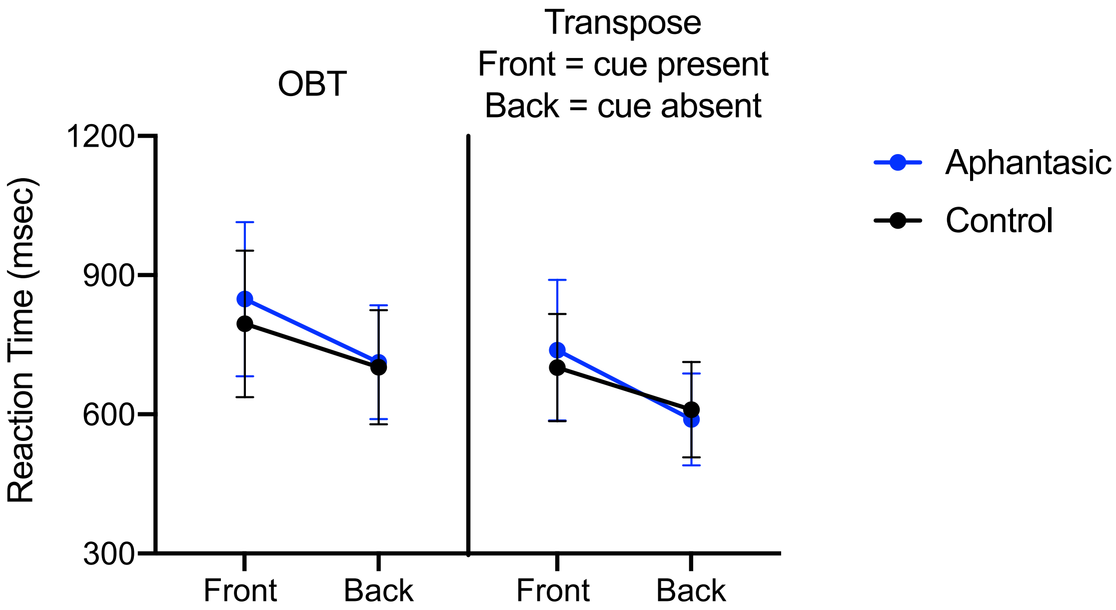


Figure 4.5: Line graph to depict the mean reaction time in milliseconds and standard deviation (represented by error bars) of aphantasic and control participants in the OBT and transpose tasks at front and back orientations. In the transpose task, cue present trials are equivalent to OBT front condition and require participants to transpose their responses.

A 2 x 2 x 2 mixed ANOVA with group (aphantasic/controls) as a between-subject factor, and within subject factors of condition (OBT and transpose) and orientation (front and back / cue present 'front' and cue absent 'back') showed a significant main effect of condition ($F(1,38) = 32$, $p < .001$ $\eta p^2 = .46$) with responses quicker in the transpose condition than the OBT condition. There was a significant main effect of orientation ($F(1,38) = 135.34$, $p < .001$ $\eta p^2 = .78$) with participants responding to back facing orientations quicker than front facing orientations and no significant main effect of group ($F(1,38) = 0.30$, $p = .59$, $\eta p^2 = .01$). There was a significant interaction between orientation and group ($F(1,38) = 6.13$, $p = .02$, $\eta p^2 = .14$), see Figure 4.6.

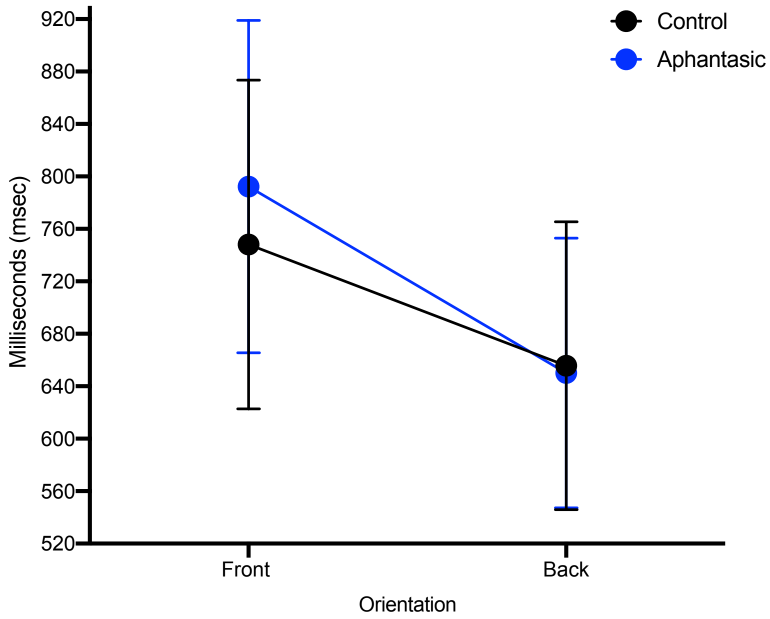


Figure 4.6: Line graph to show the orientation and participant group interaction (orientation is collapsed across the task to create 'front' and 'back' mean. Front mean: averaged response time for OBT front and cue present 'front'; back mean: averaged response time for OBT back and cue absent 'back').

No other interactions were significant ($p > .47$). To examine the orientation interaction, orientation was collapsed across task (to create front and back orientations). An independent t-test with Bonferroni-Holm correction for multiple tests was carried out to compare participant groups for each orientation. No significant difference between groups were found in front ($t(38) = -1.11$, $p = .54$, $d = -.36$) or back orientations ($t(38) = 0.25$, $p = .80$, $d = .08$). To explore differences between the two orientations for each participant group, a within-subjects t-test with Bonferroni-Holm correction for multiple tests for each participant group showed that both aphantasic ($t(19) = 10.87$, $p = .002$, $d = 4.89$) and control ($t(19) = 6.04$, $p = .002$, $d = 2.77$) participants responded significantly faster in back facing transformations compared to front-facing transformations. These results suggest that the interaction can be explained by the fact that both groups differed on front/back orientation. However, aphantasic participants showed a larger difference in front-back orientation reaction times, suggesting they were slower making these more complex transformations. Overall, the reaction times of individuals with aphantasia did not differ to participants with typical imagery at the different orientations in each condition.

4.2.4. Discussion

Experiment 6 explored aphantasic participants' performance within a spatial perspective-taking and corresponding spatial control task. The results show no significant difference in accuracy or reaction time compared to individuals with typical imagery in the OBT, which required an embodied spatial transformation of perspective. As expected, no differences were found in the transpose condition (a spatial control for the OBT), which did not require an embodied transformation. Both aphantasic and control participants exhibited longer response times within the OBT than the transpose condition, which is consistent with the findings from previous studies (Gardner, Sorhus, Edmonds, & Potts, 2012). The significant interaction between orientation (front/back) and participant group was explained that aphantasic participants showed greater variability in reaction time for front and back orientations, compared to control participants with typical imagery. Aphantasic participants also exhibited a larger variation in reaction time in the MRT (Experiment 5).

Although there were significant differences in reaction time between the two condition (i.e. the OBT/transpose conditions), suggestive that different cognitive approaches were adopted, there were no significant groups differences. Aphantasic participants' identical pattern of performance to controls participants further suggests that their reported lack of visual imagery does not hinder their ability to perform within spatial perspective-taking tasks. A possible reason for this is because the OBT loads more heavily on spatial imagery and also involves both the motor and somatosensory systems to create mental representations of the body (e.g. Deroualle et al., 2015; Falconer & Mast, 2012; Gardner & Potts, 2010; Gardner et al., 2017; Kaltner et al., 2014). This body schema is argued to be constructed from spatial and biomechanical representations as a result of multisensory integration (Falconer & Mast, 2012), thus does not rely on visual imagery alone.

Both participant groups were quicker at making back-facing transformations compared to front-facing transformations, which is consistent with the findings from the literature (Blanke et al., 2005; Gardner et al., 2012; Gronholm, Flynn, Edmonds, & Gardner, 2012; Jola & Mast, 2005; Parsons, 1987; Steggemann, Engbert, & Weigelt, 2011). However, it should be noted that aphantasic participants exhibited greater variability in front-back orientations than control participants with typical imagery. Figures in the front view are thought to require an additional and more difficult transformation (Gardner & Potts, 2011; Jola & Mast, 2005). However, the OBT can be undertaken through disembodied strategies, in that participants may learn to transpose their response when presented with front-facing figures (Gardner et al., 2013). While studies have shown faster responses when an embodied approach is adopted for the mental rotation of body limbs (Amorim et al., 2006; Jansen et al., 2012; Suggate et al., 2019), in the case of the OBT, a disembodied or allocentric approach within the task is quicker. This ‘short-cut’ strategy is less cognitively demanding compared to the transformation of one’s perceptive. The use of this strategy would also manifest longer response times for front-facing figures (similar to when an embodied approach is taken) compared to back-facing figures due to stimulus-response incompatibility (May & Wendt, 2013). It has been widely documented that responses are faster when there is a greater spatial correspondence between the location of the stimulus and location of response (Gardner & Potts, 2011; May & Wendt, 2013). This suggests that spatial compatibility effects influence laterality judgments with regards to back-facing figures (May & Wendt, 2013), which may explain why additional time is needed to make left-right judgements when a figure is front-facing.

A study by Gardner et al. (2013) reported that in the OBT, a large majority of participants (59% of their participant sample) used a disembodied spatial transposing strategy in the OBT. This shows that it is a common strategy that yields accurate performance. The influence of participants adopting this strategy within both tasks was prevented by ensuring all participants undertook the transpose condition within the second testing session. This prevented participants carrying-over this disembodied transposing strategy and subsequently using it within the OBT. The experiments in this Chapter have shown that there is wide variability in response time measures amongst individuals with aphantasia. In Experiment 4 (Chapter 4), two subgroups were identified who displayed variability in the spatial span. It is therefore of interest to examine how these participants perform within the visuospatial tasks as outlined in this Chapter, and if other subgroups that showed profound difficulties in the OTS, also display difficulties within these complex visuospatial tasks involving the manipulation of information.

Multidimensional scaling of all behavioural tasks

4.3.1. Multidimensional scaling

Multidimensional scaling (MDS) is a data visualisation technique that examines the level of similarity or dissimilarity in performance across an array of measures (e.g. Torgerson, 1952, see Chapter 3 Experiment 4, section 3.2.3.3). Individual differences exploration in

Chapter 3, Experiment 4 revealed several potential subgroups. Accuracy and reaction time measures for the MRT and front/back orientation reaction time for the OBT/transpose were converted to z-scores (as described in Chapter 3, Experiment 4, section 3.2.3.3 and see Appendix 4.1 for raw z-scores for participant groups). MDS incorporated the measures included in Experiment 4[10], and also included front and back reaction time for the OBT/transpose, and MRT accuracy and reaction time measures (that were both averaged across all angles of rotation). These were included in the MDS model (see Figure 4.7).

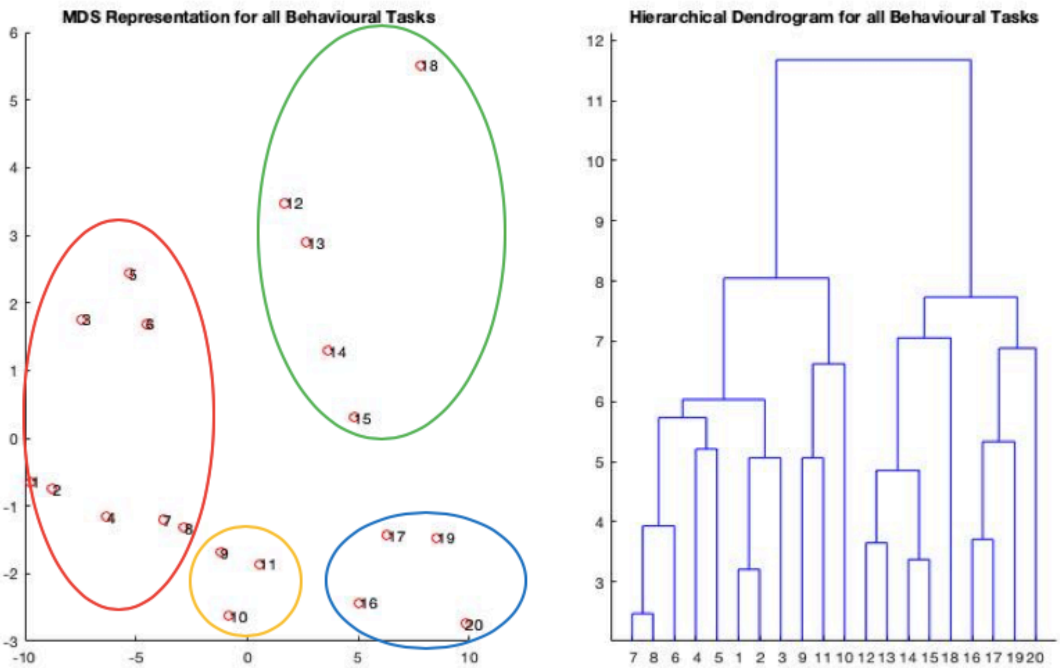


Figure 4.7: Diagrams of the multidimensional scaling representation and hierarchical dendrogram with circled aphantasic subgroups.

[10] The measures included in the MDS analysis for Experiment 4 were: VVIQ score, recall and recognition VRM measures, average OTS accuracy across moves 2-6, OTS Move 6 reaction time, SSP Spatial Span and PRM total correct

The z-scores for the four subgroups identified in Figure 4.7 were examined, with z-scores for each measure detailed in Table 4.2 and radar graph of these differences displayed in Figure 4.8.

Subgroup	VVIQ	VRM Free Recall	VRM Recog	SSP Spatial Span	PRM Acc	OTS Acc	OTS Move 6	MRT Acc	MRT RT	OBT Trans Front	OBT Trans Back
SG1 (n=8)	-3.81 (0.11)	0.14 (0.82)	-0.12 (1.13)	1.12 (1.23)	0.40 (1.17)	0.45 (0.24)	-1.04 (1.50)	0.54 (1.00)	-0.36 (0.66)	-0.23 (0.78)	0.20 (0.71)
SG2 (n=3)	-3.85 (0)	0.64 (0.84)	0.49 (0)	-0.47 (1.91)	-0.32 (1.68)	-0.35 (0.61)	-0.04 (0.33)	-0.47 (1.44)	-1.36 (2.61)	-1.45 (0.94)	-1.25 (0.95)
SG3 (n=5)	-3.72 (0.29)	-0.49 (0.83)	-0.97 (1.33)	-0.25 (0.74)	0.17 (0.76)	0.17 (0.14)	-4.24 (1.73)	0.13 (0.92)	-1.04 (1.51)	-0.09 (0.62)	0.39 (0.72)
SG4 (n=4)	-3.83 (0.04)	-0.41 (1.22)	0.49 (0)	-0.33 (2.08)	-0.27 (1.48)	-0.05 (0.37)	0.29 (0.33)	0.25 (1.10)	-0.44 (1.27)	-0.11 (1.59)	0.31 (1.04)

Table 4.2 Table to denote the mean z-scores and standard deviations for each subgroup (SG 1-4) in all of the behavioural measures (Experiments 4-6).

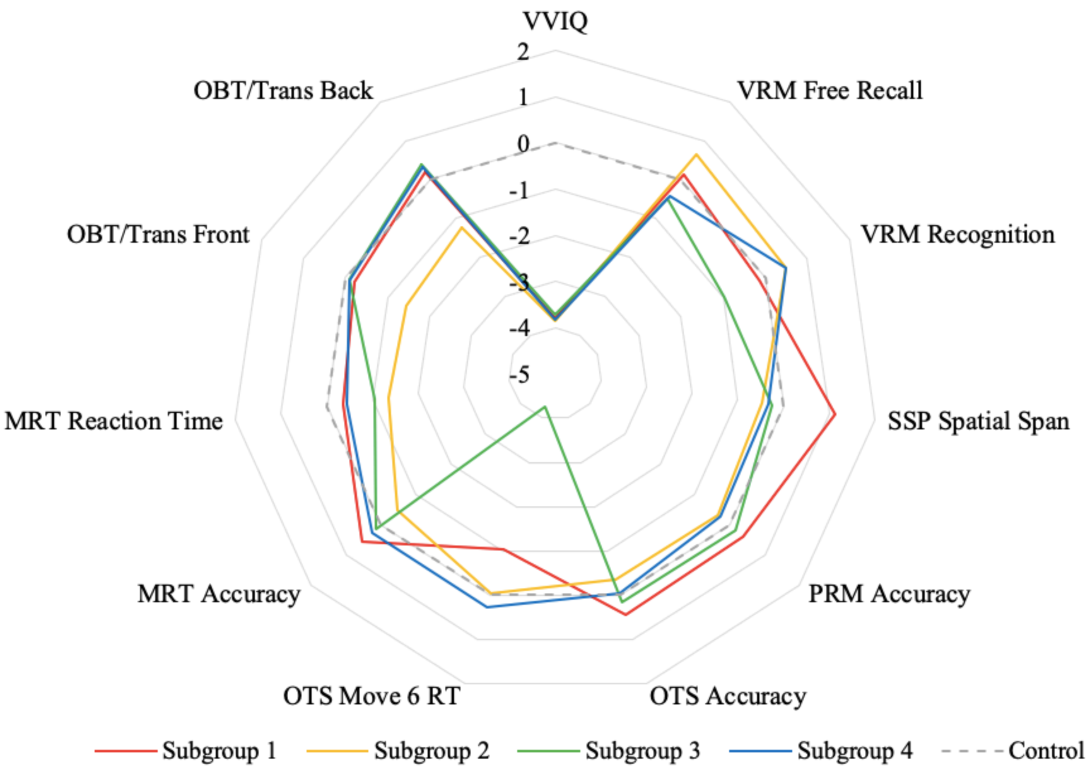


Figure 4.8: Radar graph of subgroups identified during multidimensional scaling.

4.3.2. Multidimensional scaling interpretation

In Experiment 4, four tentative subgroups were identified (as shown in Figure 4.8 and Table 4.2). While in this context they are classed as 'subgroups', ultimately MDS is a descriptive tool used to identify variations within the data. Thus, further research is necessary to confirm the existence of such subgroups and additional caution in terms of the interpretation of these subgroups is necessary given the small sample sizes. Nevertheless, this technique demonstrates variation within behavioural performance, with a number of aphantasics participants exhibiting more impaired performance in selective tasks (such as the most difficult level of the OTS) compared to other aphantasic participants. It should also be noted that, 'subgroups' who showed difficulty in the OTS did not show corresponding difficulties in spatial transformation tasks such as the OBT or MRT. While these 'subgroups' (and their respective performance) may be considered anomalous performance or 'noise' within the data, almost half of the aphantasic participants showed slower or impaired reaction times for cognitively demanding trials involving complex manipulations for the OTS (with no impairments in accuracy). This might suggest that within the sample of aphantasic participants, they are adopting differing processes (i.e. they are not all using the same process or strategy) such as using spatial imagery or verbal code, which might explain for this variation. For instance, 'subgroup 3' displayed profoundly impaired reaction times on the OTS for move 6, and showed variability in verbal memory scores, however, showed no impairments in the visuospatial working memory tasks as outlined in Experiments 5 and 6. This suggests that the impairments subgroup 3 had were selective to the nature of the OTS task. Aphantasic participants in this subgroup were further suggested to have used an alternative strategy (spatial imagery or verbal code) in the task, and this pattern of performance was similar to that exhibited by congenitally blind individuals in imagery tasks (e.g. Carpenter &

Eisenberg, 1978; Kerr, 1983; Zimler & Keenan, 1983). Slower response times in the OTS task at move 6 were also evident in 'subgroup 1,' however, at a lesser extent than subgroup 3. This group performed most accurately in the OTS, potentially suggesting an accuracy-time trade-off, and showed unimpaired performance to either the mental rotation or OBT/transpose tasks.

In Experiment 4, two 'subgroups' (subgroups 2 and 4) were suggested to have similar patterns of performance, with unimpaired performance across all tasks. However, it was observed that both of these groups had larger variability in the spatial span measure . The results of Experiments 5 and 6 suggest that 'subgroup 2' showed slower response times in the MRT and also the front and back orientations of the OBT/transpose tasks. This suggests that this subgroup of participants may have difficulties with working memory. However, this would not account for why they showed unimpaired response times on the OTS, given the complexity of the manipulation involved in the task. This might suggest that their difficulties are related to the processes surrounding the mental rotation and front/back orientations in the OBT and transpose conditions, such as the ability to undertake spatial transformations. There remains, however, a subset of aphantasic participants (subgroup 4), who show unimpaired performance across all neuropsychological and visuospatial working memory tasks. A speculative explanation for this subgroup may be that participants within this subgroup have the ability to generate visual imagery; however, have no conscious access to this imagery. This would explain their similar performance to individuals with typical imagery on the OTS, especially during the more demanding trials.

In summary, while MDS is an exploratory and descriptive technique the examination of individual differences across a range of behavioural tasks suggests there are variations in aphantasic performance. This variation is not evident when performance is analysed by participant group. While further research is necessary to explore the traits of each subgroup, the differing performance each subgroup suggests that aphantasia is not a homogenous population.

4.3.3. Chapter conclusion

The results of Experiment 2 showed no differences in performance between aphantasic and control participants with typical imagery in a visuospatial working memory task involving little manipulation. However, within a complex visuospatial working memory task in Experiment 4, significant differences in reaction time were evident between aphantasic and control participants with typical imagery in trials requiring complex manipulations (One Touch Stocking of Cambridge, OTS). Thus, it remained to be explored how individuals with aphantasia would perform within more complex visuospatial working memory tasks involving the active manipulation of visuospatial information. This Chapter investigated aphantasic participants' performance within two Experiments involving a wider variety of complex visuospatial working memory tasks. In Experiment 5, aphantasic participants' performance was examined in a MRT, which required increasing angle object rotation. In Experiment 6, complex visuospatial performance was examined through a spatial perspective-taking and spatial control paradigm (Blanke et al., 2005; Gardner & Potts, 2011). These two tasks, as outlined in the two experiments in this Chapter, required different approaches. Mental rotation involved the complex manipulation of object rotation, requiring an allocentric approach. Whereas in the OBT, participants are required to make an embodied response and transform their mental image of body position to that of an avatar (at various manipulated positions). Despite a reported lack of visual imagery, aphantasic participants were as accurate as control participants within the MRT (Experiment 5) with no differences in response time in the task with increasing angle of rotation. Similarly, in the OBT task (Experiment 6), individuals with aphantasia were as accurate as control participants with typical imagery in a task requiring spatial perspective-taking. No group differences were evident for reaction time in the two conditions. However, aphantasic participants showed greater variability than typical imagery controls in their response times for front-back orientations.

Individual differences examination of aphantasic performance by MDS identified four tentatively proposed ‘subgroups’ of aphantasic performance. Briefly, the subgroups identified were: a subgroup who exhibit profoundly impaired reaction time on complex trials of the OTS (move 6); a subgroup who also display difficulties in the OTS, but this was coupled with superior accuracy, suggesting an accuracy-time trade-off; a subgroup who exhibited difficulties for reaction time measures in the MRT and front/back orientations of the OBT/transpose task; and a subgroup who performed similarly to participants with typical imagery across all behavioural tasks (Experiments 4-6). Although this was a small sample, these differences warrant further exploration within a larger battery of tasks and suggest that aphantasia is not a homogenous experience.

At a group level, however, aphantasic participants performed as well as controls with typical imagery in visuospatial tasks requiring complex manipulation. This suggests that aphantasic participants’ self-reported lack of imagery does not impact performance within tasks requiring high levels of manipulation. The tasks within this Chapter, although they both deal with visuospatial information, load more heavily on the use of spatial imagery, for instance, making spatial transformations. Aphantasic participants self-report intact spatial imagery abilities (see Experiment 1), and evidence from the congenitally blind, suggests that these tasks can be undertaken as accurately in the absence of a ‘visual’ component (Carpenter & Eisenberg, 1978; Marmor & Zaback, 1976; Tinti et al., 2018). Individuals with aphantasia self-report low for object imagery, which concerns the pictorial presentation of visual imagery (Blajenkova et al., 2006), and as yet, aphantasics’ performance within an isolated ‘visual’ task remains to be explored. However, such a task is argued to be difficult to construct (see Kosslyn 1994). Blajenkova et al. (2006) argues that object imagery concerns the visual features of objects, such as colours, brightness and vividness. If a task could probe these features for common everyday objects, and compare performance to spatial features (i.e. size and location) of common objects, this will provide an indication into the ‘visual’ abilities of individuals with aphantasia. This will be explored in the next Chapter.

Chapter 5: What vs Where pathways

General Summary

Individuals with aphantasia self-report intact spatial imagery abilities (Experiment 1). In line with this, no group differences were found in performance on both simple (Experiment 2) and complex visuospatial imagery tasks (Experiment 5 and 6). These self-reported differences were not due to variances in personality or obvious neuropsychological differences (Experiments 3 and 4). It could be argued that the tasks undertaken thus far within this thesis could be undertaken through the use of spatial imagery in the absence of a 'visual' component. Therefore, it remains to be examined how individuals with aphantasia would perform within a task that probes 'visual' imagery alone. If aphantasic individuals cannot access visual imagery to answer questions relating to visual details, this might manifest as differences in performance between spatial and visual questions. In Experiment 7 'visual' and 'spatial' statements were created to probe imagery of everyday or common objects (e.g. '*spinach is darker than celery*' and *'a grapefruit is larger than an orange*'). The results show no significant difference in accuracy and response time between aphantasic and control participants across visual and spatial traits. If visual-spatial distinctions are difficult to distinguish in the visual domain, it is of interest to explore if visual-spatial differences can be explored within other sensory modalities. However, little is known as to how specifically individuals with aphantasia self-report their imagery across other senses and the extent of this variation. Experiment 8 examined self-reports of individuals with aphantasia within other senses. The results of these questionnaires suggest, that while there is some variation within aphantasic experiences, the majority of aphantasic participants reported the inability to form imagery within others sensory modalities. This finding warrants objective exploration (see Chapter 6).

General Introduction

Keogh and Pearson (2017) first documented that individuals with aphantasia self-report a preference for spatial imagery compared to object imagery, suggesting they have intact spatial imagery abilities. Briefly, spatial imagery concerns imagery relating to object relations (to one another), sizes, spatial locations and orientations. While object imagery (synonymous with visual imagery) concerns visual details such as colours and textures, texture could also be answered using either visual or tactile imagery[11] (Eardley & Pring, 2014). This self-reported preference for spatial imagery has since been replicated within a larger sample within Chapter 2, Experiment 1 and the underlying meaning of these differences have been explored behaviourally through the medium of a drawing paradigm (Bainbridge et al., 2020). In this study, participants were shown three real-world scenes and subsequently asked to draw these from memory. Aphantasic participants were shown to draw fewer objects, used less visual detail such as colour and more text (e.g. writing the word 'chair' compared to drawing a chair) than control participants (with typical imagery). The number of objects or visual details used also correlated significantly to the object subscale of the OSIQ. Although object and spatial differences have been documented in a number of case studies with patients with brain injury (e.g. Corballis, 1997; Della Sala et al., 1997; Farah et al., 1988; Morris et al., 1995), exploration of the nature of aphantasia may provide another route to examine these differences in a population of individuals who are unaffected by obvious brain trauma or changes in brain pathology. If there are visual and spatial processing differences between individuals with aphantasia and typical imagery, this should be investigated through additional means.

[11] within this Chapter texture is grouped with visual details, however, it is not viewed as a purely visual feature such as colour.

Aphantasics' intact spatial abilities could explain why their performance is similar to typical imagers within visuospatial tasks (Experiment 2, 5 and 6). If aphantasic participants are using spatial imagery alone to perform within previous visuospatial tasks, then questions remain with regards to how individuals with aphantasia would perform in tasks that specifically probe 'visual' details (require visual imagery). While it may be easier to define spatial and visual in the literature, in practice, however, this division is challenging to examine behaviourally in the visual domain. It may be possible, however, to explore visual-spatial differences within other sensory modalities. Equivalent to vision, audition has been suggested to have dissociated equivalent what and where pathways (which is discussed in more detail in Chapter 6). However, it can be argued that these other senses are more difficult to examine behaviourally as they are often experienced in a multi-modal capacity (Bertelson & de Gelder, 2004; Eardley & Pring, 2006).

The leading imagery theory in neurotypical sighted individuals is Kosslyn's 'theory of mental imagery,' (see Chapter 1, section 1.2.1) also suggests a distinction between spatial and visual mental images in terms of the content they represent and anatomical location (Kosslyn, 1994; Kosslyn et al., 2006). According to the theory, it is assumed that both spatial mental images and visual mental images are spatio-analogical, while both representing different types of information. Specifically, it suggests spatial mental images can contain information with regard to size and location, while visual mental images contain information on shape, colour and depth. This means that the identification of a purely visual task is challenging as visual tasks will most often have a spatial component and are in fact 'visuospatial'. For example, a classic 'visual' tasks often considered in the literature is that of an Object Form Task (Mehta, Newcombe, & De Haan, 1992), which can be haptically adapted (to be undertaken by non-visual means) so that it can be used within other populations, such as the congenitally totally blind (Noordzij, Zuidhoek, & Postma, 2007; Peelen, He, Han, Caramazza, & Bi, 2014). In the visual version of this task, participants are asked to mentally compare the outline of three common objects (that are read verbally from a card) and need to determine the odd-one-out. For individuals with typical imagery, retrieval of representations of objects occurred from long-term memory and represented retinotopically within early visual areas (or Kosslyn's visual buffer) for inspection of perceptual characteristics (Slotnick et al., 2005; see also Chapter 1 section 1.2). It could be argued, however, that the shape of an object can be recognised on the basis of the spatial relationships between their component parts (Biederman, 1987), which would suggest this task is 'visuospatial.' More recent neuroimaging has suggested that occipitotemporal areas responsible for visual representations of object shape also represent non-visual representations of the object (Peelen et al., 2014). This provides further evidence for the intertwined nature of visual and spatial representations.

Published studies examining performance within aphantasia have focused primarily on the visual domain. Nevertheless, in a small sample of 21 aphantasic respondents, approximately half self-reported a lack of imagery in the other senses (Zeman et al., 2015). Similarly, in their larger aphantasic sample (n = 2000), over 50% of their sample reported a lack of imagery across all modalities with approximately 25% reporting an absence in 'some but not all' modalities (Zeman et al., 2020). In both studies, no formal scales of sensory imagery were incorporated, and participants only commented on whether they had experiences of mental imagery in the other senses or not. A recent study proposed that 66 aphantasic participants (out of a total sample of 267) self-reported 'no imagery' across all sensory modalities on a validated non-visual questionnaire (Dawes et al., 2020). This Chapter will first examine the performance of individuals with aphantasia in a task where ‘visual’ aspects of visual imagery are isolated (Experiment 7), followed by an exploration of aphantasic participants’ self-reports within non-visual imagery questionnaires (Experiment 8). Together, this will provide a greater understanding of the ‘visual’ deficit (or not) present within aphantasia, and add to further knowledge of aphantasic experiences in other sensory domains. Insight into how individuals with aphantasia self-report on sensory questionnaires offer a possibility to further explore visual-spatial differences within other sensory domains.

Experiment 7: Isolating ‘visual’ imagery function

5.1.1. Introduction

One way in which visual-spatial differences could be investigated in the visual domain is through written statements with regards to spatial and visual properties of common everyday objects (e.g. Eddy & Glass, 1981; Howard et al., 1998; Policardi et al., 1996). Within the series of experiments investigating the effects of imagery in sentence comprehension, Eddy and Glass (1981) devised an experiment comprising of two types of sentences (requiring true or false responses). One type of sentence was termed ‘high-imagery questions’ and required the engagement of imagery (e.g. *“Tractors have two very large wheels in the back/front”*) and the other ‘low-imagery questions’ (e.g. *“there are seven days in a week”*). The authors subsequently recorded how quickly and accurately it took participants to respond to these sentences when participants read the questions, compared to when participants listened to questions that were verbally presented. The high-imagery questions involve both visual knowledge and image generation (Goldenberg, 1992) whereas the ‘low-imagery questions’ could be argued to be ‘no-imagery’ questions and are answered with semantic knowledge (without engaging visual imagery- e.g. *"middle-age comes before old age"*) and participants were able to answer low-imagery questions faster than high-imagery questions (Eddy & Glass, 1981). Within their study, the authors showed that the visual processing (i.e. reading) of a sentence selectively interfered with the comprehension of high-imagery sentences (Eddy & Glass, 1981). From this, the authors further suggested that imagery plays a significant role in the comprehension of high-imagery sentences compared to low-imagery sentences (Eddy & Glass, 1981). This is in line with other studies documenting that concrete words are better recalled than abstract words (Altarriba, Bauer, & Benvenuto, 1999; Alvio, Adric, & Smythet, 1971; Begg, 1973; Sadoski, Willson, Holcomb, & Boulware-Gooden, 2004).

Patient *MX* answered these high-imagery questions (but not the low imagery questions as described by Eddy & Glass, 1981) and his accuracy in answering these questions was at ceiling level (Zeman et al., 2010). It is possible that rather than engage in an imagery strategy, patient *MX* was relying on semantic memory. If this were the case, differences in performance might be expected. However, patient *MX* undertook these questions administered in paper versions, and while there were no differences in accuracy, there was no indication of his response times (Zeman et al., 2010). If individuals with aphantasia are not engaging visual imagery to answer such statements (like those with typical imagery), then this might manifest as differences in performance. Evidence for this stem from neuropsychological case studies. For instance, a loss of visual imagery is evident within some patients with cortical-blindness (Policardi et al., 1996) (although not in all cases, e.g. see Zago et al., 2010). In one particular case study, patient TC (with cortical-blindness) exhibited profoundly impaired accuracy on colour imagery test that probed the colour similarities, and a structural comparison task probing spatial features of common objects compared to controls (Policardi et al., 1996). The authors suggested that patient TC had a generational deficit that prevented him from converting visual knowledge to visual images (Policardi et al., 1996). This impairment suggested that TC was not using a semantic strategy in the task (Policardi et al., 1996). Another case study described a patient who following a left posterior cerebral artery infarction exhibited impairment of object colours (Goldberg, 1993). The patient showed significantly lower accuracy on high-imagery sentences relating to colour compared to controls, but conversely showed unimpaired performance within mental rotation tasks (Goldberg, 1993). Similarly, studies using high-imagery statements with regards to whether one object is darker in colour than another object have also been used within non-clinical populations (Howard et al., 1998). The authors stated that colour is encoded visually, and participants adopt an imagery strategy to perform within such tasks (Howard et al., 1998).

Individuals with aphantasia do not exhibit impairments with knowledge regarding the appearance or attributes of objects (Zeman et al., 2010) and show intact spatial imagery abilities (Experiment 1). Hypothetically, imagery statements relating to spatial properties of objects, such as size, location and shape may be answered spatially by their structural components (Biederman, 1987). Further, tactile representations of texture can be obtained through the haptic exploration of materials and objects, a technique commonly used by individuals who are congenitally blind and in sighted individuals (Lederman & Klatzky, 1993; Thompson, Chronicle, & Collins, 2003). However, questions may become more challenging to answer for visual properties, such as colour, which do not have a spatial form, therefore cannot be answered using spatial imagery. If individuals with aphantasia self-report a lack of visual imagery, then it can be assumed that they may find questions with regards to visual traits, such as colour problematic to answer. For instance, for sighted individuals with typical imagery, the comparison of colour shades of different objects would involve the conscious retrieval of object (visual) representations from long-term memory, and subsequent comparison of the perceptual features (i.e. colour) (Chang, Lewis, & Pearson, 2013). This process is unavailable to individuals with aphantasia. As a result, they may use a different process within the task, which may manifest as differences in response time. This may be similar to the performance exhibited by individuals who are congenitally blind who use alternative (non-visual) strategy to undertake imagery tasks (e.g. Carpenter & Eisenberg, 1978; Kerr, 1983; Zimler & Keenan, 1983).

Within the current experiment, the performance of individuals with aphantasia will be examined in a series of 'visual' and 'spatial' statements with regards the properties of everyday common objects. If aphantasic participants cannot form visual representations of colour, then they might be expected to perform differently on the task compared to individuals with typical imagery. Whereas within spatial statements (i.e. relating to width, size and location), and in line with their self-reported intact spatial imagery abilities, no differences are expected between aphantasic and control participants with typical imagery in the task. Ultimately, if visual-spatial differences are found within the task, it will provide a further understanding with regards to the nature of the type of imagery deficit present within aphantasia.

5.1.2. Methods

5.1.2.1. Participants

Thirty aphantasic participants[12] (VVIQ ≤ 26) were recruited by volunteer sampling. They were recruited mainly through social media platforms: the Aphantasia forum (*Aphantasia*

[12] Three of these aphantasic participants had undertaken the experiments outlined in Chapters 2 – 4. The remaining aphantasics (n = 27) had not undertaken any previous tasks/experiments as outlined in the thesis.

Forum), two Aphantasia groups on Facebook (‘*Aphantasia non-imager/mental blindness awareness group*’ and ‘*Aphantasia!*’) as well as advertised on Twitter and aphantasia forums on Reddit. Thirty control participants (VVIQ score > 33) were recruited through a combination of opportunity and volunteer sampling: from University of Westminster campuses, advertised on the website *Call for Participants* and across social media platforms, such as Twitter. Control participants were age-matched and location matched based on the regions of England where they attended Primary School (see Chapter 6, Experiment 10), to aphantasic participants (see Appendix 5.1 for the recruitment posters).

Aphantasic participants (VVIQ ≤ 26) comprised of 10 males and 20 females, mean age: 38y0m (SD = 10.98y). On the VVIQ, aphantasic participants scored a mean of 17.6 (minimum = 16, maximum = 26, SD = 2.88). Control participants comprised of 10 males and 20 females with mean age: 39y1m (SD 10.27). An independent t-test ($t(58) = 0.38$, $p = .70$, $d = .10$) confirmed no significant difference in age between aphantasic and control participants. On the VVIQ, control participants scored an average of 62.14 (minimum score = 41, maximum = 80, SD 8.90). Three controls within the sample had VVIQ scores (between 75-80, mean = 77.3) suggesting they had hyperphantasia.

The exclusion criteria for this study were individuals with: impaired hearing, colourblind and individuals who were born outside of the UK, due to the number of potentially culturally-specific references made within the Visual-Spatial task (as well as the English accents within the Voice discrimination task, see Chapter 6, Experiment 10). The protocol for the study was in accordance with the British Psychological Society guidelines and the ethical approval provided by the Psychology Department Ethics Committee of the

University of Westminster, UK. At the end of the study, participants were given a £10 Amazon voucher as a thank you for their participation within the study.

5.1.2.2. Materials

Piloting and creating the Visual-Spatial task

To create a task probing visual (colour and texture) and spatial (size and location) properties of everyday common objects, first, a number of true-false statements were chosen (n = 26), adapted or modernised from previous studies (Eddy & Glass, 1981; Policardi et al., 1996), see Appendix 5.2. A series of 60 new statements in line with the statements used in the previous studies were also created, resulting in a total of 86 statements. Of these, 44 referred to spatial properties and 42 to visual properties of the items in question. Spatial imagery statements referred to statements regarding the structure/feature or location of objects (e.g. *"a £1 coin is larger than a 2p coin"* and *"a wardrobe is more wide than tall"*) whereas visual imagery statements referred to statements regarding the colour (e.g. *"spinach is darker than celery"*) and texture (e.g. *"a brick is smoother than a tangerine"*) of various objects.

To determine how difficult the statements were to answer (and whether individuals could answer the questions accurately), all 86 statements were uploaded onto Qualtrics and circulated to individuals who had typical visual imagery. Individuals were asked to answer the statement, e.g. *"A ladle is larger than a tablespoon,"* and determine if the statement was true or false, followed by how difficult the statement was to answer (easy, moderate, hard). 175 responses were received, with 138 valid and fully completed questionnaires. Based on this data, 16 statements were excluded if they were rated: 'moderate – hard'; more than a quarter of responses (~ 35) answered incorrectly, or the statements were ambiguous resulting in an equal number of true and false responses. This resulted in 70 statements for the experiment, 41 items were spatial, and 29 items were visual.

Prior to undertaking the experimental version of the task, all participants completed a practice of the task, which comprised of 10 trials. This included two trials each for traits: colour (e.g. *"the EU flag is navy and white"*), texture (e.g. *"foil is smoother than ribbon"*), size and location (e.g. *"the number four can be written using four lines*") and width-height properties (e.g. *"a bar of soap is more wide than tall"*). For each statement, participants responded by pressing 'T' for 'true' (positioned over the letter 'S' on a standard QWERTY keyboard) and 'F' for 'false' (positioned over the letter 'I' on the keyboard). For each trial during the practice, participants received feedback for their responses. A list of all the items presented in the task was printed on A4 paper so that participants could highlight any items they were not familiar (see Appendix 5.3). The task was programmed on E-prime version 3.

5.1.2.3. Procedure

General procedure for the testing session

This Experiment was part of a wider batch of testing (see Figure 5.1), which also incorporated the Experiments 9 and 10 (see Chapter 6). The whole testing session lasted approximately 90 minutes. At the beginning of the testing session, participants were verbally briefed and were encouraged to ask any questions throughout the testing process. Following informed consent, participants completed the VVIQ, provided demographic information (see Appendix 5.4), followed by the Goldsmith Musical Sophistication Index (see Appendix 6.1) and the Bucknell Auditory Imagery Scale (Appendix 5.5). The visual-spatial task was one of four computer tasks carried out within the testing session (see Figure 5.1 and for details of the other tasks, see Chapter 6). The order of computer tasks within each session was randomised to control for order effects. At the end of the study, participants were provided with a debrief sheet and provided payment for their participant.

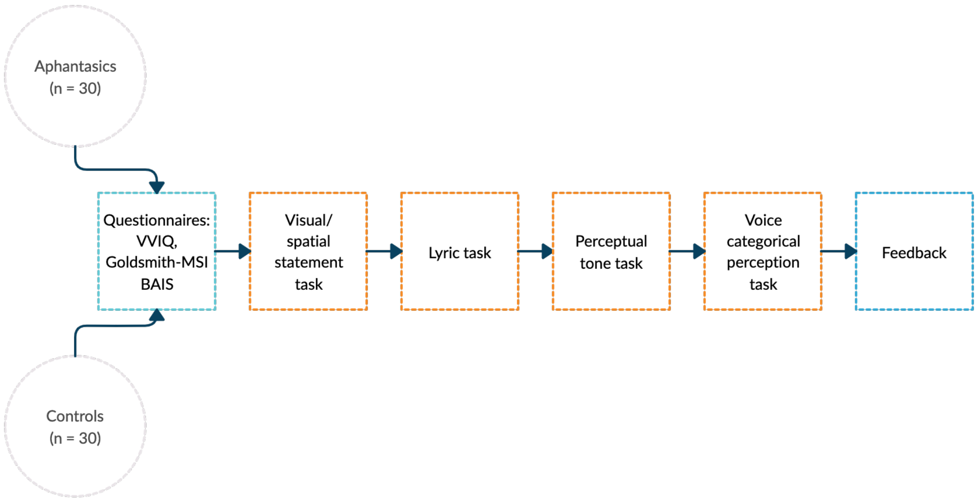


Figure 5.1: Diagram overview of the testing session. The questionnaires were completed in the same order as denoted above. The other three tasks are described in Chapter 6.

Procedure: Visual-Spatial task

All participants were informed they would be presented with a series of statements with regards to everyday common-object and would have to determine if the statement was 'true or false'. Participants were told that the statements would relate to a feature of a certain property, namely colours, textures, spatial locations or orientations and dimensions. Participants were shown the keys to press and were instructed to rest their index finger on each key and asked to respond as quickly as possible without sacrificing their accuracy. All participants first undertook a practice version of the task, comprising of 8 trials (i.e. two trials per feature) and participants received feedback for their responses. Following the practice, all participants began the experiment version (consisting of 70 trials). These trials were split depending on the characteristic into four separate blocks were presented in a fixed order with a break between the blocks: colour (20 trials), texture (9 trials), spatial location and size (21 trials), height and width (20 trials). Trials within the block were randomised for each participant. No feedback was provided during the experimental trials. Between each block, participants were given the opportunity to have a short break before continuing with the next block within the experiment. At the end of the task, participants were shown a list of items/objects that had appeared in the task, presented to them on an A4 piece of paper, and were asked to circle any of the items that were unfamiliar. Any unfamiliar items were noted, and trials where an unfamiliar item was identified, were excluded from subsequent analysis.

5.1.3. Results

Out of 60 participants, 7 participants identified one item each that they reported as unfamiliar (terracotta (3), tankard (2) woodlouse (1) and scouring pad (1)). These trials were excluded from these participants from the analysis. For data that is not normally distributed (e.g. Shapiro-Wilk < 0.05), data is transformed where stated. Greenhouse-Geisser correction is used where sphericity is violated.

5.1.3.1. Visual-Spatial Statement Task: Accuracy

Accuracy in the task was examined at each property and compared between the two participant groups (see Figure 5.2).

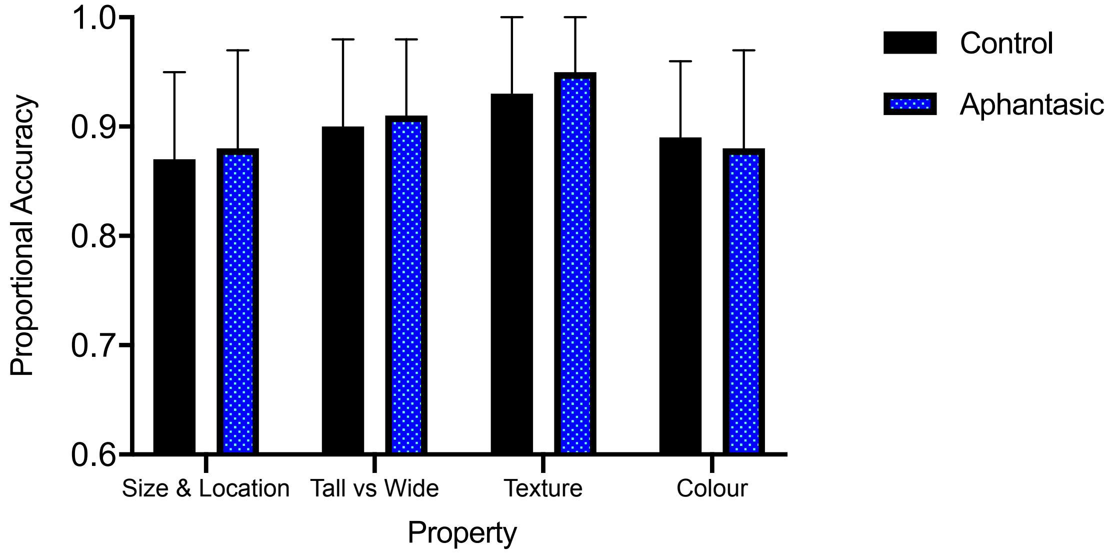


Figure 5.2: Bar chart to depict the mean proportion accuracy and standard deviation (represented by error bars) of aphantasic and control participants at the different properties within the visual-spatial task.

Data was first transformed using an arcsine transformation, as appropriate for proportion correct data (Studebaker, 1985) (see Chapter 2, section 2.2.3.4 for overview of this transformation). The accuracy of responses across the four different properties were compared between aphantasic and control participants using a 2 x 4 mixed ANOVA with factors participant group (aphantasic /controls) as a between-subject factor, and within subject factors of task of property (colour / texture/ size & location/ tall vs wide). The results showed a significant main effect of property ($F(3,174) = 15.83$, $p < .001$, $\eta^2 = .21$). Post hoc tests using the Bonferroni correction for multiple comparison, revealed a significant pairwise difference in accuracy between size & location and colour ($p < .001$), tall vs wide and texture ($p < .001$) and texture and colour ($p < .001$), and no significant pairwise difference in accuracy between tall vs wide and size & location ($p = .39$), colour and size & location as well as colour and tall vs wide both ($p = 1$). There was no significant main effect of group ($F(1, 58) = 0.26$, $p = .61$, $\eta^2 = .005$), and no significant interaction between property type and group ($F(3, 174) = 0.55$, $p = .65$, $\eta^2 = .009$). These results suggest that individuals with aphantasia perform as accurately as control participants (with typical imagery) on this task.

5.1.3.2. Visual-Spatial Statement Task: Response Time (seconds)

Response times in the task was examined at each property and compared between the two participant groups (see Figure 5.3). Response time data were transformed using the Box-Cox transformation (Box & Cox, 1964) as the data violated normality.

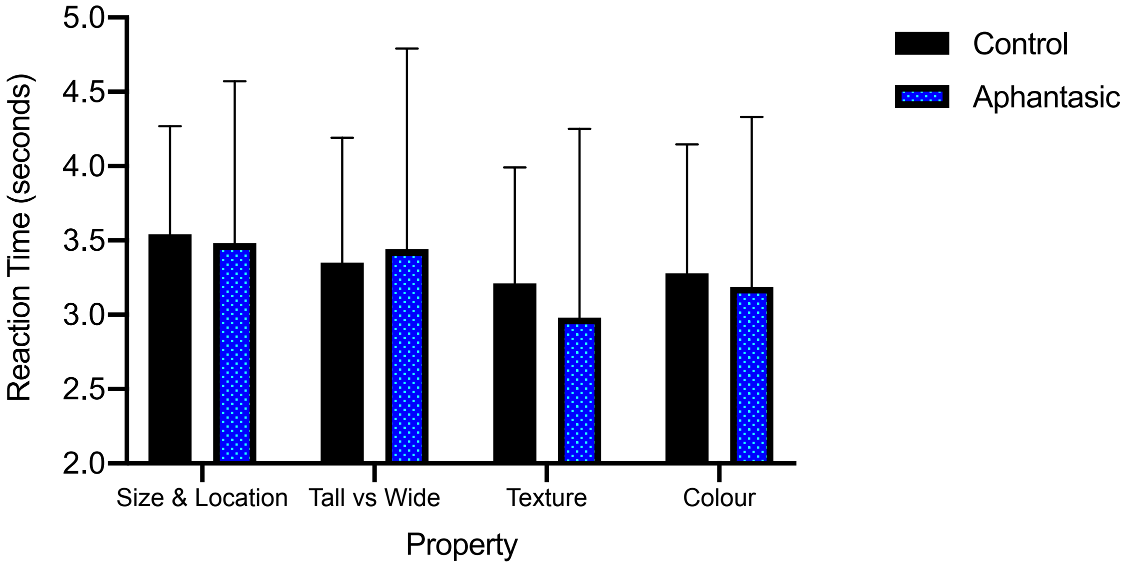


Figure 5.3: Bar chart to depict the mean response time (in seconds) and the standard deviation (represented by error bars) of aphantasic and control participants in the visual-spatial task.

Response times between aphantasic and control participants were analysed using a 2 x 4 mixed ANOVA with factors participant group (aphantasics /controls) as a between-subject factor, and within subject factors of task of property (colour / texture/ size &

location/ tall vs wide). There was a significant main effect of property (*F*(3, 174) = 9.45, $p < .001$, $\eta^2 = .14$). Post hoc tests using the Bonferroni correction for multiple comparison, revealed a significant pairwise difference in response time between size & location and texture ($p < .001$), size & location and colour ($p = .002$) and tall vs wide and texture ($p = .01$) and no significant pairwise difference in response time between size & location and tall vs wide ($p = .24$), texture and colour ($p = .79$) and tall vs wide and colour ($p = 1$). There was no significant main effect of group (*F*(1, 58) = 0.75, $p = .39$, $\eta^2 = .01$) and no significant interaction between participant group and property (*F*(3, 174) = 1.19, $p = .32$, $\eta^2 = .02$). These results suggest no difference in response time between individuals with aphantasia and control participants (with typical imagery) on this task.

5.1.4. Discussion

This experiment was designed to require responses to written statements regarding specific spatial and visual properties of everyday objects. Specifically, statements regarding spatial properties concerned features such as size, location, width and height while visual properties concerned features such as colour and texture (although texture can also be answered through tactile imagery). It was expected that on statements relating to colour, an attribute that does not have a spatial form, individuals with aphantasia would use different processes in the task that may manifest as differences in response time. The results of this experiment suggest there were no differences in accuracy or response time between aphantasic and control participants across the various properties.

For individuals with typical imagery, the statements about visual and spatial properties likely involved the generation of imagery representations of objects from long-term memory, from which subsequent inspection of the perceptual features occurred (e.g.

Chang et al., 2013; Howard et al., 1998). Neuropsychological case studies further support the use of imagery within these statements. These case studies show that in patients who have an impaired ability to generate imagery also show corresponding deficits when responding to high-imagery statements (Goldenberg, 1992; Policardi et al., 1996). However, the results of this experiment suggest that aphantasic participants, who self-report the inability to generate visual imagery, perform similar to individuals with typical imagery. This similarity is evident within the statements relating to the visual perceptual attributes of objects. Beauvois and Saillant (1985) suggested that colour knowledge stems from the contribution of both visual and verbal processes, and these processes may be difficult to distinguish within tasks that probe colour comparisons within sentences. Furthermore, it is also suggested that tasks that use statements to probe object details in imagery can be performed using semantic object knowledge or propositional code rather than generating imagery (Chang et al., 2013; McNorgan, 2012). Although comparison statements relate to a particular feature of an object, it is argued that the imagery generated as a result of that object contains other information such as shape, surface texture, luminance and colour (Chang et al., 2013). Thus, high imagery sentences do not examine one feature independently within an object representation.

A meta-analysis investigating the neural correlates of imagery across all sensory modalities showed activation of colour selective visual cortex in area V4 (McNorgan, 2012). This activation was evident within seven studies (comprising of 76 participants) that examined colour imagery (McNorgan, 2012). However, the studies reviewed within the meta-analysis for colour imagery did not include studies that used colour imagery comparison statements. Thus, it is not known whether such tasks typically activate V4. In the study by Howard et al. (1998), no activation was evident within area V4. The authors interpreted this as area V4 irrelevant to visual imagery (Howard et al., 1998). On the other hand, Chang et al. (2013) interpreted this lack of activation (during colour imagery comparison tasks involving statements) suggestive that they can be undertaken without the generation of visual imagery. Future research should investigate the type of mental representations (i.e. visual or semantic) formed within high-imagery statements for visual details. Colour is suggested to comprise of three dimensions: hue, luminance and saturation, which are features that can be examined independently (Wantz, Borst, Mast, & Lobmaier, 2015). In particular, V4 is activated within an object mental hue comparison task (Rich et al., 2006). Investigating the type of neural activations for visual comparison statements (e.g. for colour, probing features such as hue) would provide further information about the underlying processes adopted by the two participant groups.

This experiment set out to investigate visual and spatial imagery differences by probing features of common objects. Although no differences were apparent between participant groups and features, studies have alluded to a possible object imagery deficit within individuals with aphantasia (Bainbridge et al., 2020 ; Keogh & Pearson, 2017). It may be the fact that presenting written statements and examining subsequent responses is not an effective way to investigate spatial and visual imagery differences. Further that isolating and investigating the two imagery constructs is not possible within the visual domain. It may also be the case that the current experiment was too easy, with differences in performance evident within tasks with a high working memory load (see Chapter 3, Experiment 4). Consistent with previous findings within this thesis (Experiment 2, 5, 6 and 7), there remains a discrepancy between aphantasic participants' subjective experience of imagery compared to their behavioural performance within imagery tasks. If differences exist, further research is required to explore visual and spatial imagery differences within behavioural tasks. Although this may be difficult to examine in the visual domain, it could be possible within other sensory modalities. If other sensory domains are to be considered, it remains to be examined as to how individuals with aphantasia self-report within other sensory domains.

Experiment 8: Non-visual self-reports in aphantasia

5.2.1. Introduction

Although it is known that mental imagery is not restricted to the visual modality (e.g. Andrade, May, Deeprose, Baugh, & Ganis, 2014; Betts, 1909), the majority of research has focused on vision, often with the term 'mental imagery' used synonymously to describe visual imagery (e.g. Bartolomeo, 2008; Ganis & Schendan, 2011; Kosslyn, et al., 2001; Kosslyn, Behrmann, & Jeannerod, 1995). So far, studies have examined aphantasics' deficit in imagery experience but largely only examined the visual domain (with the exception of Dawes et al., 2020). Numerous studies in individuals who are congenitally blind (who have a total lack of vision) have shown they have enhanced imagery within non-visual modalities, in line with enhanced perception within non-visual domains (e.g. Noordzij et al., 2007; Voss et al., 2004). In a study by Kerr and Johnson (1991) involving the imageability of nouns, individuals who were congenitally blind were said to rate items as having 'visual' qualities despite having no visual memory of the items. The rating of such nouns having visual qualities in the absence of visual memory may be due to the use of verbal or semantic processes, or that images are not developed within one sense alone, but are in fact multi-modal. This shows that non-visual imagery is as imageable as visual imagery (Eardley & Pring, 2014). Specifically, in individuals who are congenitally blind, images generated as a result of visual, auditory and tactile words were associated with two more non-visual modalities (Eardley & Pring, 2014).

This suggests that mental imagery is experienced in a multi-modal capacity (Eardley & Pring, 2006; Nanay, 2017, 2018), For instance, in sighted individuals, a mental image (e.g. an olfactory image) can be triggered by corresponding sensory stimulation within the same (e.g. olfactory) or a different modality (e.g. visual) (Nanay, 2018). A number of studies have shown that our senses interact with each other (Bertelson & de Gelder, 2004; Vroomen, Bertelson, & de Gelder, 2001), and these interactions are not necessarily conscious (O'Callaghan, 2008).

Although a mental image can generate imagery in more than one sensory domain, research into sensory modalities generally tend to examine each modality unimodally and compare the independent experience of one sense in relation to another. For instance, sensory questionnaires tend to examine each of the sensory domains separately by asking participants to rate the vividness of familiar items within one particular sensory domain at a time (Andrade et al., 2014; Betts, 1909; Sheehan, 1967). This involves the construction of internal representations of items from long term memory (Lacey & Lawson, 2014). Subsequent judgements are based on how vivid this representation is compared to perception (Andrade et al., 2014; Marks, 1973). The vividness of an image is suggested to reflect the experience within working memory (Baddeley & Andrade, 2000), but vividness is arguably a feature of imagery experience that is easier to answer relating to the visual domain. For instance, visual images tend to be rated most vivid compared to the vividness of olfactory images (Arshamian & Larsson, 2014). Vividness is not the only property to be examined within non-visual questionnaires.

The Bucknell Auditory Imagery Scale (BAIS; Halpern, 2015) is a questionnaire specific to the auditory domain. The questionnaire asks individuals not only to rate the vividness of an image but also the 'ease of change' (BAIS-C scale) of how difficult it is to transition from one feature of an auditory image to another (Halpern, 2015). This scale has been shown to correlate significantly with performance on a pitch discrimination task (Gelding, Thompson, & Johnson, 2015; Pfordresher & Halpern, 2013). Judging the ease of transition between two different sounds is an additional way to evaluate one's auditory imagery experience and reflects a process-orientated aspect beyond the vividness of an image (Zatorre, Halpern, & Bouffard, 2010).

Zeman et al. (2015) asked aphantasic participants within their sample (of 21 participants) whether or not they experienced imagery in other sensory domains. Half of the aphantasic participants in their sample self-reported that they had an absence of imagery in the other senses (Zeman et al., 2015). However, no formal sensory scale was included to specifically examine this variation within their small sample (Zeman et al., 2015). Similarly, in their considerably larger aphantasic sample (n = 2000), over 50% of their sample reported a lack of imagery across all modalities with approximately 25% reporting an absence in 'some but not all' modalities (Zeman et al., 2020). The lack of formal sensory scale within these studies was addressed in a very recently published study by Dawes et al. (2020) by using a validated unisensory scale. The study showed that a quarter of their aphantasic sample (n = 267) reported a total absence of sensory imagery (Dawes et al., 2020). The authors commented that the remainder of the aphantasic sample did report a degree of non-visual imagery that was significantly lower (i.e. experienced as low and dim imagery) than the ratings provided by participants with typical imagery in their study (Dawes et al., 2020). However, in this study, the aphantasic sample was examined by participant group. While these studies suggest that imagery deficits are not restricted to only the visual domain, what is missing within the literature is an examination of individual differences of self-report measures. In particular, the frequency of imagery deficits and comorbidities across the sensory domains. While Zeman et al., (2020) asked the aphantasic participants in their sample to indicate if their imagery was affected in 'all modalities', 'some but not all', 'no others' and 'unsure', there is little research exploring the extent of this variation. For instance, whether there are certain domains (other than the visual domain) that are most likely to be self-reported as affected - there could be a number of ways aphantasia presents. In the case of individuals with uni-spatial neglect, neglect can either be comorbid with several sensory domains or arise within only one sensory domain (Brozzoli, Demattè, Pavani, Frassinetti, & Farnè, 2006). Thus, it is necessary to explore how aphantasic individuals self-report their imagery across the other sensory modalities, and how this may (or may not) differ to individuals with typical imagery. Moreover, the inclusion of self-report scales such as the BAIS will provide insight into process-orientated imagery within the auditory domain, which has yet to be examined within aphantasic populations.

5.2.2. Method

5.2.2.1. Participants

All data was collected via Qualtrics, an online survey. Individuals with aphantasia were recruited via forums and through social media platforms: the Aphantasia forum (Aphantasia Forum), two Aphantasia groups on Facebook ('*Aphantasia non-imager/mental blindness awareness group*' and '*Aphantasia!*') as well as through advertisements on Twitter. Individuals with typical imagery were recruited from the University of Westminster population and through social media platforms, such as Twitter. The questionnaires were also uploaded on the University of Westminster

Psychology Research Participation Scheme (RPS), which enables Psychology undergraduate students to participate in the study in exchange for course credit.

In total, 246 responses were received in Qualtrics and were downloaded into a SPSS file and 78 responses were excluded from the analysis. These were either empty responses or were partly complete. Two aphantasic participants were removed who scored 29 and 30 on the VVIQ. Another 5 controls were removed because despite self-reporting vivid imagery on the VVIQ, they self-reported no imagery (Psi-Q scores < 1) on at least one scale of the Psi-Q. This resulted in 161 valid responses: 91 aphantasic and 70 control participants. Aphantasic participants were defined by VVIQ scores ≤ 26, and scored a mean of 16.95 (minimum = 16, maximum = 26, SD = 2.25). Controls were defined by VVIQ scores > 33 and scored a mean of 61.79 (minimum = 36[13], maximum = 80, SD = 9.92). Six controls had imagery scores above 75 (mean = 77) suggesting they were hyperphantasic (see Figure 5.4 for distribution of VVIQ scores for the entire sample).

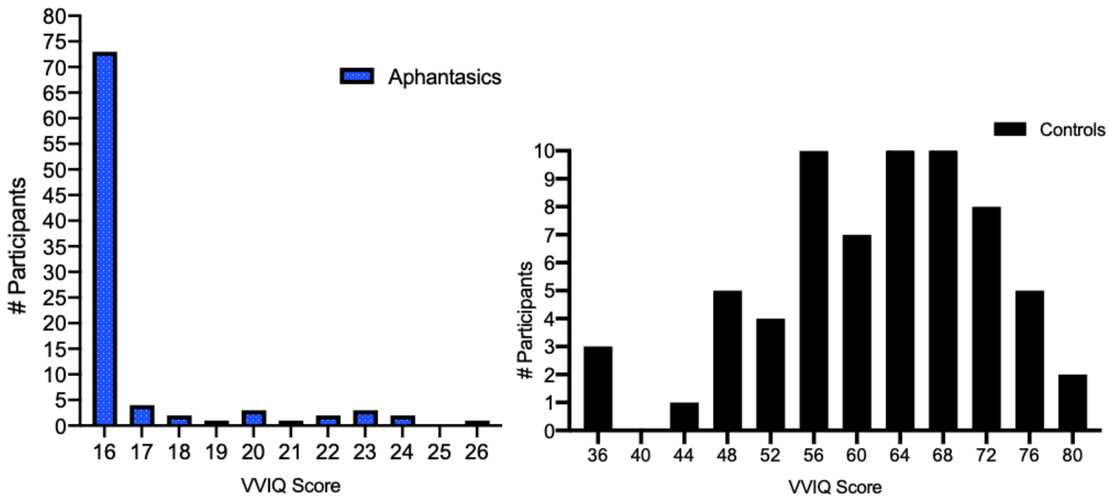


Figure 5.4: Histograms to show the frequency distribution of VVIQ scores within aphantasic and control participants.

[13] There were three control participants who scored under 40 in the VVIQ. On the VVIQ, they rated 3+ for half of the items within the VVIQ, suggesting that their imagery for some items was more vivid than for other items.

The study was carried out in accordance with the British Psychological Society ethical guidelines, and ethical approval provided by the Psychology Department Ethics Committee of the University of Westminster, UK.

5.2.2.2. Materials

One online questionnaire was created through the Qualtrics platform, comprising of the following measures.

Bucknell Auditory Imagery Scale (BAIS)

The BAIS (Halpern, 2015) comprises two subscales: a vividness (BAIS-V) and a control subscale (BAIS-C) for auditory imagery (see Appendix 5.5). The vividness subscale comprises of 14 imagined sounds that vary in their nature, from voices to musical instruments, and participants have to rate the vividness of each sound (e.g. *"consider attending a choir rehearsal, the sound of an all children's choir singing the first verse of a song"*). The control subscale comprises of 14 pairs of imagined sound, which require participants to manipulate the sound and rate 'the ease of change' or transition between the two examples (e.g. the first part: *"the sound of a saxophone solo,"* and the second part: *"now the saxophone is accompanied by a piano"*). The control and the vividness scale use the same Likert scale from 1 (no image present at all) to 7 (as vivid as actual sound). Scores are calculated by the mean response of the 14 questions for each separate subscale.

Plymouth Sensory Imagery Questionnaire (Psi-Q)

The Psi-Q (Andrade et al., 2014, see Appendix 5.6) probes the experience of seven modalities, and each sensory modality comprises of five questions (35 questions in total).

The sensory modalities are: visual (e.g. *"imagine the appearance of a cat climbing a tree"*), auditory (e.g. *"imagine the sound of the mewing of a cat"*), olfaction (e.g. *"imagine the smell of a rose"*), gustation (e.g. *"imagine the taste of toothpaste"*), tactile *("imagine touching warm sand"*), kinaesthetic (e.g. *"imagine the bodily sensation of walking briskly in the cold"*) and emotions (e.g. "*imagine feeling relieved"*). Individuals are asked to rate the vividness of their sensory experience on a Likert scale from 0 (no imagery at all) to 10 (as vivid as real life). The overall Psi-Q score are calculated by taking a mean score of all responses across the seven senses. Scores for each modality are calculated by taking the mean score of each of the five questions for all seven modalities.

5.2.2.3. Procedure

All data was collected via an anonymous link to an online questionnaire and provided with instructions. Participants were asked to provide informed consent prior to completing the questionnaires (see Appendix 5.7). Participants then undertook the VVIQ, BAIS, Psi-Q and OSIQ (OSIQ data are detailed in Chapter 2, Experiment 1). When all tasks were completed, participants were thanked for their participation and debriefed (see Appendix 5.8) with regards to the nature of the study.

5.2.3. Results

In instances when data is not normally distributed (e.g. Shapiro-Wilk < 0.05 for all variables), data is transformed where stated, or non-parametric test is used. When sphericity is violated, a Greenhouse-Geisser correction is used. All tests are 2-tailed.

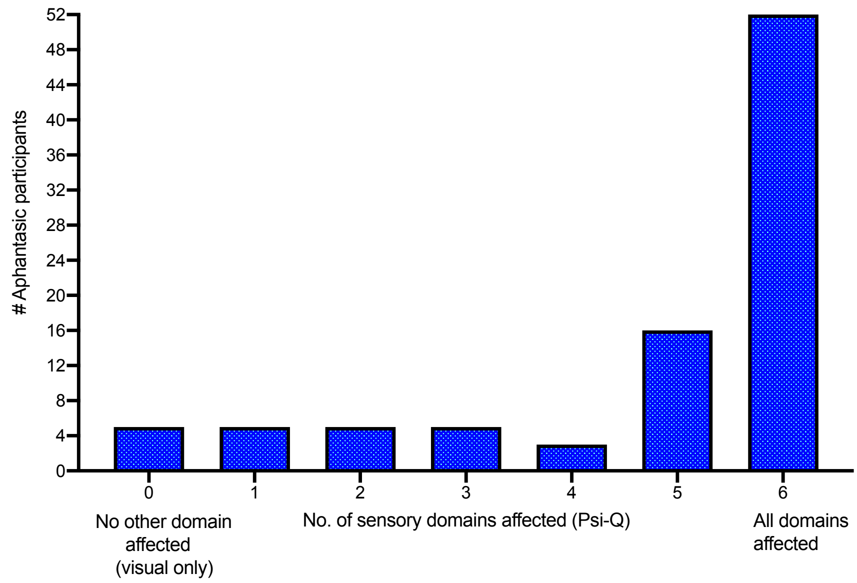
5.2.3.1. Psi-Q: Range of responses and number of sensory domains affected in aphantasia

Aphantasic participants were defined as having imagery within a domain (albeit if it was dim or vague) if the overall score for that domain had the mean score > 1. This meant that at least one question had to be rated '2' or above (the maximum score that could be provided was 10). Aphantasic participants who scored a mean rating ≤ 1 for a sensory sub-scale (suggesting they had rated all the items as '1' or at least one items as 0) were classed as having no imagery for that subscale. For the visual subscale, one aphantasic participant scored 1.33 on the subscale (their VVIQ score was 24), and this participant was removed from the analysis. All aphantasic participants scored less than 1 on the visual subscale, indicating an absence of visual imagery. Therefore, this subscale is removed from the analysis and subscale comparisons.

Frequency and comorbidity of an absence of imagery across sensory domains

Out of the sample of 91 aphantasic participants, 52 (57%) self-reported an absence of imagery across all the six sensory domains of the Psi-Q (audition, olfaction, gustation, tactile, kinaesthetic and emotion, see Figure 5.5A). The majority of these aphantasic participants (n = 45) also scored 16 on the VVIQ. When measures for kinaesthesia and emotion were excluded, an additional 15 aphantasic participants were identified as self-reporting a lack of imagery across senses: audition, olfaction, gustation and tactile, see Figure 5.5B. In total, 67 aphantasic participants (74%) self-reported a lack of imagery across the non-visual sensory domains (audition, olfaction, gustation, tactile).

A) Number of non-visual sensory domains affected on all measures of the Psi-Q



B) Number of sensory domains affected on the Psi-Q excluding kinaesthetic and emotion measures

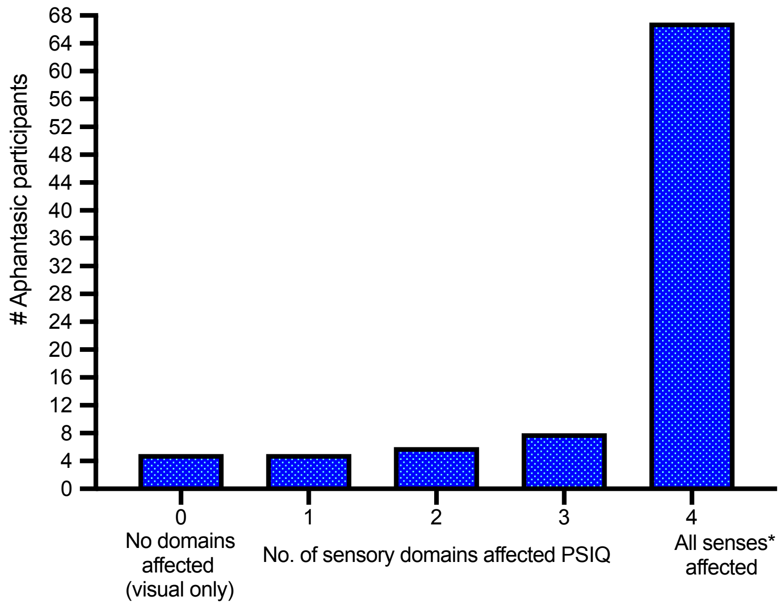


Figure 5.5: Bar charts to depict the frequency of the self-reported number of sensory domains affected by individuals with aphantasia (excluding the visual domain) in A) all measures of the Psi-Q B) In only senses*: audition, olfaction, gustation, tactile.

To examine the comorbidity of the experience of a lack of imagery in more than one sense, the number of aphantasic participants who self-reported a lack of imagery across more than one domain (audition, olfaction, gustation, tactile) was examined. Table 5.1 suggests that aphantasic participants are more likely to self-report a lack of imagery of at least three sensory domains. However, there remains a subset who self-report a lack of imagery within one-two sensory domains other than visual domain.

Number of domains affected	Domains affected	Frequency
Only visual imagery affected (n = 5)	-	5
Only one other domain other than visual (n = 5)	Olfaction	2
	Taste	1
	Tactile	2
Two domains other than visual (n = 6)	Olfactory & Taste	5
	Olfactory & Tactile	1
Three domains other than visual (n = 8)	Olfactory & Taste & Tactile	6
	Auditory & Olfactory & Taste	2
All domains affected plus visual (n = 67)	Audition, Olfaction, Gustation and Tactile	67

Table 5.1: Table to show the number of sensory domains that aphantasic participants self-report a lack of imagery (other than the visual domain) considered only within audition, olfaction, gustation, tactile domains.

The frequency of vivid (Psi-Q > 1) sensory imagery experience

Of the subset of aphantasic participants (n = 39) who self-reported a more vivid imagery experience within at least one other sensory domain (Psi-Q > 1), Figure 5.6 suggests that aphantasic participants self-reported imagery experience most frequently in kinaesthetic emotion and auditory imagery domains and least frequently in gustation and olfactory, domains

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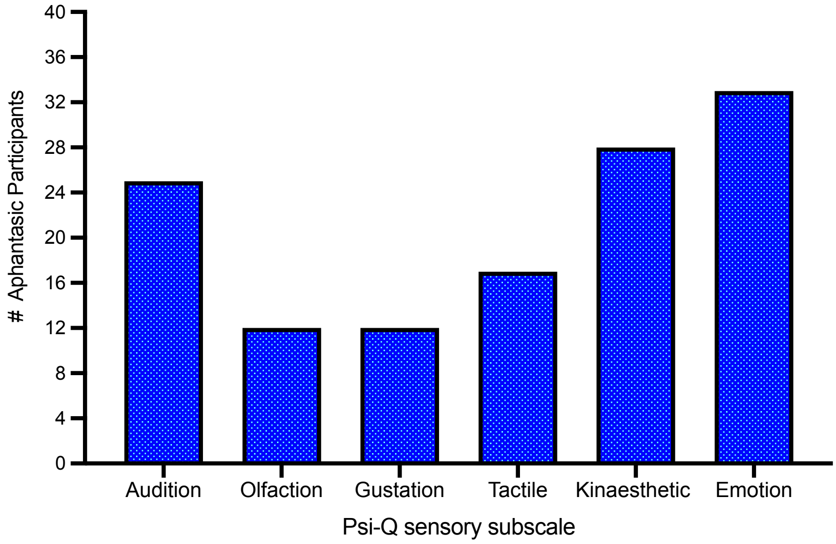


Psi-Q scores provided by aphantasic participants who experience imagery across the senses (Psi-Q > 1)				
Psi-Q scale	Aphantasic mean score (SD) *Control mean (SD)*	Aphantasic Median score /10	Aphantasic Mean Lowest score /10	Aphantasic Mean Highest score /10
Audition	5.64 (2.69) *7.68 (1.54)*	6	1.4	10
Olfaction	4.06 (2.92) *6.55 (2.08)*	3	1.4	10
Gustation	3.78 (2.63) *6.83 (2.11)*	2.5	1.4	8.8
Tactile	5.92 (2.16) *7.49 (2.04)*	6	1.4	9.4
Kinaesthetic	4.38 (2.50) *7.08 (1.77)*	5	1.2	8.8
Emotion	5.29 (2.33) *7.09 (2.08)*	6	1.4	9

Figure 5.6: Histogram of the number of aphantasic participants and summary table of their scores (mean, standard deviation and median scores) for these participants (Psi-Q > 1) who self-report an experience of imagery within non-visual sensory domains on the Psi-Q. Control mean (standard deviation) scores are also included for comparison.

5.2.3.2. Psi-Q Analysis

A) Overall analysis by participant group

Total Psi-Q scores were calculated by the mean scores provided across the sensory subscales (see Table 5.2).

	All aphantasics (n = 91)	All Controls (n = 70)
Psi-Q scale	Mean (SD)	Mean (SD)
Auditory	1.53 (2.82)	7.68 (1.54)
Olfactory	0.49 (1.57)	6.55 (2.08)
Gustatory	0.49 (1.47)	6.83 (2.11)
Tactile	1.10 (2.43)	7.49 (2.04)
Kinaesthetic	1.32 (2.36)	7.08 (1.77)
Emotion	1.82 (2.79)	7.09 (2.08)
Overall Psi-Q score (including the visual subscale)	0.98 (1.65)	7.19 (1.48)

Table 5.2: Table to depict the mean and standard deviation of all scores by aphantasic and control participants on each of the Psi-Q sensory subscales and the Psi-Q overall (which also included the visual subscale).

Overall, aphantasic participants scored low on the Psi-Q with a median of 0.17 (range: 0 – 7.77) compared to controls who scored a median of 7.23 (range: 3.43 – 10). A Mann-Whitney test showed a significant difference (Mann-Whitney U = 93.50, $p < .001$, r = .84) in overall Psi-Q scores[14] between aphantasic and control participants.

[14] This analysis also included the responses for the visual subscale of the Psi-Q.

B) Participant group analysis by all sensory domains of the Psi-Q

Mean scores for each subscale were calculated by averaging the scores across the five items for each sensory subscale (excluding the visual subscale) for each participant group (as denoted in Table 5.2).

Auditory imagery

Aphantasic participants scored a median of 0, range: 0 – 10 compared to controls who scored a median of 8.2, range: 3 – 10. A Mann-Whitney showed a significant difference (Mann-Whitney U = 470.50, $p < .001$, $r = .75$) in Psi-Q auditory imagery scores between aphantasic and control participants.

Olfactory imagery

Aphantasic participants scored a median of 0, range: 0 – 10 compared to controls who scored a median of 6.8, range: 2 – 10 on the olfactory subscale. A Mann-Whitney showed a significant difference (Mann-Whitney U = 165, $p < .001$, $r = .86$) in Psi-Q olfactory imagery scores between aphantasic and control participants.

Gustatory imagery

Aphantasic participants scored a median of 0, range: 0 – 8.80 compared to controls who scored a median of 7.1, range: 2 – 10. A Mann-Whitney showed a significant difference (Mann-Whitney U = 137.50, $p < .001$, $r = .86$) in Psi-Q gustatory imagery scores between aphantasic and control participants.

Tactile imagery

Aphantasic participants scored a median of 0, range: 0 – 9.40 compared to controls who scored a median of controls median: 7.7, range: 2.6 – 10. A Mann-Whitney showed a significant difference (Mann-Whitney U = 329.50, $p < .001$, $r = .79$) in Psi-Q tactile imagery scores between aphantasic and control participants.

Kinaesthetic imagery

Aphantasic participants scored a median of 0, range: 0 – 8.80, compared to controls who scored a median: 6.9, range: 2.6 – 10. A Mann-Whitney showed a significant difference (Mann-Whitney U = 370.50, $p < .001$, $r = .77$) in Psi-Q kinaesthetic imagery scores between aphantasic and control participants.

Emotion

Aphantasic participants scored a median of 0, range: 0 – 9, compared to controls who scored a median of 7.2, range: 1.5– 10. A Mann-Whitney showed a significant difference (Mann-Whitney U = 637, $p < .001$, $r = .70$) in Psi-Q emotion scores between aphantasic and control participants.

Together these results suggest that when examined by group, aphantasic participants do self-report statistically lower imagery ratings across sensory domains. However, variations in self-report responses are apparent, and not all aphantasic participants self-report a lack of imagery across all of the sensory modalities.

5.2.3.3. Bucknell Auditory Imagery Scale (BAIS): Range of responses

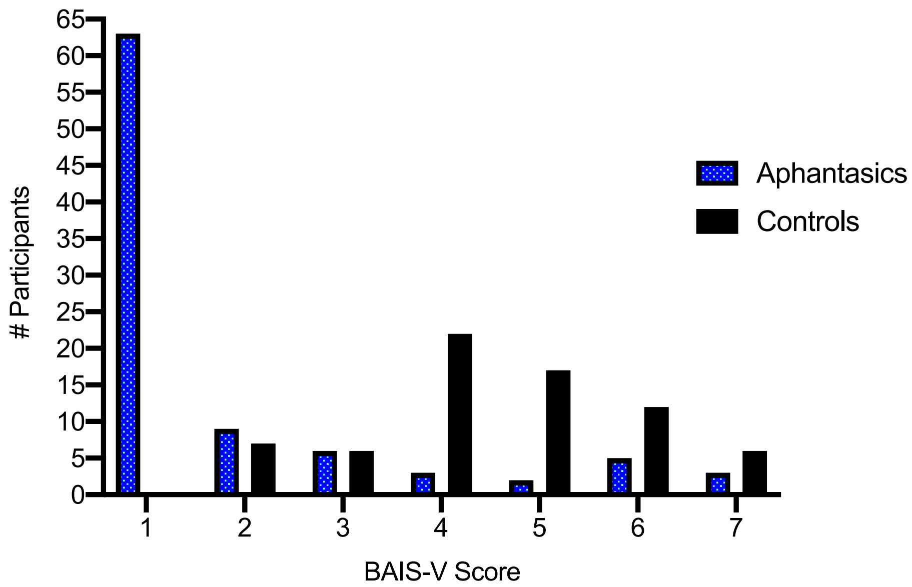


Figure 5.7: Histogram to show the distribution of BAIS-V responses for all aphantasic and control participants.

Figure 5.7 shows the mean distribution of scores on the BAIS-V subscale by aphantasic (n = 91) and control participants (n = 70). The majority of aphantasic participants (n = 71) scored BAIS-V ≤ 2; however, there were a subset of aphantasic participants (n = 20) who scored above 2 indicating a more vivid auditory imagery experience. From this subset, 18 also reported vivid auditory imagery on the Psi-Q scale (the other 2 aphantasic participants from this subset self-reported 0 on the Psi-Q auditory scale, despite a mean of 2.68 on the BAIS-V), see Table 5.3.

Controls scored BAIS-V ≥ 3 (n = 63), however, there were 7 controls who scored BAIS-V < 3 (mean = 2.57, SD = 0.26). These 7 controls had a mean VVIQ score of 52 (SD = 13.74).

Mean BAIS Score (SD)				
BAIS Subscale	Low auditory imagery aphantasics (BAIS-V ≤ 2)	High auditory imagery aphantasics (BAIS-V > 2)	All aphantasics (n = 91)	All Controls (n = 70)
BAIS-V	1.15 (0.23)	4.34 (1.89)	1.90 (1.63)	4.54 (1.20)
BAIS-C	1.27 (0.61)	4.65 (2.14)	2.07 (1.92)	4.85 (1.08)

Table 5.3: Table to denote the mean and standard deviation of low and high auditory imagery aphantasics, all aphantasic (i.e. combined low and high imagery aphantasic participants) and control participants in the BAIS.

5.2.3.4. BAIS Analysis

To examine differences in scores between participant groups (i.e. all control and all aphantasic participants, see Table 5.3), data was first transformed using a Box-Cox transformation (Box & Cox, 1964) to address issues in normality (see Chapter 2, Experiment 1, section 2.2.3.4). A two-way mixed measures ANOVA with Greenhouse-Geisser correction with factors group (aphantasic/ control) and subscale of the BAIS (vividness/ control) showed a significant main effect of subscale ($F(1, 159) = 7.62$, $p = .006$, $\eta p^2 = .05$), with participants scoring significantly higher on the BAIS-C subscale than the BAIS-V. There was a significant main effect of participant group ($F(1, 159) = 181.68$, $p < .001$, $\eta p^2 = .53$) suggesting controls scored significantly higher in both subscales compared to aphantasic participants. There was no significant interaction between the BAIS subscales and participant group ($F(1, 159) = 1.62$, $p = .21$, $\eta p^2 = .01$) indicating that there was no evidence of a difference in performance on the two subscales between groups. These results suggest that the experience of auditory imagery is different between the two groups, and participants found it easier to manipulate aspects of the auditory image than rate the vividness.

Self-reported BAIS-V scores for aphantasic and control participants were correlated using a Spearman correlation to the auditory subscale of the Psi-Q. In controls, the results showed a significant strong positive correlation ($r = .61$, $p < .001$), with a significant stronger positive correlation ($r = .76$, $p < .001$) evident within the aphantasic group. This suggests that scores provided on one type of auditory measure were similar to the scores provided on the other auditory measure.

5.2.4. Discussion

Experiment 8 examined how individuals with aphantasia self-report their imagery across other sensory domains. Specifically, this experiment examined in detail the individual variation within aphantasic participants' self-reports within non-visual sensory domains. The majority of aphantasic participants (57%) within the sample self-reported a lack of imagery across all of the seven sensory domains shown in the Psi-Q, which is in line with the findings of Zeman et al., (2020). Aphantasic participants who self-reported one to three domains as being affected most frequently self-reported the domains of olfaction, taste and tactile as absent. Few aphantasic participants self-reported intact imagery abilities across the non-visual senses, suggesting their aphantasia was not confined to the visual domain. Over a third of aphantasic participants self-reported vivid imagery experiences in at least one sensory modality. They also provided higher ratings for auditory, tactile and the emotion imagery, indicative of more vivid imagery in these domains. However, this group provided lower scores on gustation and olfactory domains suggesting that of the aphantasic participants who did experience imagery in these domains, the experience was more vague and dim compared to other senses. While this group of aphantasic participants self-reported a more vivid imagery experience, the mean ratings provided for each domain were not as high as the ratings provided by the control participants with typical imagery.

Similarly, in the BAIS questionnaire, the majority of aphantasic participants self-reported a lack of auditory imagery and provided low scores in both BAIS subscales. The scores were significantly higher in the BAIS-C subscale, suggesting that despite an absence of auditory imagery, aphantasic participants found it somewhat easier to manipulate and adjust features of the auditory experience. Less than a quarter of aphantasic participants self-reported vivid auditory imagery experience and the mean ratings provided were similar to the mean ratings of controls. Together, this suggests that there is much variability in the way that individuals with aphantasia can present with their imagery deficits. Further research should examine the profile of these subgroups of imagery experience in more detail.

The lowest scores provided by both aphantasic and typical imagery participants were for olfactory and gustatory imagery. A study by Schiffersten (2009) asked participants to rank imagery vividness across all sensory domains and showed that participants ranked olfactory and gustatory imagery as the lowest, suggesting it was more difficult to generate a vivid quality image for these senses. A reason for this is that olfactory images have been proposed to be more difficult to generate and maintain (Lacey & Lawson, 2014) and introspecting may involve multisensory confounds (Auvray & Spence, 2008; Schifferstein, 2009). For example, in individuals with typical imagery, olfactory or gustatory images may also be accompanied by an involuntary visual image (Nanay, 2018). Unlike the olfactory and gustatory domains, auditory imagery has been proposed to have numerous similarities to visual imagery and thus may be a good candidate to investigate further in aphantasia. For instance, it has spatial characteristics similar to the visual domain (Halpern, 1988; Zatorre et al., 1996). Further, evidence from neuroimaging and lesion studies have shown that auditory imagery has a 'what' and 'where' pathway similar to the 'what/where' pathways described within the visual domain (Clarke et al., 2000; Warren et al., 2002). At present, spatial and visual imagery differences in individuals with aphantasia were not evident in the visual domain, potentially due to the difficulties in isolating each construct within a behavioural task. It may be possible, however, to separate these constructs within the auditory domain, and this shall be explored within the following Chapter.

5.2.5. Chapter conclusion

This Chapter examined two broad questions. The first was whether it was possible to separate visual and spatial imagery constructs within the visual domain, and the second, how individuals with aphantasia self-report on broader sensory imagery measures. Experiment 7 investigated whether a task that isolated 'visual' imagery would show performance differences due to aphantasics' inability to access visual imagery. Specifically, this was examined in a task requiring the judgements of spatial and visual properties of everyday common objects. No difference in performance on either accuracy or response time between aphantasic and control participants were evident, especially in statements with regards to visual properties. It was concluded that written statements were not an effective means to examine visual and spatial differences. The experiment highlighted the difficulties in separating visual and spatial constructs behaviourally within the visual domain. However, visual-spatial differences could be explored further within other sensory modalities.

Experiment 8 explored the variations in self-reports provided by individuals with aphantasia within non-visual sensory modalities and also examined in more depth the imagery experiences of the auditory domain. The results suggest that the majority of aphantasic participants self-reported a lack of imagery across the senses. Furthermore, there was a small subset who experienced an absence of imagery in one to three domains, typically the olfactory, gustatory and tactile domains. On the other hand, a third of aphantasic participants self-reported vivid imagery within the other senses, suggesting that there are numerous ways aphantasia can present, and variations in aphantasic experience. Similarly, individuals with aphantasia self-report lower on the BAIS questionnaire; however, there was a subgroup of aphantasic participants who self-reported vivid auditory imagery similar to the scores self-reported by typical imagery controls. If the auditory domain has many commonalities to the visual domain, this may make it a good candidate to further examine visual-spatial (equivalent) differences. Moreover, if individuals with aphantasia self-report an absence of auditory imagery, exploring their performance objectively within tasks that require auditory imagery would contribute to the additional understanding of aphantasic imagery capabilities outside of the visual domain (Chapter 6).

Chapter 6: Auditory imagery performance in aphantasia

General Summary

Despite the fact that there is variability in non-visual self-reports (Experiment 8), the majority of aphantasic participants do report an absence of mental imagery in at least one other domain. One sensory domain that has not been explored objectively in aphantasia, is that of audition. Within this Chapter, performance is examined within two auditory experiments: a musical imagery pitch task (Experiment 9) and a voice identification task (Experiment 10). The paradigm in Experiment 9 was adapted from the seminal auditory imagery tasks by Halpern (1988). It involved two conditions, one condition whereby participants used imagery to compare the pitch of lyrics within well-known songs and a matched perceptual tone condition. Results showed no significant difference in accuracy or response time between aphantasic and control participants in either of the two conditions. Experiment 10 investigated the ability to generate internal auditory representations of different vocal identities. Participants were trained to discriminate between two speakers and then required to identify a target speaker producing a novel speech utterance that was derived from morphing between the target voice identity and another trained speaker. The category boundary between the two speakers was estimated. The results of this experiment showed that individuals with aphantasia were able to summon equivalently sharp categorical representations of the two voices, indicating that they had formed equivalently well-specified internal auditory images of the speakers' voices. Together, the results of these experiments suggest that despite self-reporting a lack of auditory imagery, there is no evidence to suggest that the performance exhibited by individuals with aphantasia differs to individuals with typical imagery.

General Introduction

Within non-visual sensory questionnaires (Experiment 8), individuals with aphantasia reported their imagery experience to be significantly lower than controls with typical imagery. This self-reported deficit in the auditory domain is supported by the findings of the Bucknell Auditory Imagery Scale (BAIS) questionnaire, in which aphantasic participants reported a lack of auditory imagery and an inability to manipulate auditory representations. Nevertheless, it should be noted that there was some variability in responses - not all aphantasic participants reported a lack of imagery across all senses. This variability has also been documented within other studies (Dawes et al., 2020; Zeman et al., 2020; Zeman et al., 2015). Therefore, in at least some individuals, aphantasia may represent a deficit that extends beyond visual imagery and across other modalities. Further, given that differences in objective imagery function have been difficult to detect in visual imagery tasks, it is possible that these deficits may be easier to detect in auditory imagery tasks. For example, it may be is easier to create tasks that require separable perceptual and spatial imagery components.

Within the visual domain, self-reports within visual imagery questionnaires (such as the Object Spatial Imagery Questionnaire, OSIQ, see Chapter 2, Experiment 1), have shown that aphantasic participants have lower self-report scores on object imagery subscales. However, they reported similar levels of spatial imagery to those with typical imagery. This preference implies (according to the subscales definitions as outlined by Blanjenkova et al., 2006) that aphantasic individuals rate their imagery representations as abstract, rather than reflecting the literal representations of objects and their respective features. Despite having low self-reported object imagery on a task that probed visual and spatial details of common everyday objects (Experiment 7), there was no evidence to suggest differences in objective performance between aphantasic and typical imagery participants. This suggests that in the visual domain, the self-reported experience of visual imagery in individuals with aphantasia differs from their objective performance within imagery tasks. Alternatively, the tasks undertaken in the visual domain (thus far in this thesis) may not have been sensitive enough to capture the differences in imagery experience. Although performance differences in tasks within the visual domain were not evident when examined by group (within Experiment 4, 5 and 6), subgroups of aphantasia were identified that had varying patterns of performance within visuospatial tasks. An important question then is whether a similar pattern may be seen in the auditory domain, i.e. will a self-reported lack of auditory imagery translate to differences in performance within auditory imagery tasks? Given that there is no evidence of performance differences in the visual domain, one might expect a similar pattern of performance for auditory imagery tasks.

Similar to visual imagery, auditory imagery can be defined as "*the introspective persistence of an auditory experience, including one constructed from components drawn from long-term memory, in the absence of direct sensory instigation of that experience,*" (Inons-Peterson, 1992, pg. 46). Auditory and visual imagery share many characteristics. For instance, like visual imagery, auditory imagery can evoke both voluntary or involuntary quasi-perceptual experiences (for instance, earworms, e.g. see Williamson et al., 2012). In self-report measures, studies have shown a correlation between visual and auditory imagery vividness, with higher self-reported vividness in one type of imagery experience, i.e. visual imagery, correlating with higher self-ratings in the other, i.e. auditory imagery (Lima et al., 2015). It should be noted, however, that while self-reported vividness of visual imagery correlates with social desirability (e.g. McKelvie, 1995), no such correlation exists with the self-reported vividness of auditory imagery (Allbutt, Ling, Heffernan, & Shafiullah, 2008). Nevertheless, there are similarities between the visual and auditory domains, for example, visual imagery can interfere or facilitate the discrimination of visual targets (Craver-Lemley & Reeves, 1992; Segal, 1971), and likewise, auditory imagery can also interfere or facilitate the discrimination of auditory targets (Hubbard & Stoeckig, 1988; Okada & Matsuoka, 1992).

Neuropsychological patient studies have also shown that damage to brain regions relating to perception confer parallel patterns of damage in mental imagery for both the visual (e.g. DeVreese, 1991, see Chapter 1 section 1.2.2) and auditory domains (Zatorre & Halpern, 1993). This suggests that imagery and perception share some common neural mechanisms across modalities. Neuroimaging studies have shown that while visual imagery corresponds to activity in the primary visual cortex (e.g. Brogaard & Gatzia, 2017; Kosslyn et al., 2001), auditory imagery corresponds to activity in the primary and secondary auditory cortex (Bunzeck, Wuestenberg, Lutz, Heinze, & Jancke, 2005; Oh, Kwon, Yang, & Jeong, 2013; Saenz & Langers, 2014). While the specific brain regions may differ, neuroimaging and lesion studies have shown that auditory imagery has a 'what' and 'where' pathway similar to the 'what/where' pathways described within the visual domain (Clarke et al., 2000; Warren et al., 2002). The auditory ventral pathway or 'what' pathway is involved with the processing of sound identity including voices or speech perception (Arnott et al., 2004; Hickok & Poeppel, 2004; Rauschecker & Tian, 2003; Zatorre et al., 2002), while the auditory dorsal pathway or 'where' pathway processes auditory spatial information (Arnott et al., 2004; Rauschecker, 1998; Rauschecker & Tian, 2003; Warren & Griffiths, 2003).

Auditory imagery also has preserved temporal (spatial) characteristics akin to visual imagery. For instance, in the visual domain, visually scanning objects that are further apart in terms of distance, or mentally rotating objects that require larger angular rotations, take participants longer to undertake (Kosslyn, 1973; Shepard & Metzler, 1971). The same has been shown within musical imagery studies whereby it takes longer to scan through an imagined melody that contains a longer series of beats (Halpern, 1988; Zatorre et al., 1996). Similarly, it takes participants longer to judge the loudness or pitch of two contrasting sounds within auditory imagery when large adjustments between the two sounds are required (Intons-Peterson, Russell, & Dressel, 1992; Intons-Peterson, 1980). These studies suggest that features of auditory images are extended in time akin to the way that visual images are extended in space (Halpern, 1988; Halpern & Zatorre, 1999).

Several studies have examined the relationship between spatial imagery (in the visual domain) and the temporal characteristics of auditory imagery. A positive correlation was found between mental rotation performance and a reversal melody task, involving the detection of melodies that were presented in reverse (Cupchik, Phillips, & Hill, 2001). The authors suggested that this demonstrated a relationship between the ability to manipulate both spatial imagery and also temporal auditory information. In a melody reversal task (i.e. a temporal auditory imagery task), fMRI showed activation of the intraparietal sulcus (Zatorre et al., 2010). This area is also activated during the mental rotation of visual stimuli (Zacks, 2008), with the activation of the intraparietal sulcus suggested to reflect spatial transformation processes of a sensory input (Zatorre et al., 2010).

Similar results were found in a study that involving the mental manipulation of language, namely the reversal of words, which was shown to engage similar mechanisms similar to those used for visuospatial mental rotation (Rudner, Rönnberg, & Hugdahl, 2005). Further evidence for shared mechanisms in the mental spatial manipulation of visual and audition information stem from studies of individuals with amusia. Individuals with amusia have spatial processing deficits, specifically, the inability to discriminate changes in pitch and perform worse on mental rotation tasks compared to neurotypical controls (Douglas & Bilkey, 2007; Tao, Huang, Li, Lu, 2015). From these results, Douglas and Bilkey (2007) suggested that pitch processing depends on the same cognitive mechanisms that are used for spatial processing. This finding remains controversial as other researchers failed to find deficits in spatial processing beyond the auditory domain (Tillmann et al., 2010; Williamson, Cocchini, & Stewart, 2011). However, subgroups of people with amusia have been identified that may explain for this variation in performance (Sun, Lu, Ho, & Thompson, 2017; Tao, Huang, Haponenko, & Sun, 2019; Williamson et al., 2011).

If visual and spatial are difficult to separate within behavioural tasks in the visual domain, it may be easier to explore these equivalents within the auditory domain. Moreover, performance in auditory imagery tasks has not yet been explored in aphantasia. This Chapter will explore auditory imagery performance of individuals with aphantasia through two different paradigms: a musical imagery pitch task (Experiment 9) and a categorical perceptual task, which examines voice identities for unfamiliar voices (Experiment 10). Both of these tasks concern the ability to generate voluntary auditory imagery. These tasks also involve the retrieval of information from long-term memory, such as, the retrieval of familiar song lyrics (Experiment 9) and novel voice representations, which are encoded into long-term memory during the training phase of the task (Experiment 10). Understanding how individuals with aphantasia, (specifically those that report a lack of auditory imagery) perform within auditory imagery tasks compared to individuals with typical imagery, will provide objective insights into the imagery capabilities of aphantasic individuals beyond the visual domain.

Experiment 9: Pitch discrimination in imagery and perception

6.1.1. Introduction

Musical imagery is a subset of auditory imagery, specifically referring to musical auditory experiences, for instance, the ability to hear music in the mind's ear (e.g. Bailes, 2007). Broadly, it is a multifaceted experience and can comprise of interactions of visual, auditory and motor domains (Bowes, 2009; Keller, 2012; Reybrouck, 2001), although it should be noted that the involvement and interaction of these domains are heavily dependent on task demands. Increased involvement of motor representations is particularly evident in individuals who have greater musical expertise. These individuals are suggested to generate anticipatory musical imagery in response to the mental planning of actions for upcoming musical notes (Bangert et al., 2006; Zatorre, Chen, & Penhune, 2007). However, activation of motor areas, such as the supplementary motor area (SMA), is also associated with the rehearsal and maintenance of auditory images within working memory (Halpern et al., 2004; Herholz, Halpern, & Zatorre, 2012; Zatorre et al.,1996). Thus, motor areas are activated irrespective of musical expertise. Typically, musical imagery studies have examined how similar imagery is to perception by asking participants to inspect and assess perceptual aspects of the musical image, such as pitch, timbre, tempo and loudness (e.g. Bishop, Bailes, & Dean, 2013; Halpern et al., 2004; Jakubowski, Farrugia, & Stewart, 2016; Janata & Paroo, 2006). However, there are conflicting arguments as to whether all perceptual features are represented within an auditory image, for example, the feature loudness, which is argued to rely more on motor imagery systems (Bishop, Bailes, & Dean, 2013; Intons-Peterson, 1980).

Many studies exploring the perceptual features of musical imagery (i.e. pitch, timbre, tempo and loudness) have examined these features within musicians who have substantial formal musical training (e.g. Bailes, 2007; Schörmann, Raij, Fujiki, & Hari, 2002; Zatorre et al., 2010). Alternatively, auditory features have also been examined within studies that compare behavioural performance or examined differences in brain activation between musicians and non-musicians (e.g. Aleman, Nieuwenstein, Böcker, & De Haan, 2000; Herholz, Lappe, Knief, & Pantev, 2008; Janata & Paroo, 2006). Features of auditory imagery, such as pitch and tempo are suggested to be more refined in musicians (Halpern, 1992; Janata & Paroo, 2006; Tervaniemi, Just, Koelsch, Widmann, & Schröger, 2005; Weir et al., 2015), with performance in short-term memory tasks that comprised of long variations of musical sequences, more biased towards those with musical backgrounds (Gelding et al., 2015).

Pitch is a perceptual attribute of sound, defined by the frequency of the sound waves and is present within all natural and artificial sounds including music and speech (e.g. Plack, Oxenham, & Fay, 2006; Yuskaitis, Parviz, Loui, Wan, & Pearl, 2015). In a musical context, melodies are produced by a combination of multiple pitches (Plack et al., 2006). The extent to which pitch processing is associated with visuospatial processing and shares common processing mechanisms remains unclear. Nevertheless, pitch is often described using spatial terms and is organised on a scale of low to high (e.g. Connell, Cai, & Holler, 2013), which gives rise to the concept of 'pitch height' along a vertical location within space (Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006). This is a concept adopted by both musicians and non-musicians (Lidji, Kolinsky, Lochy, & Morais, 2007). In a study by Mossbridge, Grabowecky and Suzuki (2011) the presentation of a high pitch sound was shown to modulate visuospatial attention, in that participants attended to a visual target within a corresponding higher spatial location. However, these results may reflect the associative feature between high pitch and spatial location rather than the idea that pitch shares common representations to spatial processes. Evidence from studies within amusia has proved inconclusive, with some studies suggesting a relationship between visuospatial processing and pitch processing (Douglas & Bilkey, 2007; Tao et al., 2015) and others finding no such association (Tillmann et al., 2010; Williamson et al., 2011). This suggests that pitch representation deficits are not necessarily comorbid with visuospatial deficits, and do not share common mechanisms. In contrast, a number of studies in neurotypical populations have suggested that there is a relationship between pitch processing, spatial positions and movements (Connell et al., 2013; Rusconi et al., 2006). Likewise, more broadly it is viewed that different sensory modalities do share common mechanisms for the processing of spatial information (Cupchik et al., 2001; Rudner et al., 2005; Zatorre et al., 2010).

Pitch is one auditory feature that has been well examined within musical imagery (e.g. Aleman et al., 2000; Gelding et al., 2015; Halpern, 1989; Janata & Paroo, 2006; Keller, Cowan, & Saults, 1995; Weir et al., 2015). It is also a feature that can be explored within individuals who have not had formal musical training (Gelding et al., 2015; Halpern, 1989; Keller et al., 1995). For instance, in perceptual pitch tasks, non-musicians have been shown to accurately discriminate between small variances in pitch on a range of different musical instruments (Tervaniemi et al., 2005). On the other hand, musicians tend to perform better than individuals who have had no musical training within imagery pitch discrimination tasks (Janata & Paroo, 2006). Nevertheless, individuals with no musical training have been shown to still perform well on such tasks (Aleman et al., 2000). Further, it has been argued that pitch is accurately represented within auditory images (Halpern, 1992; Halpern, 1989; Levitin, 1994). The accuracy of representations of pitch can be examined through temporal judgements. For instance, participants are presented with the beginning of a well-known song and using musical imagery, indicate when their auditory representation of a song has reached a certain point (Halpern & Zatorre, 1999; Herholz et al., 2008; Weir et al., 2015). Alternatively, the accuracy of pitch representations has been investigated through pitch discrimination paradigms that involve determining the highest pitch of two lyrics within a well-known song (Aleman et al., 2000; Halpern, 1989; Herholz et al., 2008; Zatorre & Halpern, 1993). Although both of these methods involve the short-term maintenance of familiar songs, participants are more accurate within tasks involving pitch discrimination compared to timing judgments (Weir et al., 2015).

At present, no study has examined the objective performance of individuals with aphantasia on imaging tasks within the auditory domain. Therefore, it is unclear how individuals with aphantasia would perform on a musical imagery task that requires the inspection of perceptual features of auditory representations. Halpern (1989) suggested that individuals have rich auditory representations for familiar music. Moreover, pitch is a perceptual auditory feature that can be accurately inspected by individuals who have had no formal musical training (Gelding et al., 2015; Halpern, 1989; Keller et al., 1995).

If individuals with aphantasia cannot generate such representations, in line with their self-reported lack of auditory imagery, then it is expected they would perform differently to individuals with typical imagery within a musical imagery pitch task. However, given that no differences in performance were found within the visual domain, despite aphantasic participants self-reported of a lack of visual imagery, it might be expected that no differences in performance would be expected. Whilst there might be deficits in auditory imagery, no deficits would be expected within a perceptual tone condition (a control task for the imagery condition) involving the pitch discrimination of tones.

6.1.2. Methods

6.1.2.1. Participants

Aphantasic (VVIQ ≤ 26) and control (VVIQ > 33) participants in this study were the same as described in Chapter 5, Experiment 7, section 5.1.2.1 and briefly summarised in Table 6.1. The ethics are also the same as described in this section.

	Participant group	
Demographics	Aphantasics (n = 30)	Controls (n = 30)
Male	10	10
Female	20	20
Mean Age	38y0m (SD = 10.98y)	39y1m (SD 10.27)
Mean VVIQ Score / 80	17.6 (SD = 2.88)	62.14 (SD 8.90)
Lowest VVIQ Score	16	41
Highest VVIQ Score	26	80

Table 6.1: Summary table of demographic information of the all aphantasic and control participants.

6.1.2.2. Materials and Piloting

Auditory Imagery Self-Reports: Bucknell Auditory Imagery Scale (BAIS)

The BAIS (Halpern, 2015) is an auditory imagery questionnaire that comprises two scales: a vividness (BAIS-V) and control (BAIS-C) auditory imagery subscale (see Appendix 5.5). See Chapter 5, Experiment 8, section 5.2.2.2 for more detail.

Goldsmiths Musical Sophistication Index (Gold-MSI): General Musical Sophistication Scale

The Goldsmiths Musical Sophistication Index (Gold-MSI, see Appendix 6.1) is a measure of musical ability, preferences and degree of sophistication of musical skill and behaviour (Müllensiefen, Gingras, Musil, & Stewart, 2014). The original Gold-MSI comprises of 5 stand-alone dimensions, each of which probe a specific aspect of musical behaviour such as perceptual ability, musical training, singing ability, musical engagement and emotion. The Gold-MSI also includes a sixth scale known as the General Musical Sophistication Scale, which encompasses all 5 of the dimensions. Questions included *"I can tell when people sing or play out of tune"* and *"I rarely listen to music as a main activity"*. The General Musical Sophistication Scale comprises of 18 questions, and individuals are asked to rate on a Likert scale of 1 (complete disagreement) to 7 (complete agreement) how much they agree or disagree with each statement. Scores of the questionnaires were copied into the Goldsmith's scoring template (see Appendix 6.2) whereby answers for certain questions are scored either positively (e.g. *"I enjoy writing about music, for example on blogs or forums"*) or negatively (*"I would not consider myself a musician"*) to provide an overall normalised score for each participant.

Musical imagery pitch task: creating and piloting

The task was adapted from the classic auditory imagery (Halpern 1988). In total, 49 popular songs were identified from a variety of sources: Plink “*Thin slices*” of music (Krumhansl & Zupnick, 2013), ‘NME Greatest Songs of All Time’ Spotify playlists: ‘classic songs, ‘well-known songs’, ‘famous songs’, ‘power ballads’, ‘NOW 100 Hits Power Ballads’, ‘iconic songs of all time’, ‘classic pop picks’ Film/TV/Disney ‘Disney’, ‘Greatest Disney’, ‘Pure Disney’, ‘Movie songs’, ‘Famous movie songs’ ‘Bond soundtrack, ‘Movie hits’, ‘Ultimate movie soundtracks’ ‘Christmas classic songs’, ‘Christmas songs’, ‘Nursery rhymes.’

Potential familiar songs were identified by four rules: the chorus should contain the main title of the song, the title of the song was to be sung in the same way (speed, tempo and pitch) in each chorus, the title of the song could not refer to another song (e.g. *“Ain’t No Mountain High Enough”* is a title of a song by two different artists, Marvin Gaye and Dianna Ross respectively), and songs must not be chosen if they comprised of one-word titles (e.g. *“Help”*- The Beatles). Songs were excluded if the song title was sung in one pitch (e.g. the chorus was sung in the same pitch with no differences in high and low pitch variations). A total of 49 songs were chosen. A Qualtrics survey was created and circulated on social media to determine how familiar songs were by individuals of different ages (see Appendix 6.3). The survey asked individuals (over the age of 18) to rate their familiarity for all 49 songs on a scale of 1-5 (1 = I do not know this song, 2 = I know of this song but I do not know it well, 3 = I can hum or sing only the chorus of this song, 4 = I can hum or sing the majority of this song and 5 = I can hum or sing this song from start to finish). In total, 248 responses were received from the Qualtrics survey, with 209 valid responses from individuals between the age of 18 and 75 (see Table 6.2).

Age range	Number of respondents
18-29	44
30-39	64
40-49	59
50-59	31
60-69	9
70-79	2

Table 6.2: Table to depict the breakdown of age group by respondents in the song familiarity survey.

The familiarity of a song (and therefore inclusion within the task) was determined if individuals had rated the song a minimum score of 3 (equating to *"I can hum or sing the chorus of this song only"*). Therefore, all songs that were rated as 3 (and above) across all ages were selected for the experiment (n = 20). Several songs were also chosen (n = 4) for the practice block. These songs were familiar to the majority of the age groups (e.g. familiar to all ages 20-50, however, were rated 2.6 and above by individuals in their 60s).

For the 20 songs, two alternative versions of high and low differentiation (known as target lyrics[15]) were chosen within each main title of the songs, which formed 40 experimental trials (see Appendix 6.4). Each version of the high-low differentiations of the song formed one block in the task (i.e. two blocks in total). The placing of high and low target lyrics was limited by the length of the song title. For instance, the longest song title *"It's Beginning to Look a Lot Like Christmas"*, comprised of 11 syllables, therefore 11 possible placings, in contrast to *"Hey Jude"*, which comprised of two syllables. Moreover, Halpern (1988) found a difference in response time; the further the two target lyrics were apart. Thus, target lyrics were either placed 0 syllables (n = 13), 1 syllable (n

[15] The term lyric within this Experiment is used to determine a word within the song title.

= 13) or 2 syllables (n = 14) apart. The first target lyric word appeared on the: first (n = 17), second (n = 8), third (n = 10), fourth (n = 2), seventh (n = 1), eight (n = 1) and tenth (n = 1).

Of the 40 trials, 21 trials presented had the second lyric higher than the first lyric (average semitone difference between the high and low pitch = 5.7), and in 19 trials the second lyric was lower than the first lyric (average semitone difference between the high and low pitch = 4.7). An independent t-test showed no significant difference ($t(38) = 1.40$, $p = .17$, $d = .44$) in semitone pitches between the two trial types. The songs for the practice task (n = 4) comprised three songs whereby the second lyric was higher than the first lyric, while in one song the second lyric was lower than the first lyric. Similarly, one song had a spacing of two syllables apart, one song a spacing of one syllable and two songs no syllables. The two target lyrics where the respective pitch was to be determined was underlined (see Figure 6.1 for an example of a trial). The title and artist of the song were also presented.

Is the second syllable higher or lower than the first?

I Wanna Dance With Somebody

Whitney Houston

Figure 6.1: Example of a trial in the lyric imagery condition where the second (underlined) syllable is lower in pitch than the first (underlined) syllable.

A matching perceptual tone condition was created with stimuli that matched the pitch of the target lyric semitones of the songs present in the lyric imagery condition. The tone stimuli (n = 40) were pure tones (sine waves) and recorded into Protools v2019.6 using a nocturn25 keyboard and Omisphere plugin. Each stimulus was presented in pairs for 750ms with a 500ms silent gap in between (these timings stayed consistent throughout). The perceptual condition comprised of two blocks (n = 20 trials in each block). Tones were presented via Sennheiser headphones (HD 25). In both the lyric imagery condition and the perceptual condition, responses were made by pressing 1 (marked 'High') and 2 ('Low') buttons on the number keypad of a QWERTY keyboard. Both tasks were programmed on E-prime version 3.

6.1.2.3. Procedure

General procedure for the testing session

The musical imagery pitch task was part of a wider battery of tasks over one testing session. At the beginning of the session, participants were verbally briefed on the rationale of the study and signed participation consent (see Appendix 6.5). The tasks within the testing session are denoted in Figure 5.1 (Chapter 5, Experiment 7) and were randomised (but the lyric imagery and perceptual conditions were run consecutively). Once a participant had completed all four tasks and questionnaires, participants were debriefed (see Appendix 6.6) and asked to sign a declaration that they had received their £20 Amazon voucher.

Procedure: musical imagery pitch task

The lyric imagery condition and the perceptual tone condition always appeared one after the other[16]; however, the order in which the tasks were run was counterbalanced. In the perceptual tone condition, participants were instructed to put on the headphones. They were told they would hear two tones one after the other and to determine whether the second tone was higher or lower in pitch than the first tone. Participants first undertook a short practice block comprising of four trials (these trials were the semitones of the practice trials in the lyric imagery condition). Following this, participants undertook the experimental perceptual tone condition. Once participants had finished the perceptual tone task, they were asked to remove their headphones, given the song familiarity list (on A4 paper) and asked to rate (with a pen) how familiar all 20 songs were on a scale of 1-5 (see Appendix 6.7). If participants rated any songs either as 1 or 2, the experimenter checked whether the participant knew the song. In many instances, participants said they knew the song. However, they were hesitant to the extent they were familiar, in which case, they were instructed to see how familiar[17] they were with the song when it was presented in the trial (often the presentation of the lyric during the task prompted the recall of the song). If participants were confident that they did not know the song, participants were instructed to skip the trial (by pressing 1 or 2).

Following the familiarity ratings for all 20 songs, participants were provided with instructions to the task, namely to determine if the pitch of the second syllable of a song was higher or lower than the first underlined lyric. Following the instructions, participants undertook the practice of the lyric imagery condition (4 trials). During the practice trials

[16] Participants were not informed that the two conditions were associated with one another
[17] If participants reported recall of the song, then the trial was included in the analysis and if they were still unfamiliar with the song, the trial was excluded from the analysis.

only, participants were verbally asked if they were familiar with the song presented in each practice trial (these songs were not presented on the song-familiarity sheet). Each practice trial was also presented with a short clip of a female singing the lyric of the song. The female voice sang the exact notes of the song as it appeared in the trial. For three of the practice trials, participants were presented with the female vocals. However, on the fourth practice trial, if participants were familiar with the presented song, participants were asked to respond in the absence of the vocal aid. Participants were asked if they understood the nature of the task, and if so, they could begin the experimental version of the task. The experimenter stayed in the room (hidden from view) with the participant to ensure they did not hum or sing the lyrics. Upon completion of the two blocks, the task was finished, and participants were briefed with regards to the following task.

6.1.3. Results

In instances when data is not normally distributed (e.g. Shapiro-Wilk < 0.05 for all variables), data is transformed where stated, or non-parametric test is used. When sphericity is violated, a Greenhouse-Geisser correction is used. All tests are 2-tailed.

6.1.3.1. Bucknell Auditory Imagery Scale (BAIS)

BAIS-V Score distribution

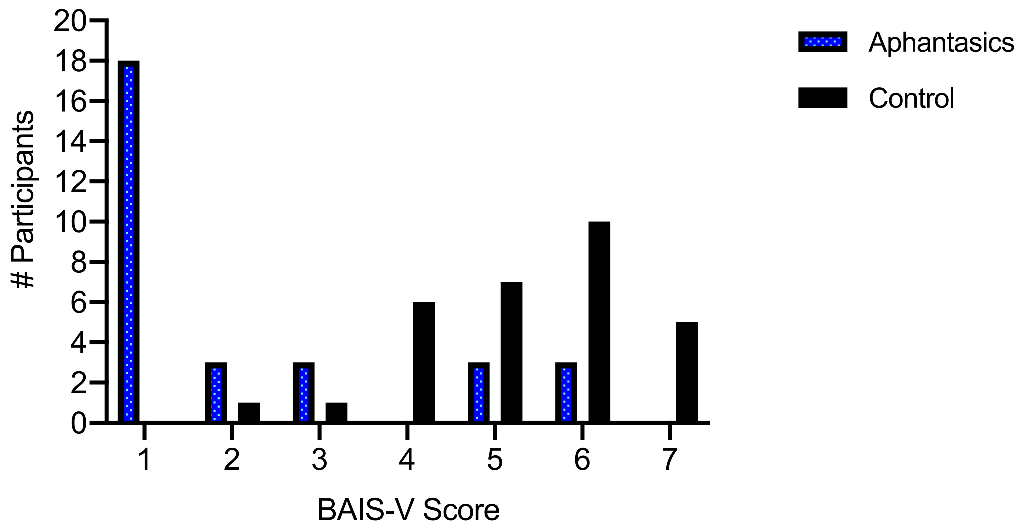


Figure 6.2: Frequency histogram to depict the mean responses on the BAIS-V by all participants.

Examining the frequency of responses on the BAIS-V (see Figure 6.2) revealed 9 aphantasic participants who scored high on BAIS-V (BAIS-V > 2, mean = 4.58, minimum = 2.14[18], maximum = 6.42, SD = 1.48) suggesting they had vivid auditory imagery experience. There were two control participants who scored (BAIS-V < 3, mean = 2.54, range: 2.43 - 2.64, SD = 0.15).

BAIS Analysis

To examine differences in the BAIS subscale between participant groups (see Figure 6.3), data was transformed using a Box-Cox transformation (Box & Cox, 1964, see Chapter 2, Experiment 2, section 2.2.3.4).

[18] The participant who scored 2.14 in the BAIS-V rated 6 questions as '3', 4 questions rated as '2' and 4 questions rated as '1'

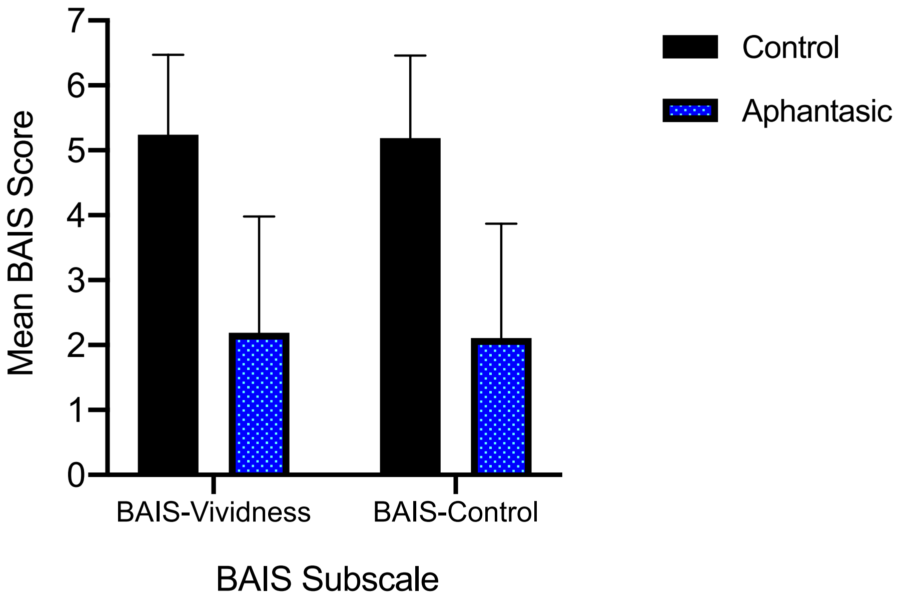


Figure 6.3: Bar chart to depict the mean and standard deviation (represented by error bars) of BAIS subscales scores provided by all aphantasic and control participants.

A two-way mixed measures ANOVA with Greenhouse-Geisser correction with factors group (aphantasic/ control) and subscale of the BAIS (vividness/ control) showed no significant main effect of subscale ($F(1, 58) = 2.48$, $p = .12$, $\eta p^2 = .04$). However, there was a significant main effect of participant group ($F(1, 58) = 65.52$, $p < .001$, $\eta p^2 = .53$), with controls rating significantly higher in both subscales than aphantasic participants. There was no significant interaction between participant group and subscale ($F(1, 58) = 0.40$, $p = .53$, $\eta p^2 = .007$) indicating that there were no evidence of a difference in relative responses on the two subscales between groups. These results suggest that the experience of auditory imagery is different between the two groups.

For the remaining experiments within this Chapter, performance will be examined for the aphantasic sample (n = 21) who score BAIS-V ≤ 2 compared to participants with typical imagery (n = 28) BAIS-V ≥ 3[19]

6.1.3.2. Goldsmiths Musical Sophistication Index (Gold-MSI): General Musical Sophistication Scale

Aphantasic participants scored a median of 41 (range: 8 – 94.5) on the Gold-MSI while controls scored a median of 74.5 (range: 45 - 149). A Mann-Whitney test showed a significant difference (Mann-Whitney U = 91.50, $p < .001$, $r = .58$), suggesting that control participants self-reported having significantly more sophisticated musical skill and abilities than aphantasic participants.

To explore whether the vividness of the auditory imagery was associated with a more sophisticated musical skill and ability, a Spearman's correlation revealed a significant strong positive correlation between the Gold-MSI and BAIS-V ($r_s = .70$, $p < .001$). There was also a significant strong positive correlation between the Gold-MSI and BAIS-C ($r_s = .68$, $p < .001$). This significance was driven by a correlation in the control group (BAIS-V: $r_s = .59$, $p = .002$; BAIS-C: $r_s = .55$, $p = .004$) but not the aphantasic group (BAIS-V: $r_s = .21$, $p = .37$; BAIS-C: $r_s = .11$, $p = .64$). This suggests that control participants who reported significantly higher auditory imagery vividness, and ability to control aspects of

[19] The remaining sample included: aphantasic participants (n = 21), 8 were male and 13 females, mean age: 39y09 (SD = 11.53), mean VVIQ score: 16.86 (minimum = 16, maximum = 24, SD = 2.36). Control participants (n = 28), 10 male and 18 females, mean age: 39y14 (SD = 10.61), mean VVIQ: 62.07 (minimum = 41, maximum = 80, SD = 9.20). An independent t-test ($t(47) = 0.14$, $p = .99$, $d = .001$) confirmed no significant difference in age between aphantasic and control participants. Three controls were hyperphantasic mean: 77.3 (SD = 2.52).

an auditory image were more likely to score higher in the Gold-MSI reflecting greater and more sophisticated musical skill and ability.

6.1.3.3. Musical imagery pitch task: Accuracy

Two control participants[20], one who self-reported as tone-deaf (his performance accuracy within the perceptual tone task was 50%) and another who showed profoundly impaired performance on the tone task (whose mean accuracy was: 0.72, compared to the mean accuracy of the remaining controls: 0.93, SD = 0.07) were additionally excluded from this analysis, resulting in 26 control participants. One additional aphantasic participant was excluded as she was unfamiliar with the majority of songs (14 out of 20 songs) within the task, resulting in 20 aphantasic participants within the subsequent analysis. These participants were also excluded from the analysis of the perceptual tone condition.

In the aphantasic sample, 52 songs in total were identified as unfamiliar, which resulted in the removal of 104 trials. In the control sample, 43 songs were identified as unfamiliar, which resulted in the removal of 86 trials. Accuracy in the two conditions was compared between aphantasic and control participants (see Figure 6.4).

[20] These participants were also excluded from Experiment 10.

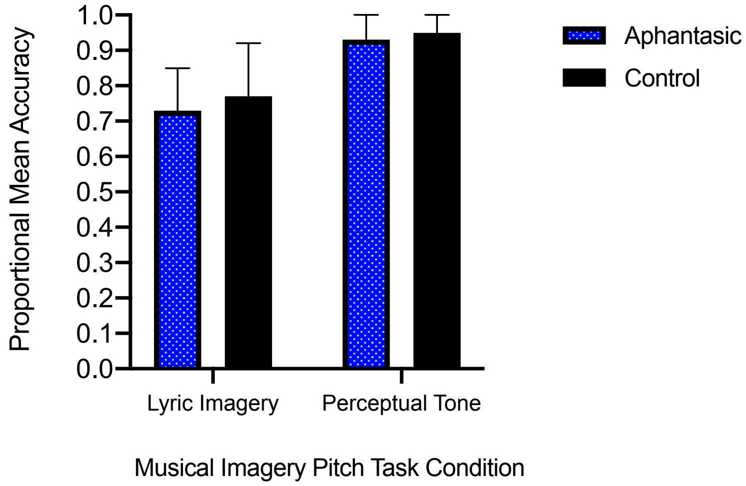


Figure 6.4: Bar chart to depict the proportional mean accuracy and standard deviation (represented by error bars) of aphantasic and control participants in the musical imagery pitch task.

A 2 x 2 mixed ANOVA with factors participant group (aphantasic/ control) and task (lyric imagery / perceptual tone) showed a significant main effect of task ($F(1, 44) = 101.51$ $p < .001$, $\eta p^2 = .70$), with both aphantasic and control participants performing more accurately in the perceptual tone condition compared to the lyric imagery condition. There was no significant main effect of participant group ($F(1, 44) = 0.37$, $p = .55$, $\eta p^2 = .008$) and no significant interaction ($F(1, 44) = 1.24$, $p = .27$, $\eta p^2 = .03$). These results suggest that aphantasic participants who self-report a lack of auditory imagery were as accurate as controls in the lyric imagery and perceptual tone conditions.

Effect of familiarity on accuracy

To examine if one participant group was more familiar with the songs than the other, familiarity ratings of songs were compared. Aphantasic participants scored lower for familiarity across all 20 songs with a median of 3 (range: 2.65 – 4.20) compared to controls who scored a median of 4 (range: 3.12 – 4.81). A Mann-Whitney test showed a significant difference (Mann-Whitney U = 76, $p < .001$, $r = .50$) in familiarity ratings of the songs within the musical imagery pitch task. This suggests that controls self-reported as more familiar with the songs in the task compared to aphantasic participants.

To examine whether the higher ratings for familiarity by control participants affected their accuracy within the musical imagery pitch task, the average familiarity and average accuracy for each song were calculated. A Spearman's rank-order correlation between the accuracy of responses for each song (within the lyric imagery condition) and familiarity scores for each song showed a weak non-significant correlation ($r_s = .27$, $p = .10$). This suggests that although control participants provided higher familiarity ratings for the songs, this did not equate to more accurate performance.

6.1.3.4. Musical imagery pitch task: Response Time

Response time in the two conditions was compared between aphantasic and control participants (see Figure 6.5).

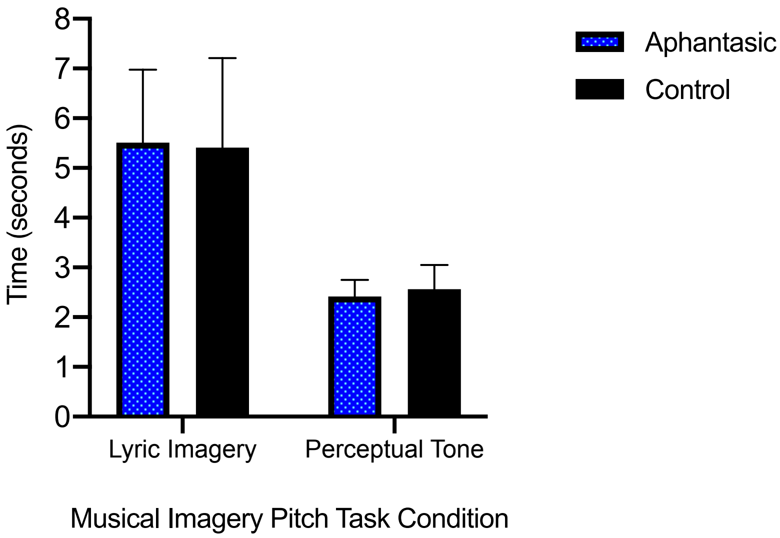


Figure 6.5: Bar chart to depict the mean response time in seconds and standard deviation (represented by error bars) of aphantasic and control participants in the musical imagery pitch task.

To examine response time differences between participant groups, a 2 x 2 mixed ANOVA with factors participant group (aphantasic/ control) and task (lyric imagery / perceptual tone) showed a significant main effect of task ($F(1, 44) = 166.36$, $p < .001$, $\eta p^2 = .79$), suggesting that participants were significantly quicker in the perceptual tone condition compared to the lyric imagery condition. There was no significant main effect of participants group ($F(1, 44) = 0.01$, $p = .95$, $\eta p^2 < .001$) and no significant interaction ($F(1, 44) = 0.25$, $p = .62$, $\eta p^2 = .01$). These results suggest that the response times of individuals with aphantasia are comparable to typical imagers on both the lyric imagery and perceptual tone condition.

6.1.4. Discussion

This experiment examined the performance of an age-matched sample of aphantasic and control participants with typical imagery on a musical imagery pitch paradigm. The results showed that individuals with aphantasia had significantly lower self-report scores on the BAIS auditory imagery questionnaire. Despite this self-reported difference in their conscious experience of auditory imagery, no significant differences in accuracy or response time were evident compared to typical imager controls. Moreover, aphantasic participants performed similarly to control participants with typical imagery despite controls rating significantly higher musical sophistication abilities. This higher musical sophistication was shown to correlate with the BAIS-V subscale. Control participants were also significantly more familiar with the songs in the task. However, this familiarity did not result in more accurate performance in the task. The lack of correlation between familiarity ratings and accuracy supports the notion that pitch is well represented within auditory images. Moreover, it suggests that one does not need to be overly familiar with a song to have a good understanding of the representation of pitch within a particular lyric.

In line with findings from visual self-reports and performance, there remains a discrepancy between self-reported auditory imagery experience and performance within an auditory imagery task. Within the current experiment, the majority of aphantasic participants self-reported an absence of auditory imagery on both subscales of the BAIS. However, there was a subset of aphantasic participants who self-reported vivid auditory image experiences. This is consistent with the findings from Experiment 8 (see also Dawes et al., 2020; Zeman et al., 2020) and suggests that impairments within the visual modality are not necessarily comorbid with impairment within all other sensory modalities. Conversely, differing experiences between visual and auditory modalities were evident within some individuals with typical imagery. Within the current experiment, two controls had high self-report scores for visual imagery; however, they had significantly lower scores when describing their auditory imagery experience. This may be because introspecting on one's imagery, especially in other senses, is more challenging (Schifferstein, 2009), or it may be a true reflection of their imagery ability within that modality. Further research should investigate these variations within aphantasic and typical imagery populations.

A tangential observation from aphantasic participants undertaking the BAIS was that there was a variation also in their experience or presence of an internal voice. Despite self-reporting a lack of auditory imagery, some aphantasic participants commented that they had an internal voice, while others reported their *"mind was silent"*. When completing the BAIS, several aphantasic participants self-reported a lack of auditory imagery, but reported the presence of an internal voice, and viewed (and used) this internal voice as auditory imagery to mimic the scenarios written within the BAIS. Inner speech is suggested to comprise auditory traits that are present in overt speech, such as pitch information (Vilhauer, 2016). Moreover, while it is viewed by some that inner speech is a subset of auditory imagery (Hubbard, 2010; Price, 2012), it has been argued they are separate processes (Alderson-Day & Fernyhough, 2015). Future research should establish the relationship between auditory imagery and the internal voice within aphantasic individuals who have and self-report an absence of auditory imagery.

Responses in both the BAIS and the lyric imagery task required the formation of auditory representations derived from long-term memory. However, the auditory task and BAIS questionnaire differed in that the BAIS asks questions relating to the vividness and control (a form of manipulation) of auditory scenarios. Vividness within the BAIS relates to the introspection and judgement of the clarity of a particular sound-scenario, with the majority of aphantasic participants providing self-reports in line with their vividness of visual imagery self-reports. On the other hand, the musical imagery pitch task arguably assesses the accuracy of the perceptual feature pitch within auditory representations. Pitch has suggested to be a temporal characteristic within auditory imagery (Connell et al., 2013; Intons-Peterson et al., 1992; Rusconi et al., 2006). Within the task, participants were asked to make a mental comparison to determine the pitch of certain lyrics of familiar songs. This does not necessarily examine the vividness of auditory experience; thus, this paradigm may be insensitive to the deficits present within aphantasia.

Moreover, the paradigm involved little manipulation. The lyrics acted as an anchor or hook for locating the respective notes within a song to be subsequently compared. This requires a greater reliance on top-down processes and involvement of motor regions associated with the retrieval of the song and its respective melody (Gelding, Thompson, & Johnson, 2019; Tervaniemi et al., 2005), from which a representation of the target notes are assessed. This is in contrast to the perceptual tone condition that relies more on bottom-up processes, involving the maintenance of novel tones within working memory.

In the lyric imagery condition, target lyrics were presented visually for each song and participants were asked to determine differences in pitch. Recall of auditory representations of each song from long term memory can be argued to also comprise associated features other than pitch, such as rhythm and language, i.e. imagery of the sung lyrics (Zatorre et al., 1996), although neither of these features would provide the necessary information about the pitch to respond in the task. Future studies examining perceptual aspects of musical imagery could include tasks that avoid the use of song lyrics. However, such tasks often involve the maintenance or manipulation of multiple tones (for instance, tasks that involve the metal reversal of melodies) and are often too complex for non-musicians to undertake (Zatorre et al., 2010; Zatorre, 2012).

Nevertheless, one such task that could be used in future investigations is the pitch imagery arrow task (PIAT), which has been made recently available as a validated task to explore pitch discrimination in both musical and non-musical populations (Gelding et al., 2020). This task has also shown to highly correlated with both the vividness and control subscales of the BAIS (Gelding et al., 2015). Tasks corresponding to the control subscale of the BAIS are suggested to be particularly challenging to examine within individuals who are non-musicians (Zatorre et al., 2010). Within the current experiment, individuals with aphantasia scored significantly lower on both subscales of the BAIS. Thus, it could be expected that aphantasic participants would exhibit different patterns of performance compared to individuals with typical imagery on a task such as the PIAT. Furthermore, other perceptual musical features not reliant on lyrics, such as timbre (Halpern et al.,

2004) could also be examined to get a better understanding of how aspects are represented within musical imagery, and the extent of the involvement of motor areas within musical imagery paradigms.

The purpose of the perceptual condition was solely to ensure that participants could discriminate between pitch, rather than investigate auditory working memory capabilities. Both aphantasic and typical imager control participants were more accurate within the perceptual condition compared to the lyric imagery condition. This finding has been found within previous studies examining other features of musical imagery (Jakubowski et al., 2016). Within the current experiment, two short novel tones were presented one after the other, separated by a silent interval. Unlike the lyric imagery condition, which required the retrieval of auditory information from long-term memory, the perceptual tone condition involved the short-term storage of auditory information. In terms of the multicomponent working memory, these non-verbal tones would be stored and rehearsed via an articulation-based process within the phonological loop (Baddeley, 2011; Baddeley & Logie, 1992). Specifically, the first tone would be rehearsed in working memory and subsequently compared to the pitch of the second note (Keller et al., 1995). Rehearsal of the note is easier given the lack of distractors in the interval between the two tones (Berti, Münzer, Schröger, & Pechmann, 2006).

If no differences in performance are apparent within a musical imagery pitch task that requires pitch discrimination in familiar songs, questions remain as to how individuals would perform within tasks that comprise of unfamiliar sounds. Pitch is an attribute not only present within music but also speech (Plack, Oxenham, & Fay, 2006; Yuskaitis, Parviz, Loui, Wan, & Pearl, 2015). Pitch information is also key to communicating word meaning (Tillmann, 2014). Another way to explore the accuracy of the generation of auditory representations within individuals with aphantasia is through a voice identification task. In this task, participants are trained to convert novel voice representations of unfamiliar speakers to long-term memory stores for subsequent retrieval within a voice identification paradigm. This will be explored within the following experiment.

Experiment 10: Categorical perception of voices in aphantasia

6.2.1 Introduction

Voices are incredibly complex in that they contain a variety of emotional, linguistic and non-linguistic information (e.g. see review Scott & McGettigan, 2015). The perception of speech or voice identity involves the processing of individual emotional, acoustic and phonetic cues at different stages of the auditory cortex (Pannese, Grandjean, & Frühholz, 2015). Vocal pronunciations of words vary largely due to individual differences in accent acquisition, as well as differences in the anatomy of vocal apparatus such as the size of vocal folds, shape of the palate and use of the vocal tract (Scott & McGettigan, 2015). Overall this variation in acoustic signatures enables listeners to recognise and discriminate between different speakers (Lavan, Burton, Scott, & McGettigan, 2019). Recognition identity of voices is enhanced if the individual is familiar with the voice (Lavan et al., 2019) or if a voice is in an individual's native language (Perrachione, Del Tufo, & Gabrieli, 2011; Perrachione, Pierrehumbert, & Wong, 2009). This is thought to be due to the familiar phonology and awareness of one's language, and this information is key during the phonological processing of speech required in voice identification (Lavan et al., 2019).

A crucial aspect of speech perception is the ability to sort the highly variable acoustic features or signals of speech into discrete phonetic categories, known as categorical perception (Liberman, Harris, Hoffman, & Griffith, 1957). In speech, for instance, a speech continuum between two vowels or phonemes, for instance, /b/ and /d/, can be synthesised so that one phoneme gradually transitions to sound like the second phoneme. Subsequently, upon hearing phonemes from within the continua, individuals perceive one phoneme (e.g. b) or the other phoneme (e.g. d) rather than something in-between (Mottonen & Watkins, 2009). Each phoneme, with its unique acoustic features, are sorted into discrete speech sounds defined by category boundaries (Mottonen & Watkins, 2009). Voice identity categorisation can be examined in a similar way by voice morphing the same vowel continua between two different speakers (Latinus & Belin, 2011). Voice morphing enables the synthesis of natural-sounding interpolates between the two different voices from which voice identity accuracy can be examined. When categorising the identity of two different voices on previously unheard speech, one must generate internal auditory representations of each speaker, and use these representations to compare to ambiguous voice syllables across the morphing continua. Performance is enhanced after a period of voice training of the specific voices within the task (Latinus & Belin, 2011). This suggests that through training, the listener has greater reliability in labelling the speakers, leading to a steeper categorical boundary in speaker identification. During training, these voice representations are converted to long-term memory for subsequent recall and compared against the ambiguous voice syllables during experimental trials.

Categorical perception paradigms are commonly used to examine auditory processing in individuals with developmental dyslexia. Individuals with dyslexia exhibit impairments in pitch processing (Lifshitz-Ben-Basat & Fostick, 2019) and show poorer categorical perception function due to a phonological awareness or coding deficit (Blomert & Mitterer, 2004; Melby-Lervåg, Lyster, & Hulme, 2012; Zoubrinetzky, Collet, Serniclaes, Nguyen-Morel, & Valdois, 2016). Within categorical perception tasks, individual with dyslexia display categorical perception slopes that are more shallow than controls (Kong & Edwards, 2016), suggesting a less precise ability to categorise phonemes around the categorisation boundary. Although auditory processing issues are not reported within aphantasia, voice identity categorisation involves the generation and synthesis of novel auditory voice representations, which are converted to long-term memory. These auditory voice representations – auditory images – are subsequently retrieved and compared to ambiguous voice syllables. If individuals with aphantasia are unable to synthesise accurate voice representations, it is expected that they would display more shallow categorical perception functions for speakers. This would suggest they are less precise at identifying the speaker during more ambiguous trials.

6.2.2. Methods

6.2.2.1. Participants

Both aphantasic (VVIQ ≤ 26) and control (VVIQ > 33) participants in this experiment were the same as described in Experiment 9 (see section 6.1.2.1). The ethics are also the same as described in this section. As well as age, aphantasic participants were matched to control participants in terms of the region of the UK[21] they attended Primary School (i.e. based in this location during the formative period of speech development ages 0-12

[21] Aspects of speech such as regional dialects can aid voice identification (Goggin, Thompson, Strube, & Simental, 1991; Lavan et al., 2019). The removal of 9 aphantasic and 4 control participants from the original sample impacted on the regional matching of participants. The full analysis for all participants matched by location (this includes all excluded participants) can be found in Appendix 6.11. The results of this analysis showed no significant difference between aphantasic and control participants.

years of age, see Table 6.3). All participants were unfamiliar with the voices used in the paradigm.

Region of the UK	Aphantasics (n= 21)	Controls (n = 26)
London	9	11
East of England	2	2
East Midlands	3	3
South East	2	2
North West	3	4
Yorkshire	0	1
West Midlands	0	1
South West	2	2

Table 6.3: Table to depict the number of participants matched per regions of the UK where they attended Primary School.

6.2.2.2. Materials

Voice discrimination task

Six male voices and seven female voices were recorded speaking 19 consonant-vowel syllables (/ba/, /ka/, /da/, /fa/, /ga/, /la/… /za/ etc.), repeated five times, each time in a randomised order (randomised in Excel, see Appendix 6.8). Each of the 13 speakers also recorded speaking 192 Bamford-Kowal-Bench (BKB) sentences (short 4-6 word sentences, such as *"the flower stands in a pot"*, *"the cat jumped off the fence"*, see Appendix 6.9). Voice recordings were undertaken in a sound-attenuated lab recorded onto GarageBand using Scarlet 2i2 with a NT1-A Rode microphone. Voices from all speakers were edited, creating multiple individual sound files for each speech syllable and BKB sentence, for each speaker.

To understand the relationship (differences and similarity) between all 13 recorded voices, three syllables (/ba/, /la/ and /va/) for each speaker (resulting in 39 sound files) were inserted into a PowerPoint slide in random order. Seven native English-speaking individuals who were unfamiliar with the voices were asked to group them in terms of how similar they were to each other (each person was sent the same starting PowerPoint slide with the voice files in the same order). For instance, voices that were similar could be grouped together, while voices that were different could be placed further apart. All seven responses were collated informing an overall diagram showing the relationship between voices, from which, subsequent morphing was based (Figure 6.6).

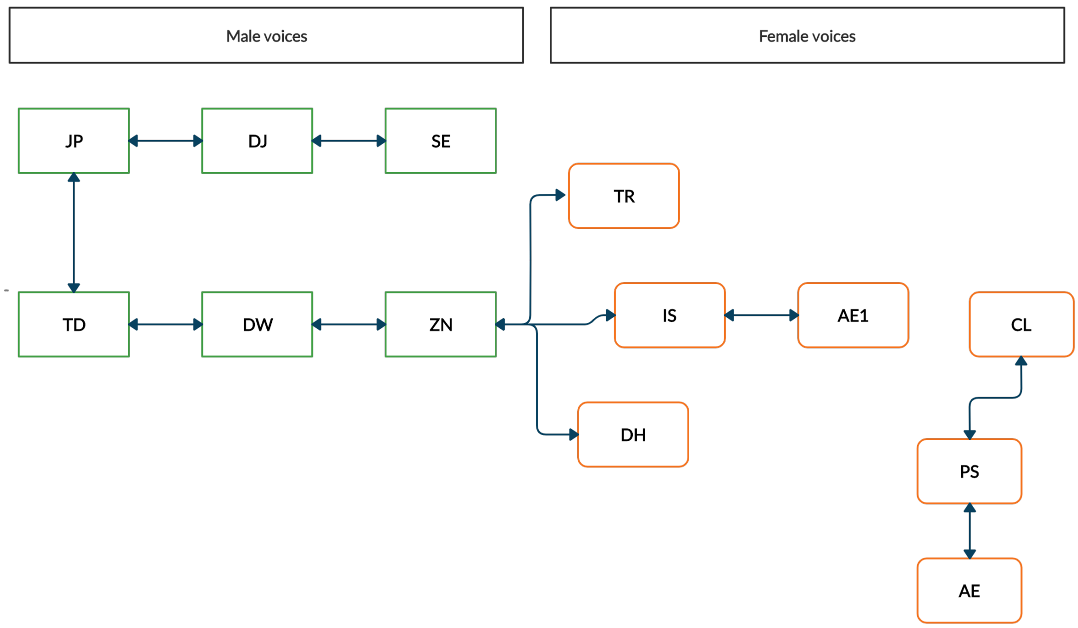


Figure 6.6: Overall diagrammatic association between voices (speakers' names are initialised) in the voice identification task. Piloting identified speakers that were most distinctive and speakers that were more similar (connected with arrows).

From the representational diagram of male and female voices, pairs of voices were chosen who were most acoustically dissimilar to each other (e.g. DH and AE) were paired. This resulted in four pairs of voices who were acoustically different from each (DH-AE, AE1-

PS, DJ-DW, TD-ZN). Six syllables (of the 19 recorded) for each pair were chosen that were similar in terms of phoneme pronunciation and duration. The pair of syllables were morphed using speech analysis, modification and synthesis system (STRAIGHT; Speech Transformation and Reproduction by Adaptive Interpolation of weighted spectrogram, Banno, Hata, Morise, Takahashi, Irino and Kawahara, 2006) in MATLAB 2017a (Mathworks, Inc., Natick, USA). STRAIGHT performs a pitch-adaptive manipulation, considering multiple parameters: f0, frequency, time, spectro-temporal density and aperiodicity across two different syllables stimuli and synthesised into a continua or single novel sound morph. For each syllable, morphs were created through a linear synthesis creating a continuum of 11 steps (i.e. 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100), with each endpoint of the continua (i.e. 0 and 100) pertaining to the original voice of each speaker. Three-to-four syllables were chosen from each male and female pair for the pilot (as underlined in Table 6.4).

Voice pairs	Syllables to be piloted	Gender of voice pairs
DH-AE	Ka, Ma,	Female
AE1-PS	La, Na,	
DJ-DW	Va, Ya	Male
TD-ZN	Ha, La	

Table 6.4: Table to show the voice pairings and syllables for the pilot. Syllables in underlined were chosen for the final experiment. Syllables for pair DJ-DW did not give rise to sharp categorical functions, so this pair of voices were removed.

Male and female voices were not paired on the basis their voices may be easier to distinguish based on differences in pitch. The volume of all syllables and BKB sentences across all speakers were RMS normalised on MATLAB to ensure they were the same volume. Voices were piloted on Gorilla, an online behavioural testing platform and sent to a different set of 15 English-speaking individuals who were unfamiliar with the voices within the task. During the pilot, individuals were asked to listen to 20 BKB sentence by each speaker (presented as 'Voice 1' and 'Voice 2') followed by a training phase of 40 BKB sentences (20 responses for Voice 1 and Voice 2) where response feedback was provided. This was followed by the experimental phase with all stages (1 to 11) of the phoneme continua presented in random order and repeated 8 times, resulting in 352 experimental trials. In the training and experimental phase, participants indicated *which* voice (either Voice 1 or Voice 2), the voice stimulus belonged to in a forced two-choice discrimination task. In the training phase, the feedback was provided to the participant (in the form of a smiley face for correct, or sad face for incorrect, see Appendix 6.10), and no feedback was provided in the experimental phase where the morphed continua were presented. The speaker assigned to Voice 1 and Voice 2 remained the same throughout the block and only changed when a new pair of speakers were presented (see Figure 6.7).

To determine the success and accuracy of the categorical perception of the phonemes, logistic curves were fit to each participant's data, as well as an overall logistic curve of overall performance. Results of the pilot showed that the morph of DJ-DW across all phoneme continua was not appropriate as the majority of participants interpreted both voices belonging to one speaker. Therefore, only three pairs of speakers: DH-AE (continua: /va/ and /ya/), AE1-PS (continua: /la/ and /na/) TD-ZN (continua: /ka/ and /ma/) were used for the real experiment. The task was programmed on the online behavioural platform Gorilla.

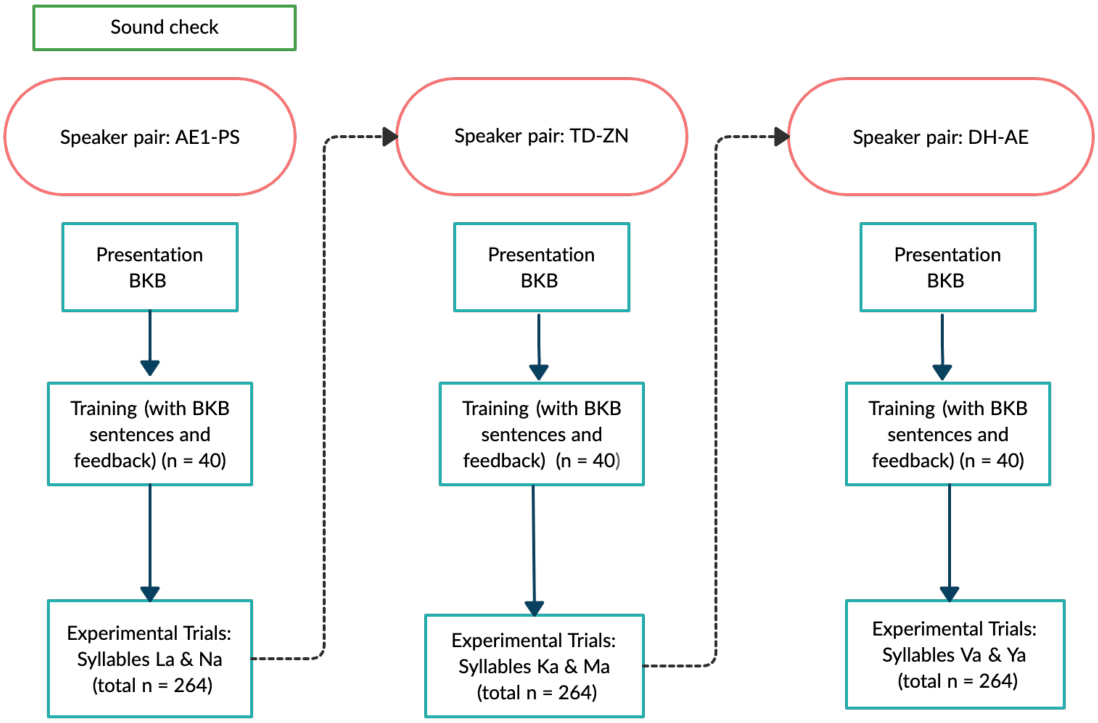


Figure 6.7: Diagram to show the structure and number of trials of the voice discrimination task.

6.2.2.3. Procedure

The task first began with a soundcheck to ensure the volume of the voices were satisfactory. Voices were presented via Sennheiser headphones (HD 25). To ensure appropriate volume levels, participants were presented (in the voice of DH) two words: ‘football’ and ‘post’ and participants were asked to type the words into a field provided. Volume was adjusted as necessary. Participants were told they would hear/be presented with the sound of three pairs of speakers, and for each pair would have to determine if it was voice 1 or voice 2 speaking. The pairs of speakers were presented one by one in a fixed order: AE1-PS, TD-ZN, DH-AE and this order did not change throughout the experiment to prevent confusion over female voices presented in close succession (see Figure 6.7).

For the first pair of voices AE1-PS, participants first undertook the presentation stage where they listened to 40 BKB sentences (20 BKB sentences for one speaker, followed by 20 BKB sentence for the other speaker). The BKB sentences were unique to one speaker (i.e. no same BKB sentence were repeated twice within a pair of speakers). Following the presentation stage, participants undertook the training phase comprising of a 40 BKB (20 BKB sentences for each speaker that were presented in a randomised order), for each sentence visual feedback was provided in the form of a smiley or unhappy face (see Appendix 6.10). The training phase was to ensure that participants could create robust auditory representations of the voices (participants who performed less than 90% during the training phase would be excluded from the task).

Following training, participants undertook all 264 trials of the experimental phase (i.e. two syllables of 11 stages of the continua repeated 12 times), feedback was not provided during these trials. Once participants completed the experimental trials, participants could take a brief pause before starting the next speaker pair (i.e. starting the presentation stage for TD-ZN). This order followed for the third speaker. The experiment was finished upon completion of the experimental trials of the last pair of speakers (DH-AE), see Figure 6.7.

6.2.3. Results

6.2.3.1. Training phase: Accuracy

Table 6.5 details the accuracy of aphantasic and control participants within the training phase of the task (40 trials per speaker pair). Both participant groups were highly accurate at identifying the two different speakers.

	% accuracy of identifying each speaker within the pair (SD)		
	AE-DH	**TD-ZN**	**AE1-PS**
Controls	99.73 (0.68)	99.43 (1.15)	99 (1.91)
Aphantasics	99.4 (1.90)	99.67 (0.76)	98.83 (2.07)

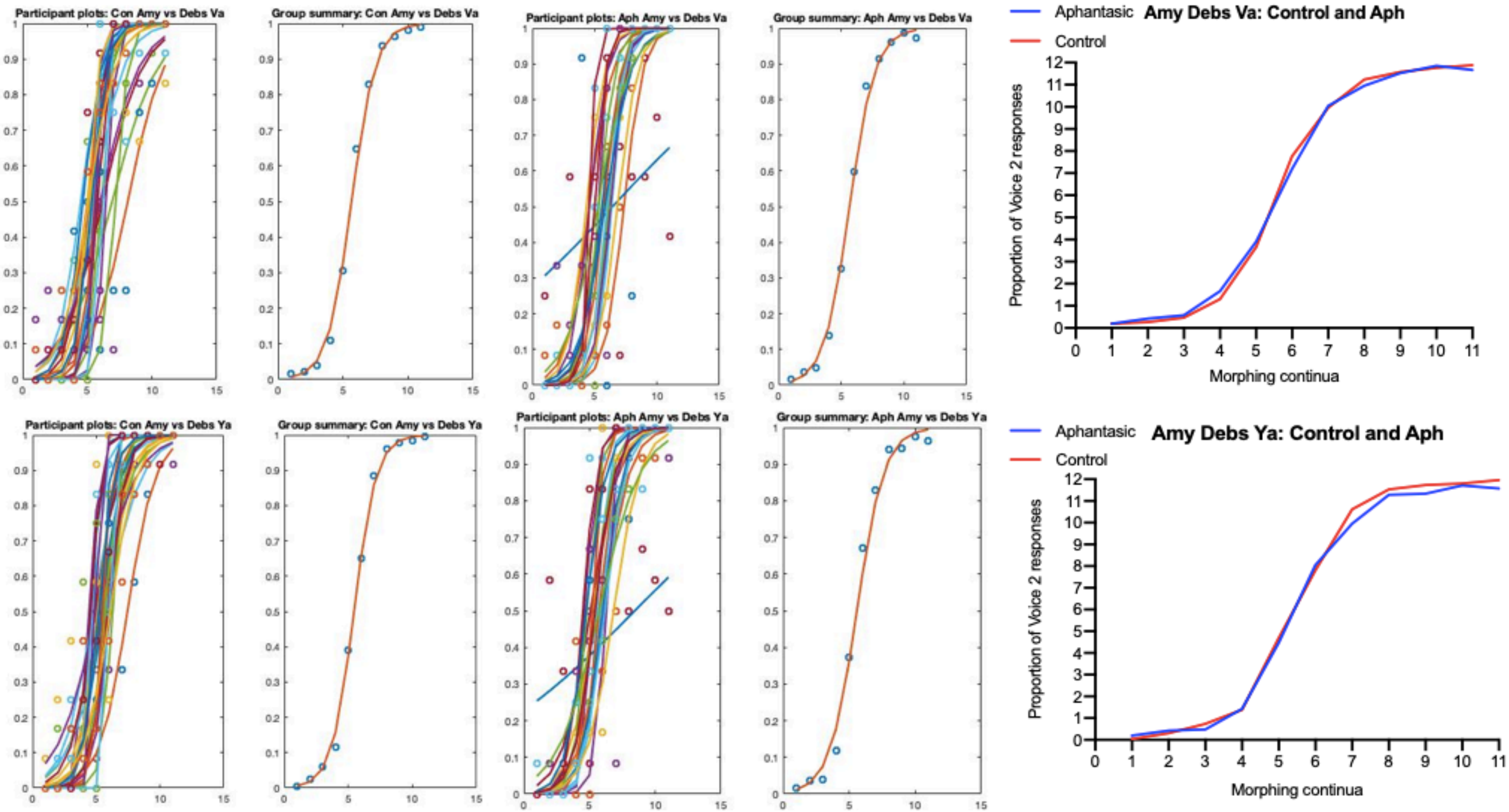
Table 6.5: Table to depict the percentage accuracy for identifying the correct speaker in each speaker pair during the training phase of the task.

6.2.3.2. Experimental phase: Accuracy

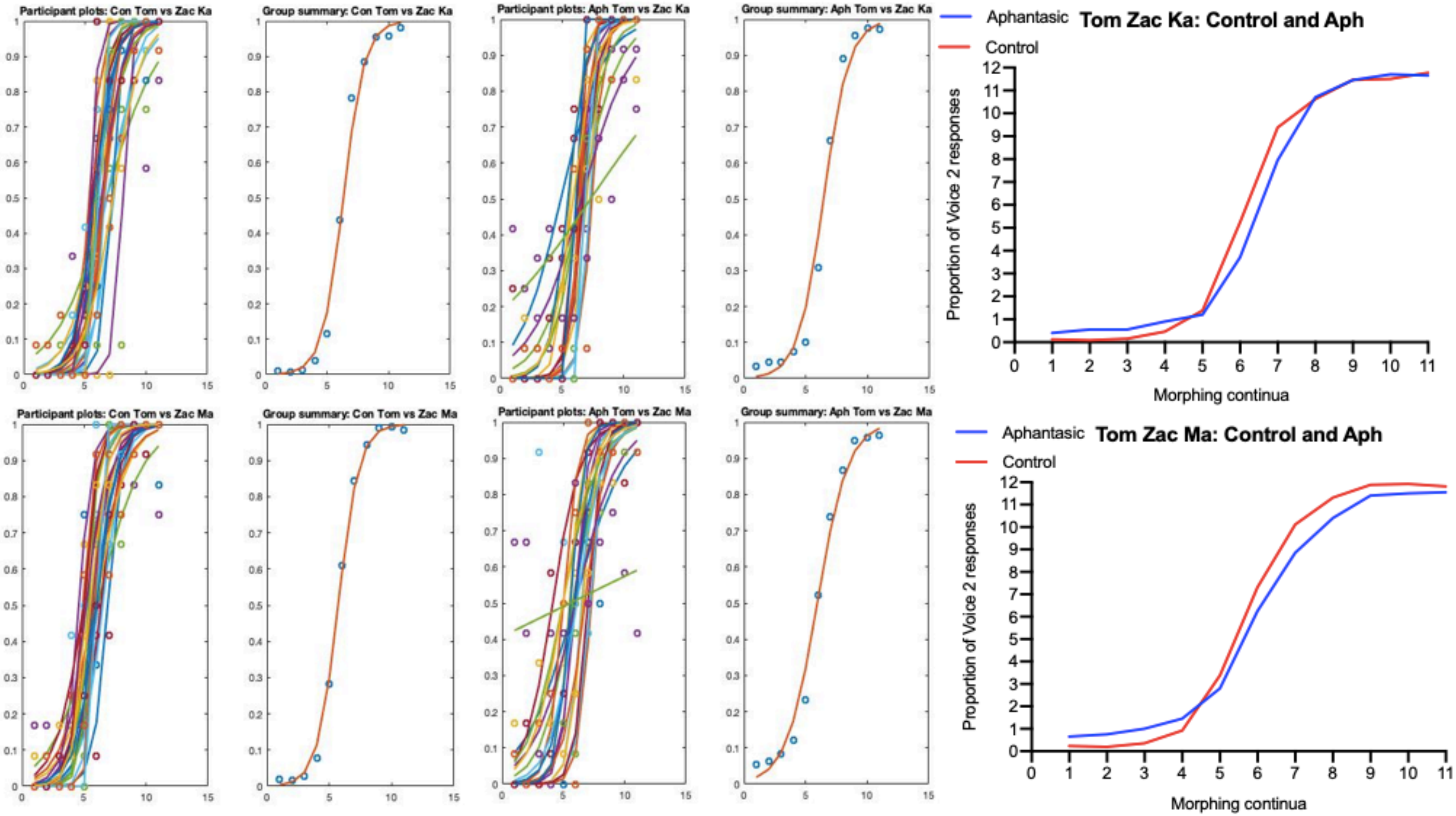
To estimate the categorical perception functions, logistic regression curves were fitted to each participant's data through the proportion of Voice 2 responses across the 11 step continua. These slopes positions showed the category boundaries for each set of speakers and syllable for each participant (see Figure 6.8). The logistic curves were fit to each participant on MATLAB (version 2017a) to obtain β values as an indication of slope gradient with the higher the slope gradient, the steeper the logistic curve and better specified internal representation of the speakers within the task. A group summary for each participant group for each syllable and speaker pair is shown in Figure 6.8.

Figure 6.8: Aphantasic and control categorical perception function, group summary functions and overall participant group comparison for each speaker pair and syllable: DH-AE (a), TD-TZ (b), AE1-PS (c)

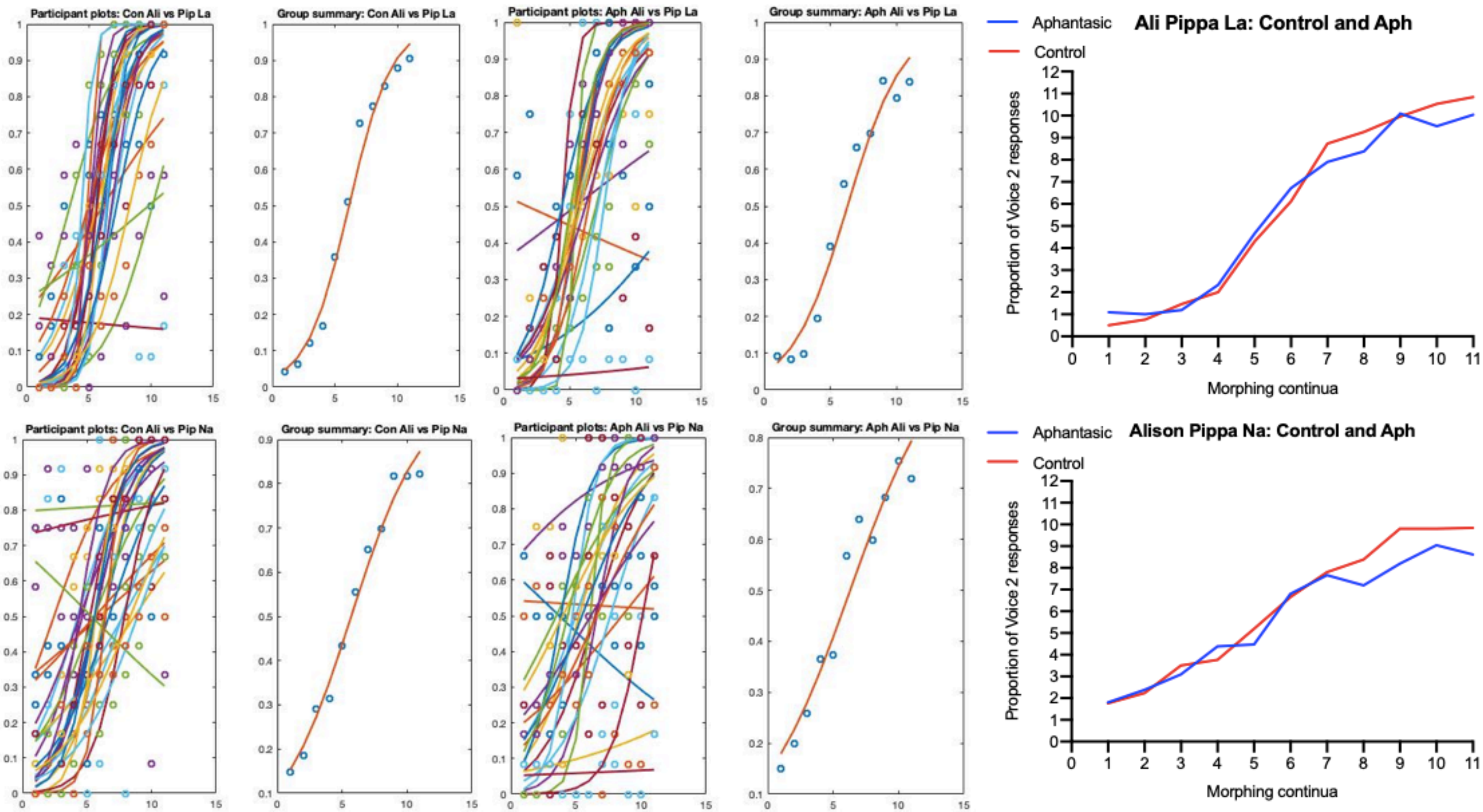
a) DH-AE /va/ and /ya/ – Aphantasic profile, control profile and overall logistic curves



b) TD-ZN: /ka/ and /ma/– Aphantasic profile, control profile and average logistic curves



c) AE1-PS: /la/ and /na/ - Aphantasic profile, control profile and average logistic curves



To compare categorical slope gradients between participants for each pair of speakers, syllables for each pair of speakers were combined, to create one β value for each speaker, averaging over speech sound. One aphantasic participant was removed from the analysis from speaker pair TD-ZN in the /ka/ and /ma/ continuum as the participant's responses indicated they had confused which speaker was which. No other participants were excluded in the analysis. An independent t-test of slope gradients across groups showed no significant difference in categorical perception function in speaker pair DH-AE ($t(45) = 0.76$, $p = .45$, $d = .21$), TD-ZN ($t(44) = 1.08$, $p = .29$, $d = .03$) or AE1-PS ($t(45) = 0.88$, $p = .38$, $d = .25$). Slope gradients were averaged across speakers to form a grand average of β-values for the two participant groups (Figure 6.9).

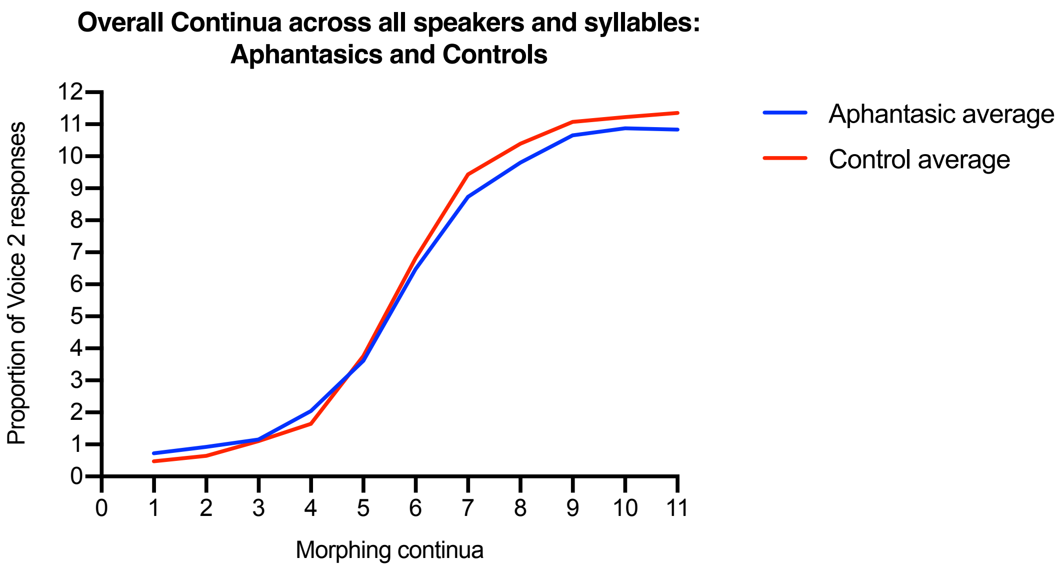


Figure 6.9: Grand average of categorical functions between aphantasic and control participants.

An independent t-test of slope gradients for aphantasic and control participants showed no significant difference ($t(45) = 1.22$, $p = .23$, $d = .37$) between groups.

The continua gradient slopes for AE1-PS (for syllables /la/ and /na/, see Figure 6.8c) suggest that these continua produced flatter and more noisy categorical function curves by each participant group. To ensure that the inclusion of these two continua did not impact on the results (i.e. there remains no significant difference between groups), an independent t-test of combined slope gradients for speakers DH-AE and TD-ZN showed no significant difference ($t(45) = 1$, p = .33, $d = .29$) between aphantasic and control participants. Together, these results suggest there is no difference between aphantasic and control participants in the ability to generate novel auditory representations of unfamiliar voices and accurately identify speakers during the presentation of ambiguous syllables.

6.2.4. Discussion

In this experiment, the ability to generate novel auditory representations of unfamiliar voices and use these representations to assign ambiguous tokens to speaker categories was examined. Specifically, the task probed the specificity of the stored representations of the speakers. The results showed that aphantasic and control participants assigned these ambiguous tokens to the speaker categories in a similar manner. The performance during training also confirmed that both aphantasic and control participants had a strong representation of the voices. Ultimately, this suggests that individuals with aphantasia have a similar stored abstract representation of voices compared to typical imagery controls, and can compare this 'image' in a similar way to individuals with typical imagery.

Pitch is an attribute present within speech (Plack, Oxenham, & Fay, 2006; Yuskaitis, Parviz, Loui, Wan, & Pearl, 2015), and combined with timbre cues aids to voice identity of a speaker (Latinus & Belin, 2012). For instance, the pitch of a voice is influenced by numerous factors such as the gender and age of the speaker (Klatl & Klati, 1990) and is crucial to communicating word meaning and emotional expressions (Tillmann, 2014). It is viewed that both speech and musical pitch processing share domain-general mechanisms, however, pitch processing is influenced by the type of auditory material that is presented, i.e. if it is musical or speech in nature (Vanden Bosch der Nederlanden, Hannon, & Snyder, 2015; Zatorre & Baum, 2012).

Pitch differences within music tend to comprise of fine-grained variations in pitch, compared to speech, which has large and more coarse variations in pitch (Ayotte, Peretz, & Hyde, 2002; Zatorre & Baum, 2012). Evidence to support the notion that speech and musical pitch processing share domain-general mechanisms stem from studies that show musical training enhances auditory processing for language and music (e.g. Nan et al., 2018; Yuskaitis, Parviz, Loui, Wan, & Pearl, 2015). Although the exact mechanism remains unclear, Yuskaitis et al. (2015) suggested that musical training enhances the neural encoding of speech. Although thought to share domain-general mechanisms, there is evidence to suggest that the two processes are also partially dissociable with music and speech comprising of domain-specific processes (Tillmann, 2014; Zatorre & Baum, 2012). For instance, individuals with congenital amusia who exhibit pitch processing deficits in music do not show such impairments in the processing of pitch within speech (Ayotte et al., 2002). However, impairments in speech are evident in congenital amusics when speech comprises of marginal fine-grained pitch distinctions, suggesting that amusia is not specific to music but a more broad psychoacoustic difficulty in fine-grained pitch resolution (Ayotte et al., 2002).

In the current experiment, although participants were not told to focus on the pitch of voices, this is an attribute that could have been used as a strategy to aid voice identification. This may have been easier given that speaker-pairs were chosen within the paradigm whose voices were most distinctive, therefore could be argued to have wider variations in pitch. Future studies could examine voice representations of speakers who have similar voices pitches. Although, if music is associated with more fine-grained variations in pitch (Ayotte et al., 2002; Zatorre & Baum, 2012), and no differences were apparent within a musical pitch discrimination task than no differences could perhaps be expected within a task comprising of voices of similar pitches.

The robustness of voice identity representations for each speaker could be investigated further using other forms of vocalisations or non-verbal vocalisations. Several studies have shown poor recognition and discrimination of voice identities that are whispered (e.g. Bartle & Dellwo, 2015; Yarmey, Yarmey, Yarmey, & Parliament, 2001). In this instance, whispered voices are more challenging to identify compared to natural speech, due to the reduction in acoustic frequency pitch (Lavan et al., 2019). However, performance within these studies in this condition did not fall below chance level (Bartle & Dellwo, 2015; Yarmey et al., 2001), suggesting sufficient acoustic information is retained in whispered voices to aid identification. Distortions in acoustic frequency pitch are also apparent in non-verbal vocalisations such as spontaneous laughter, making voice identity difficult (e.g. Bachorowski & Owren, 2001; Lavan, Scott, & McGettigan, 2016). Similarly, a study by Juslin and Lukka (2001) showed that emotional speech expressing emotions: anger, disgust, fear, happiness and sadness had different acoustic profiles for both verbal and non-verbal vocalisations (Banse & Scherer, 1996; Juslin & Laukka, 2001). An exploration of these speech-specific characteristics may show how robust voice auditory representations are within long-term memory and the ability to extract features and cues from a specific voice and apply to them to different vocalisation scenarios.

6.2.5. Chapter Conclusion

This Chapter explored aphantasics' performance within two auditory imagery tasks. The auditory domain was chosen on the basis that no objective imagery differences were found within visual imagery tasks. Moreover, deficits may be easier to detect or separate within auditory imagery tasks that require both perceptual and spatial imagery components. This Chapter explored auditory imagery performance of individuals with congenital aphantasia within a musical imagery pitch task (Experiment 9) and a voice identification task (Experiment 10). Both of these tasks concerned the ability to generate voluntary auditory imagery and retrieve information from long-term memory.

Despite self-reporting a lack of auditory imagery, the results of Experiment 9 suggest that individuals with aphantasia performed equivocally to controls in terms of accuracy and response time within a musical imagery pitch task. In individuals who self-report a lack of both visual and auditory imagery, it may be that motor areas are involved in the retrieval of familiar songs (Gelding et al., 2019; Tervaniemi et al., 2005). The retrieval of information does not occur in a purely auditory way, but through other forms of representation where information with regards to pitch can be assessed.

Musical imagery should be explored further using paradigms comprising of unfamiliar lyric-less stimuli (Gelding et al., 2020), which have been validated and shown to highly correlate to auditory self-report measures. Both aphantasic and control participants performed near ceiling in the perceptual tone task meaning they were able to distinguish differences in pitch perceptually. This Chapter also used a voice identity categorisation task to explore the specificity of synthesised and stored internal auditory representation of pairs of speakers (Experiment 10). The results of this experiment suggest that within a voice identity categorisation task requiring the synthesis of voice representations, individuals with aphantasia have a similar stored abstract representation of voices similar to individuals with typical imagery. In addition, aphantasic participants were able to compare this 'image' similarly to individuals with typical imagery. The robustness of these representations could be examined further in other forms using non-vocal vocalisations (Bachorowski & Owren, 2001; Lavan, Scott, & McGettigan, 2016).

What do these results contribute to the understanding of aphantasia? Pitch is one such spatial attribute of auditory imagery and a feature present within both experiments within this Chapter. If aphantasic participants self-report intact spatial imagery abilities in the visual domain (see Experiment 1, see also Dawes et al., 2020), these results may suggest that the equivalent is intact within the auditory domain. However, additional research is necessary to support this argument. Individuals with aphantasia (those who self-reported a lack of auditory imagery) performed as accurately as typical imagers in a task that required the mental comparison of pitches of well-known songs. A similar finding was evident within the voice identification task, whereby aphantasic participants were able to generate accurate voice representations of speakers and assign ambiguous tokens to speaker categories in a similar manner to individuals with typical imagery. Voices comprise of pitch information (Plack, Oxenham, & Fay, 2006; Yuskaitis, Parviz, Loui, Wan, & Pearl, 2015), and this may have been one spatial attribute participants represented in order to perform in the task. Accuracy within the task may have been easier, given the speaker-pairs within the study had distinctive voices. Ultimately, this pattern of performance whereby individuals with aphantasia who self-report a lack of imagery but consequently perform as well as individuals with typical imagery, is consistent with findings throughout this thesis from the visual domain. It may be the case that the tasks used within this thesis are not sensitive to the deficits that arise in aphantasia. Alternatively, this raises unanswered questions with regards to how individuals with aphantasia are undertaking imagery tasks. If they are not using spatial processes, it is possible that aphantasia may be explained due to difficulties in consciously accessing both visual and auditory imagery representations.

Chapter 7: General discussion

The overarching aim of this thesis was to examine possible explanations for the self-reported lack of visual imagery as described by individuals with aphantasia. Specifically, this thesis explored the nature and individual variation of the experience in visual and non-visual domains within matched samples. Explored across 10 experiments within the current thesis, the performance of individuals with aphantasia was compared to individuals who had a typical imagery experience. This performance was compared within a wide range of behavioural tasks and self-report measures. Despite self-reporting an absence of visual imagery experience, the findings of this thesis show minimal objective evidence of group difference in performance between aphantasic and control participants with typical imagery. However, variations in performance were apparent, and subgroups were identified within the aphantasic sample. This Chapter will first summarise the results and then discuss the reasons for this discrepancy between self-report and performance.

7.1. Summary of thesis findings

Experiment 1 and 2 interrogated the findings from the literature by including self-report measures and behavioural paradigms used within previous case studies and studies with small sample sizes. The objective of these experiments was to replicate some of these findings within larger participant samples. In Experiment 1, the subjective ratings provided in the Object Spatial Imagery Questionnaire (OSIQ, Blajenkova et al., 2006) showed individuals with aphantasia scored similar to typical imagery participants on spatial imagery, but lower for object imagery. These results replicated the finding of Keogh & Pearson (2017), and have since been replicated within several other studies (Bainbridge et al., 2020; Dawes et al., 2020). This suggests that it is a robust and consistent finding in self-reports within the aphantasia literature. Due to the fact that individuals with aphantasia scored lower for object imagery (i.e. imagery that is colourful and pictorial), this may provide an insight into the type of deficit present within aphantasia. Experiment 2 examined a finding observed by Jacobs et al. (2017), in which *AI* demonstrated impaired visuospatial working memory performance but not imagery performance. In Experiment 2, the results of the experimental design revealed contrasting performance to *AI*. The results showed that aphantasic participants were less accurate in the imagery condition, with no differences apparent in the visuospatial working memory condition.

Although the study was based on the paradigm used by Jacobs et al. (2017), there were some notable differences. Firstly, as a result of a technical error in data collection, control and experimental data was collected by two different researchers. However, no differences were found between experimenter. The second difference was that participants completed 3 blocks in this study, compared to 8 blocks in the original study. As a consequence, all participants had a shorter learning phase, which may have resulted in the differences in performance between the two tasks. With this reduced learning, aphantasic individuals were less accurate in the imagery task than the typical imagery controls. Nevertheless, individuals with aphantasia performed as well as control participants in the visuospatial condition of the task, which is in line with the performance of patient *MX* who also exhibited accurate performance within a visuospatial working memory task (Zeman et al., 2010).

Experiment 3 examined whether aphantasic individuals have a specific personality profile that may be linked to their self-reported inability to form visual imagery. It has been proposed that certain personality traits can modulate responses on self-reports (e.g. Buchanan, 2015). This is important to examine given that a self-report measure (i.e. the VVIQ) is commonly used to identify individuals with aphantasia within a population. However, the only difference in personality scales (the Big Five Inventory) between aphantasic and control participants with typical imagery, was for the trait agreeableness. This finding was explained due to a recruitment bias. In the control sample, there was a strong positive correlation between the trait openness to experience and VVIQ score. This finding was explained due to the link between openness to experience and synaesthesia (e.g. Banissy et al., 2013; Rouw & Scholte, 2016), which is an experience most frequently experienced by individuals with hyperphantasia (Zeman et al., 2020). Within the control sample, four participants were hyperphantasic, however, these participants were not asked if they had synaesthesia. Similarly, in the control sample, there was a strong positive correlation between the trait extraversion and VVIQ vividness ratings, consistent with the findings in the literature (e.g. McDougall & Pfeifer, 2012; Strelow & Davidson, 2002). Within the exploration of these correlations in a larger sample of typical imagers (Appendix 3.5), openness to experience was shown not to be a predictor for VVIQ scores and similarly, extraversion was only shown to be a smaller predictor for VVIQ scores. However, the trait conscientiousness was shown to have the strongest influence on VVIQ scores. This correlation is not evident within the literature relating to imagery vividness, but it is a trait associated with social desirability (e.g. Allbutt et al., 2008). Further research is required to explore the relationship between personality traits and self-reported imagery vividness.

Experiment 4 investigated whether the cognitive profiles of individuals with aphantasia differed to age-matched individuals with typical imagery. The battery of tasks, chosen due to their sensitivity to variances within broad cognitive domains and processes included: Pattern Recognition Memory (PRM), Verbal Recognition Memory (VRM), Spatial Span (SSP) and One Touch Stockings of Cambridge (OTS) task. It was proposed, that if differences in performance (compared to typical imagers) were evident within these tasks, it would suggest that aphantasia is associated with more global impairments in cognitive function. Overall, the findings showed no differences in accuracy across all tasks. However, differences in reaction time between aphantasic and control participants were apparent during trials in the OTS task, a complex visuospatial task that relies on executive function and imagery. Within the task, there were no differences in accuracy or reaction time during lower difficulty trials. However, aphantasic participants were slower during harder trials that required greater mental manipulation and high working memory load of visuospatial information, with no difference in accuracy. Taken together, Experiment 3 and 4 suggest that individuals with aphantasia do not differ from typical imagers on personality measures; nor do they display a shared global cognitive deficit shown through sensitive neuropsychological measures. However, subgroup variations of performance were evident, and multidimensional scaling revealed four aphantasic subgroups defined by varying patterns of performance in the neuropsychological tasks. This is a novel finding within the literature, and an assessment of individual differences of performance has not been examined.

As a result of the differences observed within the OTS, the performance was further examined within a wider variety of complex visuospatial working memory tasks. In both a mental rotation task (MRT) and a task that required spatial perspective taking, no differences were apparent in either accuracy or reaction time between aphantasic and control participants. However, aphantasic participants displayed greater variability in reaction time for front and back orientations compared to participants with typical participants. The result of multidimensional scaling, which grouped (in terms of similarity) aphantasic participants' performance across all behavioural tasks (in Experiments 4 to 6), revealed four potential subgroups: 1) a potential subgroup with spatial working memory difficulties 2) a subgroup who showed significant differences in reaction time in the OTS and possible verbal memory difficulties 3) a subgroup with borderline difficulties in the OTS but matched with high accuracy and 4) a subgroup with no difficulties in any of the tasks.

It is possible that the visuospatial working memory tasks could have been undertaken using spatial imagery alone (in the absence of a 'visual' component). Thus, it was investigated whether visual and spatial components could be separated and examined behaviourally. In an attempt to isolate 'visual' imagery, a task (Experiment 7) which required responses to statements with regards to visual (e.g. colour) and spatial (e.g. location and size) properties of common everyday objects was created. The results of Experiment 7 showed no difference in accuracy or reaction time between aphantasic and control participants with typical imagery for visual or spatial loaded statements. These results were interpreted that the task was not able to identify differences. Alternatively, as suggested by Kosslyn (2006), it may be impossible to isolate perceptual and spatial imagery within the visual modality. However, it may be possible within the auditory modality.

Experiment 8 examined how individuals with aphantasia self-reported imagery across non-visual senses compared to individuals with typical imagery. The findings of this Experiment suggested that whilst some aphantasic individuals self-reported an absence of imagery across non-visual sensory modalities (as well as the visual modality), this was not self-reported by all aphantasic participants. These findings were in line with the findings of recent studies (Dawes et al., 2020; Zeman et al., 2020) and further support the claim that aphantasia is heterogeneous. Specifically, individuals with aphantasia appear to share an absence of visual imagery but vary in experiences within the other sensory domains. While this has not been examined, it should also be noted that there may be a subset of individuals who experience an absence of non-visual imagery but not visual imagery. Current definitions of aphantasia do not reflect this heterogeneity of experience or mention the variations of these aphantasic experiences.

Based on the non-visual self-report observations, Experiment 9 and 10 investigated the self-reported absence of imagery objectively within auditory imagery tasks. Experiment 9 adapted the classic auditory imagery task developed by Halpern (1988), which required pitch discrimination for familiar songs and a matching perceptual pitch tone task. Although aphantasic participants self-reported a lack of auditory imagery, there were no differences in accuracy or reaction time in the imagery pitch discrimination task compared to individuals who reported vivid auditory imagery. Experiment 10 used a speech discrimination paradigm to explore how well individuals were able to generate internal voice representations and identify the voices of different speakers. Aphantasic participants were found to be as accurate as participants with typical imagery at distinguishing speakers in the task. Collectively, these results show that despite a self-reported lack of auditory imagery, individuals with aphantasia perform similar to individuals who have vivid imagery experiences. This thesis has raised questions with regards to the nature of imagery experience within aphantasia, and whether the difference in aphantasia is due to the differences in the conscious experience of imagery.

7.2. Discrepancy between subjective experience and behavioural performance

Consistently reported within self-report imagery measures throughout this thesis, individuals with aphantasia rate their experience of imagery as largely absent. However, within tasks that objectively explore this self-reported absence, individuals with aphantasia perform as accurately as individuals with a vivid imagery experience. Outlined are possible explanations for these discrepancies.

7.2.1. The use of different processes

The use of alternative 'strategies' or processes may be one way to explain the discrepancy between self-reports and behavioural performance by aphantasic participants. In this context, these 'strategies' are best termed as 'processes,' with the term 'strategy' implying a conscious choice, when in fact some processes are undertaken outside of conscious awareness (e.g. individuals with typical imagery do not actively 'choose' to use visual information, they unconsciously just do). For individuals with typical imagery, imagery is visuospatial in nature (e.g. Kosslyn et al., 2006). However, a number of studies have shown that tasks can be undertaken without visual experience, suggesting tasks rely more heavily on 'spatial' than 'visual' imagery. It is possible that individuals with aphantasia lack the 'visual' component of imagery, but they are still able to use spatial imagery. These adopted processes are not as effective within cognitively demanding tasks whereby large amounts of visuospatial information are required to be maintained and manipulated. If all aphantasic participants are using an alternative process (i.e. not engaging in visual imagery, but using spatial imagery alone), the use of such a strategy generally provides adequate or good performance within tasks, which may explain why throughout this thesis, no differences in performance are apparent between the two participant groups.

However, these strategies are less efficient within cognitively demanding trials, as shown by Experiment 4, specifically during the OTS task.

Historically, support for depictive theories stemmed from behavioural performance within imagery tasks, such as tasks requiring the mental visualisation of anatomical features of two animals (Kosslyn, 1975), as well as mental scanning between two points on a map (Kosslyn, 1973) and mental rotation (Shepard & Metzler, 1971). The idea that visual images retain spatial information with a linear relationship between time and distance apparent in the tasks were key to the idea that visual images were depictive. In the current thesis, aphantasic participants undertook a mental rotation task, and a linear relationship was evident between the angle of rotation and reaction time. No differences in accuracy were evident between aphantasic and control participants with typical imagery, and aphantasic participants performing highly accurately within the task. According to Kosslyn (1975), this linear relationship may suggest that individuals with aphantasia (who self-report a lack of visual imagery), are using spatial imagery in the task.

Despite a difference shown through self-reports, differentiating the differences between visual and spatial remains challenging (and potentially impossible) behaviourally (as attempted within Experiment 7) within the visual domain. This is in line with Kosslyn's theory of mental imagery that suggested visual and spatial images have a spatio-analogical structure (Kosslyn et al., 2006). Kosslyn's theory of mental imagery made a distinction between the content of visual and spatial images but suggested that the two were processed in parallel (Kosslyn, 1994; Kosslyn et al., 2006; Kosslyn, 2005). According to the theory, the 'visualised' part of a visual image referred to the content of the visual buffer, with the construction of a visual image (e.g. an object) also requiring information about its spatial properties (e.g. location), from the content of spatial images (Kosslyn, 2006). If the processing of spatial and visual images occurs in parallel, then this may imply that the two constructs are difficult to separate. Similarly, Chapter 6 explored whether perceptual and spatial imagery could be explored and isolated further in the auditory domain, with the results showing no differences in performance between aphantasic and typical imagery participants. This too may imply that it is difficult to separate sensory and spatial elements experimentally.

While the findings of Experiment 7 suggest that it is difficult to differentiate between visual and spatial imagery using imagery comparison statements, the paradigm outlined in the study by Bainbridge et al., (2020) suggests that drawing may be one sensitive tool to distinguish such differences. In this study, the authors showed visual and spatial differences in memory drawings of individuals with aphantasia. Briefly, the memory drawings of real-world scenes drawn by aphantasic participants contained fewer visual details (such as the use of colour) compared to typical imagers, however, these drawings were spatially accurate (i.e. objects were drawn in the correct location and were of the appropriate size). While aphantasic participants drew fewer objects than typical imager participants, they still drew a moderate number of objects (i.e. five objects per image) suggesting a preserved use of other non-visual representations such as verbal (e.g. use of verbal lists) and spatial memory to aid reconstruction of a scene (Bainbridge et al., 2020). This suggests that non-visual processes adopted are conducive to a certain level of performance. Although a task involving a different set of requirements, this performance is similar to the performance exhibited by aphantasic participants up to move 4 in the OTS task. In the OTS (up to move 4) aphantasics participants perform the same as typical imagers, with differences in performance only apparent with increased amount of visuospatial information that is required to be manipulated. Further research should try to explore and assess ways (possibly through drawing) to increase the amount of 'visual' information or detail presented that surpasses the amount that can be supported by non-visual representations or processes.

One way to gain an insight into participants' processes within a task is by asking them with regards to their strategies. For instance, additional qualitative data[22] could have been collected with regards to how participants approached different spatial and visual statements (within Experiment 7). However, as previously mentioned, this involves a level of conscious introspection, and it is not clear how accurate people are in the report of what they say they did, and such processes may be unconscious. In a similar way that it has been proposed that there are numerous ways to perform visuospatial working memory tasks (Keogh & Pearson, 2019), the same could be said for imagery tasks, in that they can be undertaken with different processes. In a recent study by Milton et al. (*submitted*), the authors compared the performance of hyperphantasic, control (with mid-range VVIQ scores) and aphantasic participants. The authors found a significant difference in accuracy between hyperphantasic (who performed at 88% accuracy) and aphantasic participants (who performed at 82% accuracy) in an Animal Tails Test, a 'standard imagery task'. On this task, patient *MX* scored at 90% accuracy - higher than the hyperphantasic participants in this sample denoted in Milton et al. (*submitted*). No indication of reaction times was provided. While patient *MX* may have been advantaged

[22] Informal verbal discussion (once participants had undertaken the visual-spatial statement task, Experiment 7) involved asking participants with regards to their experience of answering the statements (i.e. participants were asked: 'how they found the task', 'what was difficult'). Aphantasic participants generally commented that the visual questions were more challenging to answer compared to the spatial statements.

in the task due to the acquired nature of his aphantasia in later life, these findings suggest that imagery tasks are not pure measures of 'visual' imagery. Evidence from the congenitally blind literature suggests that tasks such as mental rotation can be undertaking using spatial imagery alone (e.g. Carpenter & Eisenberg, 1978; Kerr 1983). Thus, tasks of visual imagery may not reflect or be a measure of pure 'visual' imagery ability and should be used with caution if one is seeking to gauge participants' 'visual' imagery abilities.

7.2.1.1. Effect of working memory load

Differences between aphantasic and control participants within this thesis only arose in the OTS – a task that involved high levels of manipulation and working memory load. Briefly, the OTS is based on the Tower of Hanoi and presented increasingly difficult trials (in random order). The task required participants to rearrange ball-configurations from a minimum number of two items or 'moves' to a maximum of six in one's mind. In low load working memory trials, which required the move of no more than four balls (Fukuda, Awh, & Vogel, 2010), there were no differences in performance between aphantasic and control participants with typical imagery. This suggests that the processes the aphantasic participants adopted were conducive to a certain level. However, with increasing manipulation and working memory load, significant differences in reaction time were evident between the two groups. For individuals with typical imagery, visual imagery may serve as the most suitable mnemonic for the maintenance of large amounts of visuospatial information. However, it remains unclear as to the processes involved for aphantasic participants given their self-reported lack of visual imagery experience.

A number of studies have observed variation in the activity in the ventral and dorsal prefrontal cortex within different working memory-loaded working memory tasks (de Fockert, Rees, Frith, & Lavie, 2001; Rypma & D'Esposito, 1999). Activation of the prefrontal cortex is also evident within tasks such as the Tower of Hanoi and the OTS, reflecting the use of higher executive function within the task (Causse, Chua, & Rémy, 2019; Milla, Bakhshipour, Bodt, & Getchell, 2019). In particular, the dorsolateral prefrontal regions are associated with the maintenance and manipulation of external visuospatial information, while the rostrolateral prefrontal cortex involved in the manipulation of internally generated information (Christoff & Gabrieli, 2000; Wagner, Koch, Reichenbach, Sauer, & Schlösser, 2006). Activation of the rostrolateral prefrontal cortex was particularly evident in the higher difficulty moves (greater than move 4) compared to lower moves. Examining aphantasics' performance at a neural level within the OTS during the difficult trials may provide new insights into the differences in processes between participant groups. Comparing brain activations between aphantasic participants who exhibited significantly longer reaction times during cognitively demanding trials compared to aphantasic participants who performed similar to participants with typical imagery, could provide further insight into potential variabilities within the aphantasic experience. Further research should investigate the effects and manipulation of working memory load not only the visual but within other sensory domains to test the robust nature of internal representations.

In terms of the relationship between the visual buffer and visual cache, it has been suggested that in scenarios where highly detailed visual details are required to be maintained, it may involve the repeat generation of the image within the visual buffer, rather than maintenance of visual information in the visual cache (Darling et al., 2009;

Kosslyn & Thompson, 2003). Individuals with typical imagery may be able to use the visual cache and the visual buffer to refresh the contents, which may be true for the cognitively demanding trials of the OTS that have been suggested to engage imagery (Hodgson et al., 2000). Individuals with aphantasia cannot access the contents of the visual buffer, which may be refreshing the contents. This may especially be the case for the subgroup of participants who displayed significantly longer reaction times in the OTS task. On the other hand, the subgroup who showed no differences in performance (i.e. performance that was similar to participants with typical imagery) might have unconscious imagery. This subgroup may be able to use the visual buffer to regenerate the complex configurations (Darling et al., 2009) required with the OTS task (similar to individuals with typical imagery), despite this re-generation process occurring outside of conscious awareness. Overall, much more research is required to examine the similarities and differences between visuospatial working memory and visual imagery.

7.2.2. Imagery vividness and consciousness

The discrepancy between aphantasic self-reports and experimental measures may be explained by the fact that visual imagery vividness ratings are a limited measure of actual visual imagery ability. Vividness is characterised by the clarity and liveliness of the conscious experience of imagery (Dean & Morris, 2003; Marks, 2019). It is a process involving introspection and judgment of the visual quality of an internal representation - the actual amount of content or detail within the representation are less important. Vividness is arguably only one aspect of a visual image and does not take into consideration other aspects of a visual image that are essential to task performance. For example, the content of the visual image, visual and spatial imagery sub-types (Kozhevnikov et al., 2005) or sub-processes such as imagery maintenance or transformation (Kosslyn et al., 2006).

Numerous studies have sought to examine vividness within behavioural tasks. However, there are differences in how this is measured and defined. For instance, self-report measures such as the VVIQ or behavioural trial-by-trial ratings of vividness (i.e. vividness ratings required after each experimental trial) have been adopted within studies. It is thought that trial-by-trial ratings of vividness are more informative with regards to the ability to generate visual image within a specific context (Bergmann et al., 2016; D'Angiulli et al., 2013; Keogh & Pearson, 2011). Thus trial-by-trial ratings of vividness are suggested by some to be more reliable (D'Angiulli et al., 2013), unlike the VVIQ, which relies on the retrieval of familiar images from long-term memory. However, both trial-by-trial vividness ratings and VVIQ scores were found to predict the priming effect within a binocular rivalry paradigm (Pearson et al., 2011). The authors suggested that individuals with typical imagery have a good metacognitive understanding with regards to their imagery vividness using either method (Pearson et al., 2011), and metacognitive awareness of visual imagery can be improved with practice (Rademaker & Pearson, 2012).

Vividness is suggested to be a measure or correlate relating to the conscious experience of imagery (Runge, Cheung, & D'Angiulli, 2017). The phenomenological or conscious aspect of imagery remains understudied, however, Marks (2019; 1999) describes mental imagery as the *"basic building block of all consciousness, which plays a primary role in mental rehearsal of adaptive, goal-directed action through experimental manipulation of perceptual-motor imagery".* This viewpoint echoes non-representational theories of visual imagery that surround the concept that visual imagery depends on action (the activity of carrying out an action, see Chapter 1 section 1.1.3), and stems from the re-enactment of visual perception (e.g. Varela et al., 1991). At present, the idea of consciousness (or account for phenomenological vividness, a correlate of consciousness as suggested by Runge et al., 2017) is not explicitly mentioned within theories of visual imagery. Kosslyn's Computational Model (Kosslyn, 1981; Kosslyn, 2005) described an attentional window that allows for conscious inspection of an image or part of an image. However, this does not account for the individual differences in imagery vividness. Nevertheless, it has been suggested that vividness refers to the resolution of the visual buffer (Dean & Morris, 2003), but this is not explicitly stated. Plyshysn (2003) also does not mention consciousness but describes vividness in terms of tactic knowledge 'details' as either 'blurry' or 'clear'. This suggests that experience can differ in terms of vividness.

Similarly, conscious awareness is implied in non-representational theories of imagery. For instance, the enactive approach implies that a level of conscious awareness is needed for the re-enactment of visual perception (e.g. Varela et al., 1991). While the sensorimotor approach is described as a conscious set of rules (e.g. O'Regan & Noe, 2001) and it is not clear how such rules are accessed to support visual imagery (Di Paolo et al., 2017). The embodied representational approach also involves the act of seeing an item (Palmiero et al., 2019). This approach implies a level of consciousness and considers the variations of individual differences in imagery experience (Palmiero et al., 2019; see also Chapter 1, section 1.1.3). At present, definitions of mental imagery do not necessarily state that imagery is a conscious experience. In fact, the consciousness of internal representations seems to be an assumption among definitions; for instance, imagery is sometimes referred to as a process involving 'effortful generation'. However, it may be the case that such definitions of imagery need to be refined more so in terms of conscious and unconscious attributes.

In the literature, one way to explore the consciousness of imagery experience is through the inclusion of confidence ratings (Cheesman & Merikle, 1986). Individuals who self-reported vivid imagery provided more confident responses in relation to their imagery ability (Keogh & Pearson, 2011). This supports the idea that vividness is a characteristic of conscious experience (Runge et al., 2017). Within the current thesis, differences were evident between aphantasic and control participants with typical imagery in terms of their confidence in a visuospatial working memory and imagery paradigm (Experiment 2), contrasting with the results obtained in the case study by Jacobs et al. (2017). Although the confidence ratings provided by participants within Experiment 2 related to the confidence in their performance, not necessarily the vividness of their experience. Alternatively, conscious experience can also be explored using perceptual stimulus awareness ratings, which examine the *"degree of clearness"* of the conscious content (Ramsøy & Overgaard, 2004). This involves rating all aspects of a stimulus such as colour, stimulus position and shape as on a set categorisation scale, for instance, *"nothing, weak glimpse, almost clear image, clear image"* (Ramsøy & Overgaard, 2004). Awareness, in this case, can either be clearly conscious or a 'fringe' experience, which exists at the threshold of conscious awareness (Mangan, 2001). These fringes can be either sensory (stemming from perception of a sense) or non-sensory (the feeling of knowing or rightness), both proposed to have common features. (Mangan, 2001). Although imagery is an internal representation of sensory information, Ramsay and Overgaard (2004) suggest that the experience of imagery would constitute 'non-sensory fringe.' This degree of clearness is not to be confused with 'degrees of certainty' - one can be confident in their response in a task without considering the phenomenological experience (Ramsøy & Overgaard, 2004). How this relates to the vividness of an experience is not clearly stated. However, vividness is considered to be an aspect one considers in the introspective process when comparing the experience of a stimulus to a set categorisation scale (Ramsøy & Overgaard, 2004).

An objective way conscious experience could be examined is by galvanic skin responses. In a study of prosopagnosia (face-blindness), individuals with prosopagnosia self-reported the inability to recognise familiar faces, however, showed an emotional psychophysiological response to these familiar faces (Tranel & Damasio, 1985). The authors report that while these familiar faces were not consciously perceived, autonomic physiological processes in response to the faces were still occurring outside of conscious awareness. Similarly, studies of blindsight have shown that participants (who have lesions to the primary visual cortex) perform to a high level of accuracy (and similar reaction time) to controls within a visual discrimination task (Lau & Passingham, 2006; Weiskrantz, 1999). This high accuracy is evident despite differing on their conscious experience of the task, with participants often believing they are guessing (Lau & Passingham, 2006; Weiskrantz, 1999). Using a metacontrast masking paradigm (a mask that overlaps with the contour of a target once it is presented), Lau and Passingham (2006) found that when the mask was presented at a short time frame (33 msecs) participants reported they were 'guessing', but when it was presented after a longer delay (of 50 msecs), participants reporting 'seeing' the target with no differences in accuracy in the task at either time-frame. This suggests that individuals with blindsight lack consciousness of their performance while their ability to process visual information remained highly accurate (i.e. there were no differences in accuracy in the two-time conditions). Incorporating additional scales or techniques that tap into one's conscious experience (other than vividness) during tasks may provide more information with regards to the discrepancy between self-reported experience and performance.

7.2.3. Individual differences in the conscious experience of a lack of imagery

If aphantasia were a unified condition, it might be expected that aphantasic participants may all exhibit a similar pattern of performance. For instance, they may all display longer reaction times within the OTS task. However, this is not the case, as individual differences exploration of performance (Chapter 4) identified a subgroup of aphantasic participants who performed as accurately, and showed similar response times similar to participants with typical imagery. It may be the case that this subset of aphantasic participants has very efficient strategies that are comparable to visual imagery to perform within tasks. However, it may also be possible that this subgroup potentially can generate visual imagery; however, have no conscious access to this imagery - this visual imagery is unconscious. This means that during the OTS, they are engaging in unconscious visual imagery, which results in performance that exhibits similar response times and accuracy to controls with typical imagery.

This is in contrast to the subgroup of aphantasic participants who used a different process in the OTS that were not as efficient as the (likely visual imagery) strategy adopted by controls with typical imagery (Hodgson et al., 2000), but still resulted in highly accurate performance. This subgroup exhibited significantly longer reaction times during the more complex and difficult moves within the OTS task. It is proposed that this aphantasic subgroup are using an alternative process (such as spatial imagery, or another process) in the task, possibly because they have a complete lack of conscious and unconscious visual imagery, i.e. they have *extreme aphantasia*, characterised by a complete lack of sensory visual imagery (although not defined by a score 16 on the VVIQ, see Table 4.2, Chapter 4, section 4.3.1). The processes adopted by this subgroup are efficient only within less cognitively demanding trials. This variation in either conscious or unconscious imagery experience in individuals with aphantasia may explain these differences in performance. Specifically, a subgroup who performed as well as controls with typical imagery on all tasks, and another subgroup who exhibited significantly different reaction times, while remaining as accurate. One way to examine if such differences exist is through neuroimaging, whereby different patterns of brain activation would be expected for unconscious (activation within the primary visual cortex) and in aphantasic individuals who have a total absence of imagery (higher activation within brain regions associated with verbal or spatial strategies).

Keogh and Pearson (2017) suggested that aphantasia was due to a loss of sensory visual imagery and not because of a lack of metacognitive abilities. The authors suggested that if aphantasia were due to difficulty in the process of introspecting, a priming effect would have occurred within their binocular rivalry paradigm (see Chapter 1, section 1.4.3). However, Keogh and Pearson (2017) did not examine the individual variation in the data. Instead, they analysed the experiment by averaging across participant group (i.e. an aphantasic group and a control 'general population'), which will have averaged across any variations in priming effect. The authors suggested the majority of aphantasic participants in their sample had priming scores below chance (50%), and they showed that a proportion of the general population had priming scores at chance level (i.e. 50%) (Keogh and Pearson, 2017). In the graphs provided within the study of Keogh & Pearson (2017), it can be seen there are a few aphantasic participants who perform above chance exhibiting up to approximately 70% priming scores – a higher priming score than a large proportion of the general population (with typical imagery). The exact number of aphantasic participants this occurs in is not clear, but it is evident there are individual difference variations within the binocular rivalry priming data. If the majority performed below chance, with a few aphantasic individuals performing highly above chance, any variation in overall priming performance would not be observed when priming responses were averaged by participant group.

It may be the case that within the aphantasic sample denoted by Keogh & Pearson (2017), there was a small sub-set who had unconscious imagery, which may explain for the aphantasic participants who had high priming effects. The results of this thesis have shown that when performance is analysed by group, individual variations and differences are not apparent. In contrast, individual examination of the data offers an opportunity to identify subgroups and different patterns in behaviour. Moreover, Keogh & Pearson (2017), suggest that all individuals with aphantasia provided low trial-by-trial vividness ratings (between 1-2 out of a scale of 4) within the binocular rivalry paradigm. This assumes that scores within this range were also provided by the aphantasic participants who displayed above chance priming, suggesting that their self-reported vividness experience contrasted to their priming performance (as a possible result of their unconscious visual imagery).

The visual imagery priming condition of the binocular rivalry experiment denoted by Keogh & Pearson (2017) required participants to voluntarily generate a colour rivalry-display – this voluntary aspect is under conscious control and a process unavailable to individuals with aphantasia. However, this does not mean that the same priming responses would be obtained within conditions where unconscious visual imagery is involuntarily generated. This has been examined so far, in one study, whereby participants were asked to 'avoid imagining' an object (such as a red apple), and participants were instructed to push a button if they failed to follow this instruction (i.e. they generated the image of a red apple) (Kwok, Leys, Koenig-Robert, & Pearson, 2019).

While this heavily relies on the accurate introspection and reliability of participants' reports. The authors found that when participants successfully reported suppressing the image (of a red apple), their subsequent responses within the rivalry were still biased at a similar level to when the images were not suppressed (Kwok et al., 2019). The authors suggested that these suppressed images are likely to comprise of sensory representations that are represented in visual areas such as the primary visual cortex (Kwok et al., 2019).

In two additional priming conditions, a luminance condition (whereby a highly luminous yellow stimulus was presented during suppression) and a spatial condition (binocular rivalry display was presented within a different spatial location), priming was still found to occur, although at a significantly lower level, but still above chance (Kwok et al., 2019). Both the luminous and spatial conditions are suggested to interfere with the low-level visual features in V1 of the primary visual cortex (Goodyear & Menon, 1998), and interfere with the formation of intentional visual images (Pearson et al., 2008). While the authors did not state that this suppression involved unconscious imagery, Nanay (2019, 2021) suggests that this suppression might be indicative of the use of unconscious imagery. At present, this paradigm involving the suppression of images has not been investigated within individuals with aphantasia. If a subset of individuals with aphantasia do have unconscious imagery, this could be examined further within voxel decoding paradigms (Naselaris et al., 2015), which might show differences in decoded activity compared to aphantasics with a total lack of sensory visual imagery.

Whether an equivalence of the binocular rivalry paradigm can be translated across to other sensory domains (other than the visual domain) remains a challenging notion. While such a paradigm in the visual domain provides evidence for the sensory strength of visual imagery, it is unknown whether this can be translated to other senses. For instance, ensuring equal dominance in each eye is key to the binocular paradigm. However, this would be more challenging in translation to other senses such as the auditory domain, whereby it is more likely that there may be vast individual differences with regards to hearing abilities. Moreover, in the investigation of unconscious imagery within binocular rivalry paradigms, luminance and spatial conditions were added to interfere with the primary visual cortex. Equivalent control conditions may be more difficult to establish for other senses. For example, a spatial control in the auditory domain would involve an auditory image extended over time, rather than location as in the visual domain. Further, the act of suppression (i.e. avoiding the imagined experience of a sense) is not the norm, and it may be more difficult to introspect suppression attempts that are successful, as well as the act itself, may be more challenging to investigate in other senses.

On a tangential note, if there is a subgroup of individuals with aphantasia who have unconscious imagery, it would be of interest to explore whether there is a correlation between individuals who have unconscious imagery to those who self-report experiences of flashes of imagery, or who dream visually. It has been documented in three studies that despite the inability to generate voluntary visual imagery, individuals with aphantasia do dream and can recall this visual contents (Dawes et al., 2020; Zeman et al., 2015; Zeman et al., 2020). These are arguably imagery experiences occurring within different consciousness states. One way that this variability may be explained is that individuals who experience unconscious imagery may be more predisposed to dreaming. Fosshage (2013), defines dreaming as *"unconscious thinking"*, and patient and child developmental studies suggest that there may be shared neural organisation in wakeful visual imagery and dreaming (Foulkes, 1999; Kerr, Foulkes, & Jurkovic, 1978). However, this is purely speculation, and an exploration of the differences in imagery generation during wakeful voluntary imagery and unconscious-states are necessary.

More broadly, further research should explore aphantasics' ability to dream. In one study, the self-reported examination of dream content revealed that aphantasic participants dreamt significantly less than controls with typical imagery (Dawes et al., 2020). Moreover, their dream content comprised of less vivid emotions and sensory details (Dawes et al., 2020). Although the authors suggested no difference within spatial details of dreams (gathered through self-report measures), no indication is provided with regards to the visual (or object) details of the format of dreams, such as colour. The nature of this content has yet to be examined in more detail. It is unknown whether aphantasic participants who experience a lack of imagery within one sensory modality, if this is also absent within dream content. For individuals who once had vision, over time there is a gradual shift in dream content containing more references to other senses such as, audition, gustation and olfaction (Hurovitz, Dunn, Domhoff, & Fiss, 1999; Kirtley, 1975). Given that the dream content of sighted individuals contains high visual content, dream content of aphantasic individuals may reveal important information about visual function. In addition, while some individuals with aphantasia self-report visual dream content, it is not known the stage of sleep this originated. For instance, whether aphantasic individuals can recall their dreams or even have lucid visual dreams, a dreaming state whereby individuals are conscious that they are dreaming and can control dream content (LaBerge, 2000; Voss, Holzmann, Tuin, & Hobson, 2009). The findings of dream self-reports in the study by Dawes et al. (2020) showed that individuals with aphantasia self-reported less control over their dreams. However, this implies there was still an element of control, albeit less than individuals with typical imagery. This has implications for differences between a distinction between wakeful visual imagery and dream imagery, which have been suggested to share common neural mechanisms (Domhoff, 2003) despite their voluntary and involuntary basis.

7.3. Future research

At the outset of the PhD, the largest published sample size within the aphantasic literature was fifteen. This thesis was exploratory, and it was not known how easy or hard it would be to recruit participants with aphantasia. Since starting this PhD, general awareness of aphantasia within the general public and research literature has dramatically increased. For example, the experience has been publicised in a number of different news outlets, television programmes and social media platforms. Although the behavioural experiments in this thesis had low statistical power (i.e. with sample sizes between 20-30 in each participant group), larger effect sizes were obtained for the self-report measures, which used the internet to recruit large aphantasic samples. Future research should adopt online behavioural methodologies in order to gather larger participant samples.

In addition to providing evidence of the difference between self-report and performance on objective imagery measures in aphantasic individuals, this thesis shows that aphantasia is unlikely to be a homogenous experience and that there are subgroups or subtypes of aphantasia. This is evident in the individual differences' behavioural exploration in Chapter 4 and the sensory exploration in Chapter 5. In the behavioural individual differences exploration, several possible subgroups emerged. Given the sample sizes, the proposed nature of these groups is tentative. However, this work provides an important evidence base upon which future research can build. Large sample sizes will enable researchers to confirm and profile the extent or presence of the impairments in the subgroups. Similarly, the results of the non-visual questionnaires showed that individuals with aphantasia differed in their experience of imagery across the sensory modalities. It is not known whether these subgroups differ either behaviourally or at a neural level. If these subgroups differ, then new terms are required to describe these variations, rather than one set definition generalising to one type of experience.

Exploration of the potential subgroups within aphantasia can provide an empirical basis for the different degrees of aphantasia. In the study by Zeman et al. (2020), the authors referred to aphantasic participants who scored 16 on the VVIQ as *"extreme aphantasia"*. Similarly, those who scored between 17-23 on the VVIQ were defined as *"moderate aphantasia"* (Zeman et al., 2020). It has not been examined whether there are objective differences between individuals who fall within these two groups. Although the majority of individuals with aphantasia scored 16 (the lowest score) on the VVIQ, some also scored above 30 on the VVIQ (Dawes et al., 2020; Wicken et al., *submitted*; Zeman et al., 2015). Currently, there is no consensus of a cut off in the literature to define aphantasia, and different research groups have adopted various cut-off criteria (Dawes et al., 2020; Wicken et al., 2021; Bainbridge et al., 2020).

Similarly, where stated, there are no set criteria for the definition of typical imagers. However, the meta-analysis undertaken by McKelvie (1995) provided some normative VVIQ scores for 'high' and 'low' imagery groups. In the current thesis, control participants with typical imagery were defined by scores VVIQ > 33, in line with the wide range of VVIQ scores for typical imagers adopted by previous studies (Dawes et al., 2020; Wicken et al., *submitted*). More broadly, however, what is lacking in the literature is an investigation of performance between different scores of the VVIQ. For instance, examine if there are any differences between typical imagers who have a conscious experience of weak imagery (e.g. VVIQ scores between 30-40) compared to aphantasic individuals who score between 25-30 on the VVIQ. Alternatively, whether there are any differences between individuals who have a conscious experience of weak imagery compared to individuals with *"extreme aphantasia".* The identification of hyperphantasia, an experience characterised by highly vivid visual imagery, also provides the opportunity to compare performance across imagery extremes. A recent study by Milton et al. (*submitted*) showed that within three visual imagery tasks, there was no difference in performance between aphantasic and control participants (who had mid-range VVIQ scores). This is similar to the findings of this thesis. However, there was a significant difference in performance in an object imagery task between aphantasic and hyperphantasic participants. Future studies should examine hyperphantasia – although this may be a more difficult population to identify owing to the subjectivity of their experience.

Kosslyn's theory of mental imagery, as well as the majority of evidence to support depictive theories, stem from the idea that visual imagery shares processes and mechanisms to visual perception (e.g. Kosslyn et al., 1999; Naselaris et al., 2015; Thirion et al., 2006). However, the extent of this overlap in resources has been contested by numerous neuroimaging studies failing to find common overlaps and patient case studies (e.g. Bartolomeo et al., 1998; Farah 1984; Ishai et al., 2000, Winlove et al., 2018). The discovery of a population of individuals who self-report the inability to use visual imagery but have intact visual perception also provides evidence against the notion of these two processes sharing identical mechanisms. Further neuroimaging research comparing individuals with typical imagery to individuals with aphantasia may reveal differences between the neural networks involved in visual perception and visual imagery.

In Chapter 6, individual differences in auditory experience were apparent as some aphantasic participants self-reported the presence of an internal voice, despite a self-reported lack of auditory imagery. Anecdotal evidence collected through conversation revealed several aphantasic participants self-reported a lack of auditory imagery, but reported the ability to use their internal voice (inner speech). On the other hand, others self-reported both a lack of auditory imagery and internal voice ("*mind silent*"). Inner speech is suggested to comprise of auditory traits as found in overt speech, for instance, pitch, loudness and emotional tone (Vilhauer, 2016), and is thought by some to be a subset of auditory imagery (Hubbard, 2010). Evidence to suggest that inner speech is a form of auditory imagery stem from articulatory suppression studies and neuroimaging studies which show they both activate similar brain regions (Hubbard, 2010; Price, 2012). However, neuroimaging studies have also documented different patterns of activation (Fegen, Buchsbaum, & D'Esposito, 2015; Zatorre & Halpern, 2005). This suggests that although inner speech and auditory imagery may share common mechanisms, such as the use of phonological information (Shergill et al., 2001), they are somewhat separable processes (Alderson-Day & Fernyhough, 2015). Furthermore, it has been argued that inner speech is a form of articulated language representations with more overlaps with overt speech than auditory imagery speech representations (Alderson-Day & Fernyhough, 2015; Zatorre & Halpern, 2005). Future studies could explore the differences between inner speech and auditory imagery experience. This feature and distinction may aid further to characterise the auditory experience within individuals with aphantasia. Similarly, it may provide additional evidence to whether the two processes are separable.

7.4. Thesis conclusion

The objective of this thesis was to use objective experimental measures to investigate the cognitive basis of aphantasia – a variant of human experience defined by a self-reported lack of visual imagery. Despite the difference in self-reported conscious experience, individuals with aphantasia performed as well as individuals with typical imagery in a range of visual/spatial imagery, visuospatial working memory and auditory imagery tasks. The main findings of this thesis showed a discrepancy between subjective experience and behavioural performance. However, in one task, significant differences in response time were evident during cognitively demanding trials (but this pattern of performance was not exhibited by all aphantasic participants). This suggests that there may be different processes that underpin performance, and these processes are less effective with an increase in working memory load. Although it was proposed that individuals with aphantasia use spatial imagery in the absence of the 'visual' component, the results showed no evidence to support this notion, but this may be due to the insensitivity of the paradigm. A key finding of this thesis concerns individual differences, specifically, the possibility of aphantasic subgroups who have unconscious visual imagery and other subgroups who have a total absence of sensory imagery (extreme aphantasia). Further research should examine whether there are behavioural and neural differences to support the existence of these subgroups and explore the role of consciousness within imagery experience. Visual imagery is key to many cognitive processes, and the discovery of aphantasia suggests that our mental experiences are not experienced universally, but there are vast (and fascinating) variations within our inner lives. Understanding the unique mental experience of individuals with aphantasia will provide novel insights and offers exciting opportunities to investigate further the nature of visual imagery, perception and memory.

APPENDICES for Chapter 2:

Appendix 2.1: Vividness of Visual Imagery Questionnaire (VVIQ)

For each item on this questionnaire, try to form a visual image, and consider your experience carefully. For any image that you do experience, rate how vivid it is using the five-point scale described below. If you do not have a visual image, rate vividness as '1'. Only use '5' for images that are truly as lively and vivid as real seeing. Please note that there are no right or wrong answers to the questions, and that it is not necessarily desirable to experience imagery or, if you do, to have more vivid imagery.

Perfectly clear and vivid as real seeing	5
Clear and reasonably vivid	4
Moderately clear and lively	3
Vague and dim	2
No image at all, you only "know" that you are thinking of the object	1

For items 1-4, think of some relative or friend whom you frequently see (but who is not with you at present) and consider carefully the picture that comes before your mind's eye.

1. The exact contour of face, head, shoulders and body ________________
2. Characteristic poses of head, attitudes of body etc. ________________
3. The precise carriage, length of step etc., in walking ________________
4. The different colours worn in some familiar clothes ________________

Visualise a rising sun. Consider carefully the picture that comes before your mind's eye.

5. The sun rising above the horizon into a hazy sky ________________
6. The sky clears and surrounds the sun with blueness ________________
7. Clouds. A storm blows up with flashes of lightning ________________
8. A rainbow appears ________________

Think of the front of a shop which you often go to. Consider the picture that comes before your mind's eye.

9. The overall appearance of the shop from the opposite side of the road ________________
10. A window display including colours, shapes and details Of individual items for sale ________________
11. You are near the entrance. The colour, shape and details of the door. ________________
12. You enter the shop and go to the counter. The counter assistant serves you. Money changes hands ________________

Finally think of a country scene which involves trees, mountains and a lake. Consider the picture that comes before your mind's eye.

____

13. The contours of the landscape ________________
14. The colour and shape of the trees ________________
15. the colour and shape of the lake ________________
16. A strong wind blows on the trees and on the lake causing waves in the water. ________________

Appendix 2.2: Object-spatial imagery questionnaire (OSIQ)

1. I was very good in 3-D geometry as a student.
2. If I were asked to choose between engineering professions and visual arts, I would prefer engineering.
3. Architecture interests me more than painting.
4. My images are very colourful and bright.
5. I prefer schematic diagrams and sketches when reading a textbook instead of colourful and pictorial illustrations.
6. My images are more like schematic representations of things and events rather than detailed pictures.
7. When reading fiction, I usually form a clear and detailed mental picture of a scene or room that has been described.
8. I have a photographic memory.
9. I can easily imagine and mentally rotate 3-dimensional geometric figures.
10. When entering a familiar store to get a specific item, I can easily picture the exact location of the target item, the shelf it stands on, how it is arranged and the surrounding articles.
11. I normally do not experience many spontaneous vivid images; I use my mental imagery mostly when attempting to solve some problems like the ones in mathematics.
12. My images are very vivid and photographic.
13. I can easily sketch a blueprint for a building that I am familiar with
14. I am a good Tetris player.
15. If I were asked to choose between studying architecture and visual arts, I would choose visual arts.
16. My mental images of different objects very much resemble the size, shape and colour of actual objects that I have seen.
17. When I imagine the face of a friend, I have a perfectly clear and bright image.
18. I have excellent abilities in technical graphics.
19. I can easily remember a great deal of visual details that someone else might never notice. For example, I would just automatically take some things in, like what colour shirt someone wears or what colour are his/her shoes.
20. In high school, I had less difficulty with geometry than with art.
21. I enjoy pictures with bright colours and unusual shapes like the ones in modern art.
22. Sometimes my images are so vivid and persistent that it is difficult to ignore them.
23. When thinking about an abstract concept (e.g. ‘a building’) I imagine an abstract schematic building in my mind or its blueprint rather than a specific concrete building.
24. My images are more schematic than colourful and pictorial.
25. I can close my eyes and easily picture a scene that I have experienced.

26. I remember everything visually. I can recount what people wore to a dinner and I can talk about the way they sat and the way they looked probably in more detail than I could discuss what they said.
27. I find it difficult to imagine how a 3-dimensional geometric figure would exactly look like when rotated.
28. My visual images are in my head all the time. They are just right there.
29. My graphic abilities would make a career in architecture relatively easy for me.
30. When I hear a radio announcer or a DJ I've never actually seen, I usually find myself picturing what he or she might look like.

Appendix 2.3: Wechsler Test of Adult Reading (WTAR)

AGAIN	CONSCIENTIOUS
ADDRESS	HOMILY
COUGH	MALADY
PREVIEW	SUBTLE
ALTHOUGH	FECUND
MOST	PALATABLE
EXCITEMENT	MENAGERIE
KNOW	OBFUSCATE
PLUMB	LIAISON
DECORATE	EXIGENCY
FIERCE	XENOPHOBIA
KNEAD	OGRE
AISLE	SCURRILOUS
VENGEANCE	ETHEREAL
PRESTIGIOUS	PARADIGM
WREATHE	PERSPICUITY
GNAT	PLETHORA
AMPHITHEATRE	LUGUBRIOUS
LIEU	TREATISE
GROTESQUE	DILETTANTE
IRIDESCENT	VERTIGINOUS
BALLET	UBIQUITOUS
EQUESTRIAN	HYPERBOLE
PORPOISE	INSOUCIANT
AESTHETIC	HEGEMONY

Appendix 2.4: Predicted Full-Scale IQ (FSIQ) scores from WTAR scores by participant group.

Con	**Age**	**WTAR**	**Standard score**	**Full-scale IQ (FSIQ)**		**Aph**	**Age**	**WTAR**	**Standard score**	**Full-scale IQ (FSIQ)**
1	25	42	110	107		101	54	44	110	107
2	29	25	80	88		102	33	45	115	110
3	66	49	123	115		103	31	45	115	110
4	37	44	111	108		104	37	42	110	107
5	25	50	129	119		105	57	46	113	109
6	28	48	120	114		106	30	46	117	112
7	24	45	120	114		107	37	47	119	113
8	58	46	113	109		108	41	45	115	110
9	69	28	84	91		109	55	42	106	105
10	41	48	120	114		110	37	43	111	108
11	23	41	113	109		111	42	45	115	110
12	35	42	110	107		112	39	39	104	104
13	31	47	119	113		113	29	45	115	110
14	27	45	115	110		114	31	39	104	104
15	32	49	122	115		115	38	37	101	102
16	32	27	84	91		116	42	42	110	107
17	23	45	120	114		117	28	39	104	104
18	27	38	103	103		118	38	47	119	113
19	31	47	119	113		119	46	47	115	110
20	63	50	125	117		120	55	42	106	105
Mean	36.3	42.8	112	108.55		**Mean**	40	43.35	111.2	108
SD	15.06	7.64	14.00	8.88		**SD**	9.15	3.01	5.44	3.21

Appendix 2.5: Participant information and consent
This research is being conducted by Elena Vryzakis as part of an MSc Psychology at the University of Westminster. It is being supervised by Sam Evans and Zoe Pounder in the Psychology Department and it has been approved by the Departmental Ethics Committee.

Aim
The aim of the study is to examine visual imagery and working memory performance in healthy individuals.

Design
The study requires you to complete an online screening questionnaire to see whether you are eligible to take part in the study. If you are eligible, you will be asked to attend two testing sessions at the University of Westminster Cavendish campus, spaced one week apart. Each session will last approximately 40 minutes. During the two sessions, you will complete several questionnaires and a computerised imagery task. Each computerised task will have a practice element or demo so you understand the nature of the task before starting.

Confidentiality of the data
The data and responses you provide will remain confidential in accordance with the University of Westminster ethical guidelines and British Psychological Society code of human research ethics. It will be securely stored and managed in accordance with the General Data Protection Regulation 2018 and the Data Protection Act 2018. The data you have provided may be shared with the project supervisors and the project markers. No individuals will be identifiable from any written report of the research, or any publications arising from it. Additionally, you have the right to ask for any data you have provided to be destroyed.

Voluntary participation
It is important that you know that your participation in this experiment is entirely voluntary, and you have the right to withdraw at any time without having to give a reason. Furthermore, you do not have to answer particular questions if you do not wish to and you have the right to ask for your data to be withdrawn after the session until the research has been published/submitted.

Debrief
Please note that you will receive written debriefing information at the end of the study.

Questions
As a participant, you have the right to ask questions at any time, even during the experiment. If you need to contact the researcher after participating, please send an email to Elena Vryzakis at w1704957@my.westminster.ac.uk; Zoë Pounder z.pounder@my.westminster.ac.uk; or Sam Evans S.Evans@westminster.ac.uk 24

Consent Form
Please tick each box, as appropriate, to confirm that your participation has been explained to your satisfaction.

• My participation in this research is on an entirely voluntary basis.

• I am able to stop at any point during the process without having to provide an explanation.
• Once I have taken part, I am still able to withdraw my data at any point until the research has been published/submitted as part of my research project, or has been anonymised.
• I do not have to answer all questions asked, and I can decline to answer any questions as I see fit. • My data will be anonymised, and all identifying features will be removed so that my contribution will not be identifiable when reporting this research.
• If I provide any personal identity data this will be treated confidentially and in accordance with the University of Westminster ethical guidelines and British Psychological Society code of human research ethics. It will be securely stored and managed in accordance with the General Data Protection Regulation 2018 and the Data Protection Act 2018.
• My personal information may be shared with members of the research and/or teaching team, and the University of Westminster External Examiner.
• The duty of confidentiality is not absolute and in exceptional circumstances this may be overridden by more compelling duties such as to protect individuals from harm.
• My anonymised contribution to this research may be used for future research, and may undergo secondary analysis. Future research may be related or unrelated to the goals of this study.

If you consent to participate under these conditions, please sign below. This consent form will be stored separately from any data you provide so that your responses remain anonymous.

I have read the Participation Information Sheet, I have confirmed my understanding of it and I am willing to participate in the research study.
Print name ________________________________
Signature___________________________________
Date________________________
All reasonable steps have been taken to provide an appropriate explanation of the research to the participant. Signed _______________________ Researcher ________________ Date________

APPENDICES for Chapter 3:

***Appendix 3.1:** Predicted Full-Scale IQ (FSIQ) scores from WTAR scores by participant group.*

The aphantasic participants here are the same as those documented in Appendix 2.4.

Con	Age	WTAR	Standard score	Full-scale IQ (FSIQ)		Aph	Age	WTAR	Standard score	Full-scale IQ (FSIQ)
1	28	44	113	109		101	54	44	110	107
2	30	40	106	105		102	33	45	115	110
3	26	40	106	105		103	31	45	115	110
4	25	45	115	110		104	37	42	110	107
5	25	36	99	100		105	57	46	113	109
6	27	37	101	102		106	30	46	117	112
7	57	47	115	110		107	37	47	119	113
8	37	44	113	109		108	41	45	115	110
9	32	48	120	114		109	55	42	106	105
10	25	33	94	97		110	37	43	111	108
11	42	40	106	105		111	42	45	115	110
12	52	43	108	107		112	39	39	104	104
13	46	37	97	99		113	29	45	115	110
14	55	47	115	110		114	31	39	104	104
15	44	43	111	108		115	38	37	101	102
16	40	43	111	108		116	42	42	110	107
17	51	44	110	107		117	28	39	104	104
18	30	47	119	113		118	38	47	119	113
19	54	43	108	106		119	46	47	115	110
20	55	45	111	108		120	55	42	106	105
Mean	39.05	42.3	108.9	106.6		**Mean**	40	43.35	111.2	108
SD	11.90	4.12	7.02	4.42		**SD**	9.15	3.01	5.44	3.21

Appendix 3.2: Recruitment posters for aphantasic and control participants

Cognitive Neuroscience Group, Psychology Department — UNIVERSITY OF WESTMINSTER

Can you imagine a purple elephant?

We are undertaking a study looking at cognitive function in people with aphantasia. Individuals with aphantasia are unable to imagine with their mind's eye.

What does the study involve?

- ❖ Attending two sessions (one week apart) to complete computer tasks

Who can participate?

- ❖ Males and Females
- ❖ Between 18-55 years of age
- ❖ No history of mental illness
- ❖ Normal to correct-normal vision

You will be awarded £20 in vouchers for your participation

For more details, please contact: z.pounder@my.westminster.ac.uk

Cognitive Neuroscience Group, Psychology Department — UNIVERSITY OF WESTMINSTER

Can you imagine a purple elephant?

We are undertaking a study looking at cognitive function in people with aphantasia. Individuals with aphantasia are unable to imagine with their mind's eye. We are seeking **healthy participants** to act as a control for this study.

What does the study involve?

- ❖ Attending two sessions (one week apart) to complete computer tasks

Who can participate?

- ❖ Males and Females
- ❖ Between 18-55 years of age
- ❖ No history of mental illness
- ❖ Normal to correct-normal vision

You will be awarded £20 in vouchers for your participation

For more details, please contact: z.pounder@my.westminster.ac.uk

Appendix 3.3: Informed consent, participation sheet (continued) and debrief

I have read and understood the information on the "Information for Participants" sheet, and I have received enough information about the study. I have understood that my participation is completely voluntary and that I can at any instance discontinue the experiment, and such discontinuation does not affect my treatment in the future.

With my signature, I confirm my participation to this study, and volunteer for a research subject.

Name of participant

………………………………………………………………………………..……..

Address

…………………………………………………………………………………………

…….

Signed ……………………………………………… Date

……………………………………….

On behalf of Principal Investigators:
Dr Jane Jacob
Dr Juha Silvanto
Dr Maria Flynn
Miss Zoë Pounder

Address:
Cognitive Research Group
Westminster University
115 New Cavendish St
Fitzrovia
London
W1W 6UW

Appendix 3.3: Informed consent, participation sheet (continued) and debrief

Introduction

We would like to invite you to participate in our study regarding cognitive function in individuals who have aphantasia (lack visual mental imagery) and individuals who have visual imagery. Before you sign the informed consent form, we would like to ask you to read the following information carefully.

Aim of this study

The goal of this study is to examine cognitive function in individuals with aphantasia compared to non-aphantasics (controls).

Criteria for Study

To take part in this study you must have **normal or correct to normal vision**, and no history of mental illness

Design of the study

The study requires you to attend two sessions one week apart. Each session will last approximately 2 hours and you will be paid for your time with *love2shop* vouchers. During the two sessions you will undertake a range of cognitive tasks. Each task will have a practice element or demo so you understand the nature of the task before starting.

What is asked of you

We would like to ask you to pay attention to the following. Please make sure that you do not drink more than 2 units of alcohol and do not take any drugs on the day of the study or the night before. Furthermore, make sure that you are well rested before the experiment. If you have recently started to take any medication, you feel tired or not rested, please inform the experimenter (see phone number below) before coming to the experiment.

Confidentiality of the data

Your privacy will be assured by coded gathering and analysis of the data. The data will only be available to current members of the research team, and not be Transposemitted to a third party. The data will be preserved for a maximum of 15 years.

Voluntary participation

It is important that you know that your participation in this experiment is completely voluntary, and that you can stop at any moment, without reason.

Questions

As a participant, you have the right to ask questions at any time, even during the experiment. It is also possible that you have questions after having finished the experiment. In that case, please contact Zoë Pounder at z.pounder@my.westminster.ac.uk.

Appendix 3.3: Informed consent, participation sheet (continued) and debrief

Thank you for attending the two testing sessions and taking part in our study.
This study aims to examine cognitive function in healthy individuals and in individuals who have aphantasia (lack visual mental imagery). The tests which you have undertaken in the two sessions involve visual imagery and aspects of working memory. The data gathered will be used to examine how cognitive performance (e.g. working memory) in individuals with aphantasia differs from those participants who have normal imagery.

If you have any further queries regarding this research, please contact Zoë Pounder at z.pounder@my.westminster.ac.uk.

Appendix 3.4: The Big Five Inventory (BFI)

Here are a number of characteristics that may or may not apply to you. For example, do you agree that you are someone who lies to spend time with others? Please write a number next to each statement to indicate the extent to which you agree or disagree with that statement

Disagree strongly	Disagree a little	Neither agree nor disagree	Agree a little	Agree strongly
1	2	3	4	5

I see myself as someone who

__1. Is talkative

__2. Tends to find fault with others

__3. Does a thorough job

__4. Is depressed, blue

__5. Is original, comes up with new ideas

__6. Is reserved

__7. Is helpful and unselfish with others

__8. Can be somewhat careless

__9. Is relaxed, handles stress well

__10. Is curious about many different things

__11. Is full of energy

__12. Starts quarrels with others

__13. Is a reliable worker

__14. Can be tense

__15. Ins ingenious, a deep thinker

__16. Generates a lot of enthusiasm

__17. Has a forgiving nature

__18. Tends to be disorganised

__19. Worries a lot

__20. Has an active imagination

__21. Tends to be quiet

__22. Is generally trusting

__ 23. Tends to be lazy

__ 24. Is emotionally stable, not easily upset

__25. Is inventive

__26. Has an assertive personality

__ 27. Can be cold and aloof

__28. Perseveres until the task is finished

__29. Can be moody

__30. Values artistic, aesthetic experiences

__31. Is sometimes shy, inhibited

__32. Is considerate and kind to almost everyone

__33. Does things efficiently

__34. Remains calm in tense situations

__35. Prefers work that is routine

__36. Is outgoing and sociable

__37. Is sometimes rude to others

__38. Makes plans and follows through with them

__39. Gets nervous easily

__ 40. Likes to reflect, play with ideas

__41. Has few artistic interests

__42. Likes to cooperate with others

__43. Is easily distracted

__44. Is sophisticated in art, music, or literature

Please check: Did you write a number in front of each statement?

Appendix 3.5: Investigating the relationship between self-report of visual imagery and extraversion

Summary

During Experiment 3, the results of 20 participants with typical imagery showed a strong correlation between personality and self-reported vividness of visual imagery. Specifically, individuals with higher extraversion scores tended to report more vivid experiences. This is important in the context that the VVIQ is used to diagnose elements of a disorder or experience such as in the case of individuals with synaesthesia who score high on the VVIQ (Barnett & Newell, 2008). The aim of this study is to investigate whether this relationship between extraversion and imagery vividness exists in a larger sample.

Methods

Participants and ethics

419 responses were received in Qualtrics and were downloaded into a SPSS file. A number of participants were excluded: 10 participants did not give consent to participate at the start of the Qualtrics questionnaire, 5 participants did not provide consent at the end of the study, 5 participants were removed due to their age (under the age of 16) and 2 participants were removed as they did not provide their age. As a result, this left 397 participants. Of these 397 participants, 259 were female, 119 were male and 19 respondents did not specify their gender.

The protocol for the study was in accordance with the British Psychological Society guidelines and the ethical approval provided by the Psychology Department Ethics Committee of the University of Westminster, UK. All participants consented to undertake the study, and were debriefed upon completion of the study.

Table 1: Participant demographics for Experiment 2	
Variable	**N**
Age	
18-40	236
41-65	145
65+	16
Highest level of education	
Grammar/ Secondary/ High school/ Vocational	108
College/ University/ University graduate	191
Postgraduate	44
Postgraduate/Professional Degree	53
Missing/ No details provided	1
Occupation	
Employed	154
Self-employed	30
Seeking employment	19
Homemaker	15
Student	135
Retired	24
Unable	7
Missing/No details provided	13

Materials

Participants were asked to complete two visual imagery questionnaires: the Vividness of Visual Imagery Questionnaire (VVIQ) and the Spontaneous Use of Imagery Questionnaire (SUIS). Participants also undertook the 41-item Five Factor personality inventory validated for use on the Internet (Buchanan, Johnson & Goldberg, 2005) that provides quick measures of Extraversion, Agreeableness, Conscientiousness, Neuroticism (emotional stability), and Openness to Experience An additional Extroversion scale of the Five Factor Model of personality comprising of 8 questions was also included (see Appendix III).

Procedure

Participants were recruited via a personality-testing website (www.personalitytest.org.uk). This website is a privately owned research tool and educational resource, separate to the University of Westminster. The website has existed for a number of years, and attracts around six thousand users per month. No attempt was made to recruit respondents or otherwise attract them to the site - they were referred by other sites or found the website through search engines.

Respondents receive brief feedback on the 'meaning' of each variable, and how their own scores compared to a reference sample (above average, average, below average scores). On completion of the personality questionnaire, respondents are invited to volunteer for a second study (Investigating the relationship between self-reports of visual imagery and extraversion). Once participants provided consent to participate in the study, participants were asked to complete 8 questions regarding extraversion taken from the Five Factor Model of personality. Subsequently, participants completed the VVIQ (16 questions) and the SUIS (12 questions). Participants were asked to complete some additional questions regarding demographics: age, location (country), gender, level of education, occupation status. At the end of the study, participants were provided with feedback in relation to their visual imagery scores in comparison to the imagery scores.

Data analysis

Cronbach's alpha examined the internally reliability of the four questionnaires. A Pearson's correlation was undertaken for all of the personality traits in the Five Factor Model and two imagery questionnaires. A regression examine personality influences on imagery questionnaires, including age and gender as predictors of scores.

Results

The 41-item Five Factor personality inventory was used and found to be highly reliable for each trait: neuroticism (8 items; $\alpha = 0.841$), extraversion (9 items; $\alpha = 0.865$), conscientiousness (10 items; $\alpha = 0.856$), agreeableness (7 items; $\alpha = 0.748$). Although openness to experience had a lower level of internal consistency (7 items; $\alpha = 0.685$). The BFI Extraversion scale, an additional measure of extraversion comprised of 8 questions ($\alpha = 0.879$). The VVIQ (16 items) and SUIS (12 items) also have high levels of internal consistency ($\alpha = 0.902$ $\alpha = 0.764$ respectively).

	Scale	Mean score (SD)
Imagery Questionnaires	*VVIQ /80*	61.97 (11.39)
	SUIS /60	40.64 (8.80)
BFI Extraversion scale	*Extraversion /40*	24.37 (7.09)
Five Factor Scale	*Extraversion /45*	27.60 (7.69)
	Agreeableness /35	28.06 (4.49)
	Conscientiousness /50	34.58 (7.72)
	Neuroticism /38	21.75 (7.09)
	Openness to Experience /35	27.96 (4.63)

Table 2: Means and standard deviations (SD) for VVIQ, SUIS and for the personality measures (Five Factor and BFI Extraversion scale).

	Trait	VVIQ	SUIS
Five Factor Scale	Extraversion	$r = .19, p < .001$	$r = .10, p = .06$
	Agreeableness	$r = .15, p = .003$	$r = .19, p < .001$
	Conscientiousness	$r = .31, p < .001$	$r = .14, p = .005$
	Neuroticism	$r = -.17, p = .001$	$r = -.01, p = .76$
	Openness to Experience	$r = .02, p = .69$	$r = .08, p = .10$
BFI Extraversion scale	Extraversion	$r = .16, p = .002$	$r = .04, p = .38$
Demographic Factors	Age	$r = .17, p = .001$	$r = .006, p = .91$
	Sex	$r = .06, p = .24$	$r = .19, p < .001$

Table 3: Pearson correlation between personality/demographic factors and imagery questionnaires (VVIQ and SUIS)

A regression analysis was used to examine if the personality traits on the Five Factor personality inventory predicted participants' ratings on both the VVIQ and SUIS. Age and gender were also included as predictors as they influence responses provided on the VVIQ and SUIS. The regression analysis of personality, age and gender on VVIQ (R^2 = .132) suggests that individual differences account for over 10% of variance in VVIQ scores. Out of all the personality traits extraversion ($\beta = 0.125, p = 0.021$) and especially most significantly conscientiousness ($\beta = 0.271$, $p<0.001$) are the main predictors of high VVIQ scores[23].

[23] The other traits: agreeableness ($\beta = 0.091, p = .09$), neurotiscm ($\beta = 0.04, p = .52$) and openness to experience ($\beta = 0.04, p = .46$).

The regression analysis of personality, age and gender on SUIS ($R^2 = .096$) suggests that individual differences account for less than 10% of variance in SUIS scores. Traits extraversion ($\beta = .109$, $p = .05$), agreeableness ($\beta = .179$, $p = .001$), conscientiousness ($\beta = .148$, $p = .01$), neuroticism ($\beta = .138$, $p = .03$) and gender ($\beta = .144$, $p = .005$) are statistically significant predictors of high SUIS scores.

Discussion

Self-report questionnaires are one way in which to gain an insight into an individual's experiences. There is a considerable amount of research suggesting that certain personality traits can influence the way an individual may self-perceive and consequently report their experiences (Buchanan, 2015). This experiment examined the relationship between the personality trait extraversion and self-reported visual imagery vividness within a large sample. The results showed that although extraversion is a small predictor for VVIQ scores, other traits such conscientiousness have a stronger influence.

Despite this, extraverted individuals did self-report their visual imagery experience as more rich, other traits had a stronger influence on vividness scores. Moreover, there was a significant trend between SUIS scores and the Five Factor extraversion scale, however, the results suggest that this effect size would be small, for instance a small difference in the amount of self-reported spontaneous imagery. This indicates the effect of extraversion is unique to the VVIQ, rather than being a response bias. This reflects the nature of the two scales: the VVIQ requires individuals to visualise specific details of scenes while the SUIS considers the frequency or likelihood to which imagery is used in certain everyday life scenarios (Reisberg et al., 2003). While the SUIS has good reliability (McCarthy-Jones et al., 2012), the VVIQ has been shown to have a high internal validity for measuring a mental construct (Campos, 2011).

If personality explains 10% of variance on these scales, the question is with regards to the amount that this variation matters. This depends on the context in which the VVIQ is used to diagnose elements of a disorder or experience. For instance, the VVIQ has been used to examine the relationship between the vividness of visual imagery and schizotypal traits in a non-clinical population (Bell & Halligan, 2010). Moreover, individuals with synaesthesia tend score highly on the VVIQ (Barnett & Newell, 2008). In a forensic setting, extraverted individuals are more likely to provide partial false memories (Porter, Birt, Yuille, & Lehman, 2000) or express memories which they have imagined (Heinstroöm, 2003), although vividness of visual imagery is not normally assessed in such a setting. Overall the practical implication are that individual differences should routinely be measured in research which uses imagery scales, so that effects can be controlled for in analyses.

MATERIALS FOR THIS SUB-STUDY (undertaken on Qualtrics)

Appendix 3.5.A: Participation information and consent for The Big Five Inventory (BFI)

Thank you for your interest in this online personality test, which is based on an International Personality Item Pool representation of the Five Factor Model of personality. The Five Factor Model (also known as the "Big 5" or BFI) is based on the idea that five main dimensions are necessary and sufficient for broadly describing human personality.

The next page contains the 41 items of the test and some additional questions. Once you have filled these in and submitted the test for scoring, you will be told your scores on these five basic dimensions and given some information about what they mean.

This version of the inventory was developed for use in online psychological research projects and at times may still be used to collect data. Additional questions may also be added from time to time. However, it is possible to take the test without your data being used in research, and you will have the opportunity to request this.

All of the information you provide will be treated as confidential.
No information about your identity will be requested at any stage.
Please answer the questions as honestly and accurately as possible.
Please make sure you respond to all the items and do not leave any blanks (your test scores cannot be computed if you miss any out).

No risks or benefits to you as an individual are anticipated as a result of your participation.
It is assumed that you are taking the test purely for interest: you should never use the information given here for any serious "real life" purposes.
If you wish to take the test, but do not wish your data to be used for research purposes, you will have the opportunity to say so before submitting the test for scoring.
You might occasionally get a message that there has been an 'Internal Server Error'. If this happens, refreshing the page should fix things. Apologies for any inconvenience this causes.
This website might change or go away entirely with no warning at any time. There are no current plans to take it down, but also no guarantee of its continued existence.

By clicking below you are giving your consent to proceed under the conditions outlined on this page.

I understand and wish to continue

Instructions

On the following pages, there are phrases describing people's behaviours. Please use the rating scale below to describe how accurately each statement describes *you*. Describe yourself as you generally are now, not as you wish to be in the future. Describe yourself as you honestly see yourself, in relation to other people you know of the same sex as you are, and roughly your same age. So that you can describe yourself in an honest manner, your responses will be kept in absolute confidence. Please read each statement carefully, and then fill in the bubble that corresponds to your reply.

Appendix 3.5.B: The Big Five Inventory (BFI)

Here are a number of characteristics that may or may not apply to you. For example, do you agree that you are someone who lies to spend time with others? Please write a number next to each statement to indicate the extent to which you agree or disagree with that statement

Disagree strongly	Disagree a little	Neither agree nor disagree	Agree a little	Agree strongly
	2	3	4	
1				5

I see myself as someone who

__1. Is talkative

__2. Tends to find fault with others

__3. Does a thorough job

__4. Is depressed, blue

__5. Is original, comes up with new ideas

__6. Is reserved

__7. Is helpful and unselfish with others

__8. Can be somewhat careless

__9. Is relaxed, handles stress well

__10. Is curious about many different things

__11. Is full of energy

__12. Starts quarrels with others

__13. Is a reliable worker

__14. Can be tense

__15. Ins ingenious, a deep thinker

__ 23. Tends to be lazy

__ 24. Is emotionally stable, not easily upset

__25. Is inventive

__26. Has an assertive personality

__ 27. Can be cold and aloof

__28. Perseveres until the task is finished

__29. Can be moody

__30. Values artistic, aesthetic experiences

__31. Is sometimes shy, inhibited

__32. Is considerate and kind to almost everyone

__33. Does things efficiently

__34. Remains calm in tense situations

__35. Prefers work that is routine

__36. Is outgoing and sociable

__37. Is sometimes rude to others

__16. Generates a lot of enthusiasm	__38. Makes plans and follows through with them
__17. Has a forgiving nature	__39. Gets nervous easily
__18. Tends to be disorganised	__ 40. Likes to reflect, play with ideas
__19. Worries a lot	__41. Has few artistic interests
__20. Has an active imagination	__42. Likes to cooperate with others
__21. Tends to be quiet	__43. Is easily distracted
__22. Is generally trusting	__44. Is sophisticated in art, music, or literature

What is your age in years? (Pick from this list)
Where are you located? (Pick from this list)
Are you male or female? (Pick from this list)
What is the highest level of formal schooling you have *completed?* (Pick from this list)
Which of these best describes your main current occupational status? (Pick from this list)
How did you come to be taking this test? (Pick from this list).

Feedback

The test that you have just taken is based on the Five Factor Model of personality. There is a broad consensus amongst personality theorists that this model, which describes five major 'domains' or traits, is the best current description of the structure of personality. The five major dimensions, and your scores on them, are described below. Try to interpret your results on the basis of the overall pattern, rather than just concentrating on particular scores.

Factor I : Extraversion (AKA Surgency)

This trait reflects preference for, and behavior in, social situations. People high in extraversion are energetic and seek out the company of others. Low scorers (introverts) tend to be more quiet and reserved. Compared to other people who have taken this test, your score on this dimension (25) is *about average*.

Factor II : Agreeableness (AKA Friendliness)

This trait reflects how we tend to interact with others. People high in agreeableness tend to be trusting, friendly and cooperative. Low scorers tend to be more aggressive and less cooperative. Compared to other people who have taken this test, your score on this dimension (19) is *relatively low*.

Factor III : Conscientiousness (AKA Will or Dependability)

This trait reflects how organized and persistent we are in pursuing our goals. High scorers are methodical, well organized and dutiful. Low scorers are less careful, less focussed and more likely to be distracted from tasks. Compared to other people who have taken this test, your score on this dimension (30) is *about average*.

Factor IV : Neuroticism

This trait reflects the tendency to experience negative thoughts and feelings. High scorers are prone to insecurity and emotional distress. Low scorers tend to be more relaxed, less emotional and less prone to distress. Compared to other people who have taken this test, your score on this dimension (20) is *about average*.

Factor V : Openness (AKA Culture or Intellect)

This trait reflects 'open-mindedness' and interest in culture. High scorers tend to be imaginative, creative, and to seek out cultural and educational experiences. Low scorers are more down-to-earth, less interested in art and more practical in nature. Compared to other people who have taken this test, your score on this dimension (27) is *about average*.

A word of caution - your score on each scale was interpreted relative to a large (2448) sample of other people who have done the test: 'relatively low' means your score was in the bottom 30%, 'relatively high' in the top 30%, and 'about average' somewhere in the middle. However, it is known that different groups of people (e.g. men and women) are likely to score differently on various measures. Therefore, the people you were compared to in generating the feedback may not have been people exactly like you.

If you wish to know more about this personality inventory and how it was developed, you may find the following paper useful:

Buchanan, T., Johnson, J. A., & Goldberg, L. R. (2005). Implementing a Five-Factor Personality Inventory for Use on the Internet. European Journal of Psychological Assessment, 21, 115-127.

Would you be willing to quickly help with a research project?

We are doing a project looking at people's experiences of visual imagery. Participating is quick and easy, and should take no more than 10 minutes. Participants will find out how they score on two measures of visual imagery. If you would be willing to help, or just want to know more about the project, you can find further information here.

Thank you for your participation in this project.

Appendix 3.5.C: Participant information and consent, visual imagery study.

Thank you for your interest in this project, which is concerned with individual differences in how we experience visual imagery.

If you choose to take part, you will be asked to answer a few more questions about your typical thoughts, feelings and behaviour. You will then be asked to complete two short questionnaires about your experiences of visual imagery. Participating in this study should take most people about 10 minutes.

Once you've completed the study, you'll be given more information about it and told what your scores on the imagery questionnaires were.

No information from which you can be personally identified (names, email addresses, or similar) will be collected or shared at any time, or published in research outputs arising from this project. We will take care to respect your privacy at all times. The duty of confidentiality is not absolute and in exceptional circumstances this may be overridden by more compelling duties such as to protect individuals from harm.
Your responses to the personality questionnaire you just completed will be combined with the data you provide in this study.

If you change your mind about participating, you have the right to stop at any time without giving a reason. Data you have already submitted in this study will not be analysed. Once you have indicated your consent at the end of this study, it will no longer be possible to withdraw your data, as you are responding anonymously.
The data you provide will be stored indefinitely on computer systems controlled by the University of Westminster. The data you provide may be re-used in other research projects at the University of Westminster or elsewhere. The data may be Transposeferred or made openly available to other researchers, e.g. through a data repository, for such purposes.

No risks or benefits to you as an individual are anticipated as a result of your participation.

If you have read the information above, and give your consent to participate under these conditions, please tick "I wish to take part in the study" and then click the 'Continue' button.

I wish to take part in the study
I do not wish to take part in the study

Section 1 (BFI)

Here are a number of characteristics that may or may not apply to you. For example, do you agree that you are someone who likes to spend time with
others? Please select a response next to each statement to indicate the extent to which you agree or disagree with that statement.

I see myself as someone who….

Is talkative

Is reserved

Is full of energy

Generates a lot of enthusiasm

Tends to be quiet

Has an assertive personality

Is sometimes shy, inhibited

Is outgoing, sociable

Appendix 3.5.D: Vividness of Visual Imagery Questionnaire (VVIQ)

For each item on this questionnaire, try to form a visual image, and consider your experience carefully. For any image that you do experience, rate how vivid it is using the five-point scale described below. If you do not have a visual image, rate vividness as ‘1’. Only use ‘5’ for images that are truly as lively and vivid as real seeing. Please note that there are no right or wrong answers to the questions, and that it is not necessarily desirable to experience imagery or, if you do, to have more vivid imagery.

Perfectly clear and vivid as real seeing	5
Clear and reasonably vivid	4
Moderately clear and lively	3
Vague and dim	2
No image at all, you only “know” that you are thinking of the object	1

For items 1-4, think of some relative or friend whom you frequently see (but who is not with you at present) and consider carefully the picture that comes before your mind’s eye.

1. The exact contour of face, head, shoulders and body ________________
2. Characteristic poses of head, attitudes of body etc. ________________
3. The precise carriage, length of step etc., in walking ________________
4. The different colours worn in some familiar clothes ________________

Visualise a rising sun. Consider carefully the picture that comes before your mind’s eye.

5. The sun rising above the horizon into a hazy sky ________________
6. The sky clears and surrounds the sun with blueness ________________
7. Clouds. A storm blows up with flashes of lightning ________________
8. A rainbow appears ________________

Think of the front of a shop which you often go to. Consider the picture that comes before your mind’s eye.

9. The overall appearance of the shop from the opposite side of the road ________________
10. A window display including colours, shapes and details Of individual items for sale ________________
11. You are near the entrance. The colour, shape and details of the door. ________________
12. You enter the shop and go to the counter. The counter assistant serves you. Money changes hands ________________

Finally think of a country scene which involves trees, mountains and a lake. Consider the picture that comes before your mind's eye.

13.	The contours of the landscape	________________
14.	The colour and shape of the trees	________________
15.	the colour and shape of the lake	________________
16.	A strong wind blows on the trees and on the lake causing waves in the water.	________________

Appendix 3.5.E: Spontaneous Use of Imagery Scale (SUIS)

Please read each of the following descriptions and indicate the degree to which each is appropriate for you. Do not spend a lot of time thinking about each one, but respond based on your thoughts about how you do or do not perform each activity. If a description is always completely appropriate, please write "5"; if it is never appropriate, write "1"; if it is appropriate about half of the time, write "3"; and use the other numbers (2,4) accordingly.

1. When going to a new place, I prefer directions that include detailed descriptions of landmarks (such as the size, shape, and colour of a gas station) in addition to their names.
2. If I catch a glance of a car that is partially hidden behind bushes, I automatically "complete it," seeing the entire car in my mind's eye.
3. If I am looking for new furniture in a store, I always visualise what the furniture would look like in particular places in my home.
4. I prefer to read novels that lead me easily to visualise where the characters are and what they are doing instead of novels that are difficult to visualise.
5. When I think of visiting a relative, I almost always have a clear mental picture of him or her.
6. When relatively easy technical material is described clearly in a text, I find illustrations distracting because they interfere with my ability to visualise the material.
7. If someone were to tell me two-digits numbers to add (e.g., 24 and 31), I would visualise them in order to add them.
8. Before I get dressed to go out, I first visualise what I will look like if I wear different combinations of clothes.
9. When I think about a series of errands I must do, I visualise the stores I will visit.
10. When I first hear a friend's voice, a visual image of him or her almost always springs to mind.
11. When I hear a radio announcer or DJ that I've never actually seen, I usually find myself picturing what they might look like.
12. If I saw a car accident, I would visualise what happened when later trying to recall the details.

Total: Out of 60.

Appendix 3.5.F: Debrief

Thank you very much for taking part in this study.

In a pilot study, we found a relationship between personality and the experience of visual imagery. Specifically, people with higher extraversion scores tended to report more vivid experiences. In this study, we wanted to confirm that finding, and also to look at relationships between personality and other aspects of imagery. The data you have provided will help us to do this. You completed two established questionnaires dealing with how we experience imagery. In our analyses, we will look at how personality scores (specifically extraversion) correlate with scores on these two measures.

Having a high or low score on these scales doesn't mean your experience of imagery is 'good' or 'weak'. It just tells us about your subjective experience. There are no right or wrong answers in the questionnaires. It is not necessarily desirable to experience imagery, or if you do, to have more vivid imagery. However, participants are often curious to know what their scores were.

On the Vividness of Visual Imagery Questionnaire, your score was out of a possible 80 points. In our pilot study using 20 people, we found the average score for participants was 64 points. However, remember these may not have been people exactly like you so your scores may not be directly comparable.

On the Spontaneous Use of Imagery Scale, your score was out of a possible 60 points. Again, it is difficult to give you anything to compare this score with. However, in our previous pilot study using 20 people, we found the average score for participants was 39 points.

Once again, thank you for participating in our research. The study is now over, and you may close this browser window.

Zoe Pounder
Tom Buchana

Appendix 3.6: Psychometric Conversion Tables

PSYCHOMETRIC CONVERSION TABLE

Standard Score	Percentile Rank	Scaled Score	ETS Score	T-Score	Z-Score	Description
150	>99.9					Very Superior
149	>99.9					Very Superior
148	99.9					Very Superior
147	99.9					Very Superior
146	99.9					Very Superior
145	99.9	19	800	80	+3.0	Very Superior
144	99.8					Very Superior
143	99.8					Very Superior
142	99.7		775	78	+2.75	Very Superior
141	99.7					Very Superior
140	99.6	18	767	77	+2.67	Very Superior
139	99.5					Very Superior
138	99					Very Superior
137	99		750	75	+2.50	Very Superior
136	99					Very Superior
135	99	17	733	73	+2.33	Very Superior
134	99					Very Superior
133	99		725	72	+2.25	Very Superior
132	98					Very Superior
131	98					Very Superior
130	98	16	700	70	+2.00	Very Superior
129	97					Superior
128	97		675	68	+1.75	Superior
127	96					Superior
126	96					Superior
125	95	15	667	67	+1.67	Superior
124	95					Superior
123	94		650	5	+1.50	Superior
122	93					Superior
121	92					Superior
120	91	14	633	63	+1.33	High Average
119	90					High Average
118	88		325	62	+1.25	High Average
117	87					High Average
116	86					High Average
115	84	13	600	60	+1.00	High Average
114	82					High Average
113	81		575	58	+0.75	High Average
112	79					High Average
111	77					High Average
110	75	12	567	57	+0.67	Average
109	73					Average
108	70		550	55	+0.55	Average
107	68					Average
106	66					Average
105	63	11	533	533	+0.33	Average
104	61					Average
103	58					Average
102	55		525	52	+0.25	Average
101	53					Average
100	50	10	500	50	0.00	Average
99	47					Average
98	45		480	48	-0.25	Average
97	42					Average
96	40					Average
95	37	9	467	47	-0.33	Average
94	34					Average
93	32		450	45	-0.50	Average
92	30					Average
91	27					Average
90	25	8	433	43	-0.67	Average

Appendix 3.6: Psychometric Conversion Tables (continued)

PSYCHOMETRIC CONVERSION TABLE

Standard Score	Percentile Rank	Scaled Score	ETS Score	T-Score	Z-Score	Description
89	23					Low Average
88	21		425	42	-0.75	Low Average
87	19					Low Average
86	18					Low Average
85	16	7	400	40	-1.00	Low Average
84	14					Low Average
83	13		375	38	-1.25	Low Average
82	12					Low Average
81	10					Low Average
80	9	6	367	37	-1.33	Low Average
79	8					Borderline
78	7		350	35	-1.50	Borderline
77	6					Borderline
76	5					Borderline
75	5	5	333	33	-1.67	Borderline
74	4					Borderline
73	4		325	32	-1.75	Borderline
72	3					Borderline
71	3					Borderline
70	2	4	300	30	-2.00	Borderline
69	2					Impaired
68	2		275	28	-2.25	Impaired
67	1					Mild (69-55)
66	1					Mild (69-55)
65	1	3	267	27	-2.33	Moderate (54-40)
64	1					Moderate (54-40)
63	1		250	25	-2.50	Severe (39-25)
62	1					Severe (39-25)
61	0.5					Profound (<25)
60	0.4	2	233	23	-2.67	Profound (<25)
59	0.3					Profound (<25)
58	0.2		225	22	-2.75	Profound (<25)
57	0.1					Profound (<25)
56	0.1					Profound (<25)
55	0.1	1	200	20	-3.00	Profound (<25)
54	0.1					Profound (<25)
53	0.1					Profound (<25)
52	0.1					Profound (<25)
51	<0.1					Profound (<25)
50	<0.1					Profound (<25)

Appendix 3.7: Z-scores and psychometric description of performance for aphantasic (A) and control participants (B) in the CANTAB Battery

Highlighted yellow figures indicate z-scores that equate to: impaired to profoundly impaired performance in the tasks.

A) Aphantasic (Aph) z-scores and psychometric description of performance for each participant by CANTAB task

Aph	Z-scores by task											
	VRM			OTS: - Accuracy - Reaction Time (+ve z-scores = slower RT)					SSP			PRM
	Age	Recall Correct	Recognition Correct	Move 2	Move 3	Move 4	Move 5	Move 6	Spatial Span	Total errors	Total usage errors	Total correct
101	54	0.27 Average	0.49 Average	0.35 Average 0.30 Average	0.66 Average 0.51 Average	0.76 High Av 0.95 High Av	-0.38 Average 0.87 High Av	-0.25 Average -0.45 Average	1.74 Superior	0.33 Average	-1.00 Low Av	1.24 High Av
102	33	0.82 High Av	0.49 Average	0.35 Average 0.47 Average	0.66 Average 0.71 High Av	0.76 High Av 0.91 High Av	0.88 High Av -0.14 Average	1.05 High Av 0.05 Average	1.74 Superior	1.82 Superior	1.27 High Av	1.06 High Av
103	31	0.82 High Av	0.49 Average	0.35 Average 0.54 Average	0.66 Average 0.21 Average	0.76 High Av 1.04 High Av	0.80 Low Av -3.23 Profound	0.53 Average -2.58 Severe	1.74 Superior	-0.25 Average	-1.25 Low Av	-0.37 Average
104	37	-0.82 Low Av	-1.95 Borderline	0.35 Average 0.50 Average	0.66 Average 0.49 Average	0.76 High Av 0.63 Average	0.88 High Av -0.04 Average	0.79 High Av 0.67 Average	-1.57 Borderline	0.78 High Av	0.01 Average	0.49 Average
105	57	-0.82 Low Av	-1.95 Borderline	0.35 Average -0.34	0.66 Average 0.59	-0.62 Average -4.20	0.46 Average -4.07	0.27 Average -3.05	0.08 Average	-0.16 Average	-0.02 Average	1.24 High Av

				Average	Average	Profound	Profound	Profound				
106	30	-0.82 Low Av	0.49 Average	0.35 Average 0.72 High Av	0.66 Average 0.05 Average	0.76 High Av -0.43 Average	0.88 High Av 0.77 High Av	0.27 Average -2.76 Profound	1.74 Superior	0.04 Average	0.01 Average	0.77 High Av
107	37	0.82 High Av	0.49 Average	0.35 Average 0.19 Average	0.66 Average 0.46 Average	0.76 High Av 1.06 High Av	0.46 Average -0.37 Average	1.05 High Av -0.36 Average	1.74 Superior	0.04 Average	0.64 Average	0.49 Average
108	41	0.82 High Av	0.49 Average	-0.53 Average 0.12 Average	-0.35 Average 0.39 Average	0.07 Average 0.46 Average	0.88 High Av 1.15 High Av	0.79 High Av 0.19 Average	1.74 Superior	-1.11 Low Av	1.35 Superior	2.88 Very Superior
109	55	-0.27 Average	0.49 Average	0.35 Average -1.60 Borderline	-0.35 Average -1.49 Borderline	-3.39 Profound -3.11 Profound	-0.38 Average 0.19 Average	-0.77 Low Av 0.09 Average	-1.57 Borderline	0.66 Average	-0.02 Average	-0.60 Average
110	37	0.82 High Av	0.49 Average	0.35 Average 0.01 Average	0.66 Average -0.12 Average	0.07 Average -0.13 Average	-0.38 Average -1.02 Low Av	0.79 High Av 0.21 Average	1.74 Superior	0.34 Average	1.27 High Av	0.49 Average
111	42	1.37 Superior	0.49 Average	0.35 Average 0.48 Average	0.66 Average 0.70 High Av	-2.00 Borderline -0.50 Average	-1.22 Low Av -0.01 Average	0.01 Average -0.41 Average	-1.57 Borderline	-0.14 Average	-0.44 Average	2.88 Very Superior

112	39	-0.27 Average	-1.95 Borderline	0.35 Average 0.62 Average	0.66 Average 0.37 Average	0.07 Average -0.39 Average	-0.38 Average -5.94 Profound	0.01 Average -4.94 Profound	0.08 Average	-0.40 Average	-0.62 Average	1.06 High Av
113	29	-1.37 Borderline	-1.95 Borderline	-0.53 Average -0.54 Average	0.66 Average 0.09 Average	0.76 High Av -0.69 Low Av	0.46 Average -2.45 Moderate	0.27 Average -3.69 Profound	0.08 Average	-0.25 Average	-1.25 Low Av	0.77 High Av
114	31	0.27 Average	0.49 Average	0.35 Average 0.32 Average	0.66 Average 0.47 Average	0.07 Average 0.12 Average	0.04 Average -2.08 Impaired	0.27 Average -3.28 Profound	0.08 Average	-0.40 Average	-0.62 Average	0.49 Average
115	38	-1.37 Borderline	0.49 Average	0.35 Average 0.00 Average	-0.35 Average 0.29 Average	0.07 Average 0.19 Average	0.04 Average -1.54 Borderline	0.53 Average -2.43 Moderate	-1.57 Borderline	0.04 Average	0.64 Average	0.49 Average
116	42	0.27 Average	0.49 Average	0.35 Average 0.40 Average	-0.35 Average 0.23 Average	0.07 Average 0.31 Average	-1.64 Borderline -2.20 Impaired	-0.25 Average 0.74 High Av	1.74 Superior	-0.70 Low Av	0.15 Average	2.88 Very Superior
117	28	0.82 High Av	0.49 Average	0.35 Average 0.52 Average	0.66 Average 0.78 High Av	0.76 High Av -0.19 Average	-0.38 Average 0.01 Average	0.53 Average 0.17 Average	0.08 Average	0.49 Average	0.64 Average	0.77 High Av
118	38	0.27 Average	-1.95 Borderline	0.35 Average -0.12 Average	0.66 Average 0.38 Average	0.07 Average 0.72 High Av	-1.22 Low Av -9.77 Profound	0.01 Average -6.88 Profound	0.08 Average	0.93 High Av	-0.62 Average	0.20 Average

	Age	Recall Correct	Recognition Correct	Move 2	Move 3	Move 4	Move 5	Move 6	Spatial Span	Total errors	Total usage errors	Total correct
119	46	-1.92 Borderline	0.49 Average	0.35 Average 0.54 Average	0.66 Average 0.34 Average	0.76 High Av 0.40 Average	-1.64 Borderline -2.43 Moderate	0.53 Average 0.28 Average	0.08 Average	-0.14 Average	0.75 High Av	-5.74 Profound
120	55	-0.82 Low Av	0.49 Average	-0.53 Average -0.24 Average	-0.35 Average 0.03 Average	-0.62 Average 0.29 Average	0.04 Average -1.28 Low Av	-0.25 Average -0.05 Average	-3.22 Profound	-0.98 Low Av	0.96 High Av	0.14 Average

A) Control z-scores and psychometric description of performance for each participant by CANTAB task

Controls	Z-scores by task											
		VRM		OTS: - Accuracy - Reaction Time (+ve z-scores = slower RT)					SSP			PRM
	Age	Recall Correct	Recognition Correct	Move 2	Move 3	Move 4	Move 5	Move 6	Spatial Span	Total errors	Total usage errors	Total correct
1	28	-1.37 Borderline	0.49 Average	0.35 Average -0.14 Average	0.66 Average 0.60 Average	0.76 High Av 0.23 Average	0.04 Average -0.75 Low Av	-0.25 Average -0.41 Average	0.08 Average	0.64 Average	0.64 Average	0.49 Average
2	30	0.27 Average	0.49 Average	0.35 Average -0.30 Average	-0.35 Average -0.43 Average	0.07 Average -0.34 Average	0.04 Average -0.90 Low Av	0.53 Average -0.89 Low Av	0.08 Average	-1.58 Borderline	0.64 Average	0.20 Average
3	26	-0.82 Low Av	0.49 Average	-0.53 Average 0.64 Average	0.66 Average 0.64 Average	0.76 High Av 1.06 High Av	0.46 Average 1.30 High Av	1.05 High Av 1.32 High Av	1.74 Superior	0.93 High Av	1.27 High Av	0.77 High Av

4	25	0.82 High Av	0.49 Average	0.35 Average -0.30 Average	0.66 Average 0.14 Average	0.07 Average -0.98 Low Av	0.04 Average 0.64 Average	-0.25 Average -0.63 Average	1.74 Superior	-1.88 Borderline	0.01 Average	1.06 High Av
5	25	0.27 Average	-1.95 Borderline	-4.03 Profound -3.75 Profound	-2.38 Moderate -2.94 Profound	-2.00 Borderline -2.27 Mild	-2.90 Profound -0.51 Average	0.77 Low Av 0.27 Average	0.08 Average	-0.10 Average	-1.25 Low Av	0.20 Average
6	27	-0.27 Average	0.49 Average	0.35 Average 0.64 Average	-0.35 Average 0.06 Average	-2.00 Borderline -0.94 Low Av	0.88 High Av 1.26 High Av	1.29 High Av 1.63 Superior	0.08 Average	-0.69 Low Av	-1.25 Low Av	0.49 Average
7	57	0.27 Average	-1.95 Borderline	0.35 Average 0.26 Average	0.66 Average 0.81 High Av	0.76 High Av 0.78 High Av	0.46 Average 0.32 Average	0.53 Average 0.86 High Av	0.08 Average	0.66 Average	0.47 Average	0.14 Average
8	37	0.82 High Av	0.49 Average	0.35 Average 0.50 Average	0.66 Average 0.23 Average	0.76 High Av 1.12 High Av	0.88 High Av -1.17 Low Av	0.01 Average -1.74 Borderline	0.08 Average	-0.55 Average	0.01 Average	1.06 High Av
9	32	-0.27 Average	0.49 Average	-0.53 Average 0.65 Average	-0.35 Average -0.39 Average	-1.31 Low Av -1.72 Borderline	0.88 High Av 1.33 High Av	0.53 Average 0.37 Average	-1.57 Borderline	0.93 High Av	-0.62 Average	1.06 High Av
10	25	1.37	0.49	0.35	0.66	0.76	0.88	-0.25	0.08	0.64	0.01	0.77

		Superior	Average	Average 0.26 Average	Average 0.48 Average	High Av 0.97 High Av	High Av -0.16 Average	Average -0.90 Low Av	Average	Average	Average	High Av
11	42	1.37 Superior	0.49 Average	0.35 Average 0.72 High Av	-0.35 Average -0.26 Average	0.07 Average 0.51 Average	0.46 Average 0.63 Average	0.79 High Av 0.45 Average	-1.57 Borderline	1.53 Superior	-1.04 Low Av	2.88 Very Superior
12	52	-1.92 Borderline	-1.95 Borderline	0.35 Average -0.17 Average	-0.35 Average -0.06 Average	0.07 Average 0.45 Average	-1.22 Low Av 0.78 High Av	0.27 Average 1.67 Superior	0.08 Average	0.01 Average	0.47 Average	0.14 Average
13	46	0.27 Average	0.49 Average	0.35 Average 0.64 Average	0.66 Average 0.69 High Av	0.76 High Av 0.93 High Av	0.46 Average 0.81 High Av	0.53 Average -0.38 Average	0.08 Average	1.39 Superior	0.75 High Av	1.16 High Av
14	55	-0.82 Low Av	0.49 Average	0.35 Average 0.17 Average	0.66 Average -0.11 Average	-1.31 Low Av -1.35 Borderline	0.04 Average -0.91 Low Av	-1.03 Low Av 0.16 Average	0.08 Average	-0.81 Low Av	0.96 High Av	0.51 Average
15	44	0.27 Average	0.49 Average	0.35 Average 0.37 Average	0.66 Average 0.80 High Av	0.76 High Av 0.80 High Av	0.04 Average -0.66 Average	-3.11 Profound -0.66 Average	-1.57 Borderline	0.28 Average	0.75 High Av	1.16 High Av
16	40	-0.27 Average	0.49 Average	0.35 Average -0.33 Average	0.66 Average 0.55 Average	0.76 High Av 0.46 Average	-1.22 Low Av -1.47 Borderline	-0.25 Average -0.54 Average	0.08 Average	0.56 Average	1.35 Superior	-2.29 Mild

17	51	1.37 Superior	0.49 Average	-0.53 Average 0.11 Average	0.66 Average 0.10 Average	-1.31 Low Av 0.08 Average	-1.64 Borderline -0.78 Low Av	0.01 Average -0.83 Low Av	0.08 Average	0.83 High Av	0.47 Average	0.14 Average
18	30	0.82 High Av	0.49 Average	0.35 Average 0.91 High Av	0.66 Average 0.95 High Av	0.07 Average 0.83 High Av	0.88 High Av 1.82 Superior	1.05 High Av 1.68 Superior	-1.57 Borderline	1.37 Superior	-0.62 Average	1.06 High Av
19	54	-0.27 Average	-1.95 Borderline	0.35 Average 0.14 Average	-1.37 Borderline -2.37 Moderate	0.76 High Av -0.18 Average	0.04 Average -1.09 Low Av	0.79 High Av -0.91 Low Av	0.08 Average	0.66 Average	-0.02 Average	-0.23 Average
20	55	-1.92 Borderline	0.49 Average	0.35 Average -1.00 Low Av	-2.38 Moderate 0.49 Average	0.76 High Av -0.45 Average	0.46 Average -0.46 Average	1.05 High Av -0.51 Average	1.74 Superior	-1.64 Borderline	1.44 Superior	-0.60 Average

<u>APPENDICES for Chapter 4:</u>

Appendix 4.1: Z-scores aphantasic and control participants within the MRT and OBT/transpose tasks with psychometric descriptions

a) *Aphantasic z-scores on the Mental Rotation Task*

APHANTASIC PARTICIPANTS: MRT Z-scores accuracy and reaction time						
	MRT: Accuracy			**MRT: Reaction Time**		
	40°	**85°**	**220°**	**40°**	**85°**	**220°**
101	1.23 *High vA*	0.71 *High Av*	0.02 *Average*	0.91 *High Av*	0.57 *Average*	0.72 *High Av*
102	0.03 *Average*	-0.65 *Average*	-0.68 *Low Av*	-0.70 *Low Av*	-1.38 *Borderline*	-1.69 *Borderline*
<u>103</u>	0.78 *High Av*	0.71 *High Av*	1.54 *Superior*	-0.07 *Average*	-0.66 *Average*	-0.94 *Low Av*
104	0.78 *High Av*	1.02 *High Av*	1.19 *High Av*	0.49 *Average*	0.54 *Average*	0.24 *Average*
<u>105</u>	-1.10 *Low Av*	-2.95 *Profound*	-0.44 *Average*	-0.44 *Average*	-0.32 *Average*	-0.24 *Average*
106	0.40 *Average*	1.13 *High Av*	1.31 *High Av*	-0.69 *Low Av*	-0.43 *Average*	-0.60 *Average*
107	1.01 *High Av*	1.34 *Superior*	1.31 *High Av*	-0.69 *Low Av*	-1.32 *Low Av*	-0.84 *Low Av*
108	0.63 *Average*	1.44 *Superior*	2.25 *V Superior*	-0.11 *Average*	-0.45 *Average*	-0.52 *Average*
109	-1.71 *Borderline*	-1.90 *Borderline*	-2.32 *Mild*	0.74 *High Av*	0.92 *High Av*	1.10 *High Av*
110	0.78 *High Av*	0.71 *High Av*	1.19 *High Av*	-3.74 *Profound*	-4.71 *Profound*	-4.18 *Profound*
111	0.03 *Average*	-0.02 *Average*	-1.03 *Low Av*	-0.83 *Low Av*	-0.74 *Low Av*	-0.78 *Low Av*
<u>112</u>	0.40 *Average*	1.02 *High Av*	1.31 *High Av*	-3.43 *Profound*	-2.84 *Profound*	-2.86 *Profound*
<u>113</u>	0.03 *Average*	1.65 *Superior*	1.89 *Superior*	-0.36 *Average*	-0.40 *Average*	-0.33 *Average*
<u>114</u>	0.55 *Average*	-2.63 *Profound*	-0.80 *Low Av*	-2.72 *Profound*	-1.11 *Low Av*	-2.34 *Moderate*
<u>115</u>	-0.88 *Low Av*	-0.13 *Average*	-0.68 *Low Av*	-0.49 *Average*	-0.75 *Low Av*	-0.32 *Average*
116	-0.50 *Average*	-2.11 *Impaired*	-0.80 *Low Av*	0.28 *Average*	0.52 *Average*	0.75 *High Av*
117	-0.05 *Average*	-0.44 *Average*	0.26 *Average*	-0.57 *Average*	-0.48 *Average*	-0.17 *Average*
<u>118</u>	0.03 *Average*	-0.13 *Average*	0.26 *Average*	0.82 *High Av*	0.75 *High Av*	0.80 *High Av*
119	1.01 *High Av*	0.50 *Average*	1.19 *High Av*	0.33 *Average*	0.51 *Average*	0.29 *Average*
120	0.78 *High Av*	1.65 *Superior*	1.54 *Superior*	-2.24 *Impaired*	-2.34 *Moderate*	-2.18 *Impaired*

b) Control z-scores on the Mental Rotation Task

CONTROL PARTICIPANTS: MRT Z-scores accuracy and reaction time						
	MRT: Accuracy				**MRT: Reaction Time**	
	40°	**85°**	**220°**	**40°**	**85°**	**220°**
1	-0.80 *Low Av*	0.00 *Average*	0.49 *Average*	0.69 *High Av*	1.10 *High Av*	0.87 *High Av*
2	0.18 *Average*	0.00 *Average*	-0.68 *Low Av*	-0.17 *Average*	-0.04 *Average*	-0.16 *Average*
3	0.40 *Average*	-0.10 *Average*	-0.44 *Average*	0.93 *High Av*	1.02 *High Av*	0.93 *High Av*
4	0.63 *Average*	0.16 *Average*	0.84 *High Av*	0.14 *Average*	-0.43 *Average*	-0.30 *Average*
5	-2.91 *Profound*	-0.27 *Average*	-1.38 *Borderline*	2.04 *V.Superior*	1.95 *Superior*	1.88 *Superior*
6	0.85 *High Av*	0.00 *Average*	0.84 *High Av*	1.07 *High Av*	0.91 *High Av*	1.15 *High Av*
7	0.63 *Average*	0.10 *Average*	0.49 *Average*	0.31 *Average*	0.43 *Average*	0.24 *Average*
8	0.78 *High Av*	0.10 *Average*	0.84 *High Av*	-0.26 *Average*	-1.44 *Borderline*	-1.56 *Borderline*
9	-0.05 *Average*	-0.08 *Average*	0.96 *High Av*	0.78 *High Av*	0.63 *Average*	0.78 *High Av*
10	0.55 *Average*	0.17 *Average*	0.61 *Average*	-0.65 *Average*	-0.64 *Average*	-0.16 *Average*
11	-0.05 *Average*	-0.04 *Average*	-1.15 *Low Av*	0.36 *Average*	0.70 *High Av*	0.48 *Average*
12	-0.27 *Average*	0.08 *Average*	-0.09 *Average*	-0.39 *Average*	-1.12 *Low Av*	-0.97 *Low Av*
13	-1.93 *Borderline*	-0.15 *Average*	-0.44 *Average*	-1.01 *Low Av*	-0.41 *Average*	-0.71 *Low Av*
14	-0.65 *Average*	-0.19 *Average*	-2.32 *Mild*	-1.15 *Low Av*	-1.18 *Low Av*	-1.31 *Low Av*
15	0.55 *Average*	-0.04 *Average*	-0.44 *Average*	0.69 *High Av*	1.01 *High Av*	1.11 *High Av*
16	-0.05 *Average*	0.02 *Average*	-1.38 *Borderline*	-2.59 *Severe*	-1.89 *Borderline*	-1.88 *Borderline*
17	0.18 *Average*	-0.01 *Average*	0.49 *Average*	-0.57 *Average*	-0.12 *Average*	-0.20 *Average*
18	0.40 *Average*	0.03 *Average*	0.02 *Average*	0.39 *Average*	0.41 *Average*	0.54 *Average*
19	1.23 *High Av*	0.13 *Average*	1.54 *Superior*	-0.88 *Low Av*	-0.87 *Low Av*	-0.88 *Low Av*
20	0.33 *Average*	0.10 *Average*	1.19 *High Av*	0.27 *Average*	-0.01 *Average*	0.13 *Average*

c) Reaction time Z-scores for control participants in the OBT/transpose conditions.

	Controls OBT: Reaction time z-scores			
	OBT		**Transpose**	
	Front	**Back**	**Que Present**	**Que absent**
1	-2.20 *Impaired*	-1.15 *Low Av*	0.14 *Average*	0.79 *High Av*
2	-0.81 *Low Av*	0.03 *Average*	0.46 *Average*	0.23 *Average*
3	-0.98 *Low Av*	0.44 *Average*	-0.13 *Average*	0.26 *Average*
4	0.99 *High Av*	0.93 *High Av*	0.80 *High Av*	1.31 *High Av*
5	-0.73 *Average*	-1.49 *Borderline*	-1.49 *Borderline*	-1.20 *Low Av*
6	0.44 *Average*	-0.96 *Low Av*	-0.01 *Average*	-0.84 *Low Av*
7	0.21 *Average*	0.40 *Average*	-0.22 *Average*	-0.33 *Average*
8	0.98 *High Av*	1.14 *High Av*	1.03 *High Av*	0.32 *Average*
9	0.73 *High Av*	0.91 *High Av*	2.14 *V. superior*	1.89 *Superior*
10	0.35 *Average*	0.77 *High Av*	-0.62 *Average*	0.01 *Average*
11	0.83 *High Av*	0.29 *Average*	0.37 *Average*	0.05 *Average*
12	-1.61 *Borderline*	-1.67 *Borderline*	-1.70 *Borderline*	-1.57 *Borderline*
13	-0.57 *Average*	-1.10 *Low Av*	-0.13 *Average*	-0.52 *Average*
14	0.60 *Average*	0.96 *High Av*	0.47 *Average*	0.95 *High Av*
15	0.29 *Average*	0.49 *Average*	0.08 *Average*	0.06 *Average*
16	0.49 *Average*	-0.37 *Average*	-0.18 *Average*	-0.55 *Average*
17	-0.62 *Average*	-1.05 *Low Av*	-0.34 *Average*	-1.23 *Low Av*
18	2.22 *V. superior*	2.07 *V. superior*	1.26 *High Av*	2.09 *V. superior*
19	-0.77 *Low Av*	-0.90 *Low Av*	-2.37 *Moderate*	-1.24 *Low Av*
20	0.15 *Average*	0.26 *Average*	0.45 *Average*	-0.47 *Average*

d) *Reaction time Z-scores for aphantasic participants in the OBT/transpose conditions*

	Aphantasic OBT: Reaction time z-scores			
	OBT		**Transpose**	
	Front	**Back**	**Que Present**	**Que absent**
101	0.95 *High Av*	0.24 *Average*	-3.32 *Profound*	-1.54 *Borderline*
102	0.15 *Average*	1.06 *High Av*	0.39 *Average*	0.42 *Average*
103	0.83 *High Av*	0.81 *High Av*	1.35 *Superior*	1.31 *High Av*
104	-1.04 *Low Av*	-0.62 *Average*	-0.31 *Average*	-0.50 *Average*
105	-0.33 *Average*	-0.58 *Average*	0.08 *Average*	0.68 *High Av*
106	0.94 *High Av*	0.37 *Average*	-0.48 *Average*	0.82 *High Av*
107	-1.09 *Low Av*	-0.29 *Average*	-0.98 *Low Av*	-0.82 *Low Av*
108	-0.85 *Low Av*	0.92 *High Av*	-0.04 *Average*	0.71 *High Av*
109	-0.24 *Average*	-0.58 *Average*	-0.69 *Low Av*	-0.11 *Average*
110	-1.99 *Borderline*	-2.73 *Impaired*	-2.36 *Moderate*	-1.57 *Borderline*
111	-1.20 *Low Av*	-1.27 *Low Av*	-1.74 *Borderline*	-0.84 *Low Av*
112	-0.63 *Average*	-0.76 *Low Av*	0.01 *Average*	0.18 *Average*
113	0.89 *High Av*	0.30 *Average*	0.02 *Average*	0.81 *High Av*
114	-0.91 *Low Av*	0.31 *Average*	0.01 *Average*	1.56 *Superior*
115	-1.85 *Borderline*	-1.05 *Low Av*	1.11 *High Av*	0.43 *Average*
116	-1.76 *Borderline*	-0.64 *Average*	0.69 *High Av*	0.24 *Average*
117	1.31 *High Av*	1.35 *Superior*	1.05 *High Av*	0.88 *High Av*
118	0.90 *High Av*	1.30 *High Av*	0.02 *Average*	0.98 *High Av*
119	0.59 *Average*	0.78 *High Av*	1.54 *Superior*	1.64 *Superior*
120	-1.40 *Borderline*	-0.77 *Low Av*	-2.49 *Moderate*	-0.94 *Low Av*

APPENDICES for Chapter 5:

Appendix 5.1: Recruitment posters advertising for aphantasic and control participants

Appendix 5.2: True/False statements

Key for statements: New statements / Eddy & Glass (1981) as used in Zeman et al., (2015) / Cortical blindness and visual imagery (Policardi 1996)

Each of these sentences is either true or false. I would like you to tell me whether you think each sentence is true or false and respond as accurately and as quickly as possible. (Answers are in brackets).

VISUAL DETAILS

Colour discrimination

1. Apricots are darker than a banana skin (T) /
2. Raspberries are darker than strawberries (T)
3. Aubergines are darker than Blueberries (T)
4. Tangerines are darker than terracotta (F)
5. Daffodil are darker than hay (F) X
6. Milk is darker than spaghetti (F)
7. Oats are darker than talcum powder (T)
8. Radish are darker than ham (T)
9. The inside of a grapefruit is darker than the insides of an orange (T)
10. Avocado skin is darker than spinach (T)
11. A post box is darker than a UK passport (F)
12. Turmeric is darker than paprika (F)
13. Grass is darker than a pine tree (F)
14. Spinach is darker than celery (T)
15. Walnuts are darker than a coffee bean (F)
16. Milk chocolate is darker than Brown bread (T)
17. A tomato is darker than a red onion (F)
18. Potatoes are darker than a cauliflower (T)
19. Pumpkin is darker than a butternut squash (T)
20. The colour of Blue-Tack is darker than the colour of lavender X (F)
21. Avocado skin is darker than a kiwi (T)

Colour feature statements

1. A 'No Entry' sign is red and white (T)
2. Fire exit signs are usually blue (F)
3. Cadburys packaging is purple (T)
4. First aid signs are usually green (T)
5. The EU flag is navy and white (F)
6. Donald Trump has brown hair (F)
7. The central cross on the Union Jack is white (T)
8. A first class stamp is red (T)
9. A second class stamp is green (F)

10. A tennis ball is yellow (T)
11. An ambulance is red (F)

Texture (smooth) statements

1. A raspberry is smoother than a grape (F)
2. A brick is smoother than a tangerine (F)
3. A petal smoother than hay (T)
4. A piece of chocolate smoother than a slice of bread (T)
5. A shell of a walnut is smoother than marshmallow (F)
6. A pebble is smoother than glass (F)
7. A scouring pad is smoother than paper (F)
8. Bubble wrap is smoother than tree bark (T)
9. Foil is smoother than ribbon (T)
10. An apple is smoother than a tennis ball (T)

SPATIAL

Size discrimination statements/ Structure/location statements

1. A recycle symbol is comprised of three arrows (T)
2. The figure in the Starbucks logo is male (F)
3. The number four can be written using four lines (F)
4. A star of David has five points (F)
5. Tractors have two very large wheels at the front (F)
6. The number eight can be constructed by two circles (T)
7. The symbol for degrees is a tiny circle (T)
8. A rugby ball is spherical (F)
9. A wheelbarrow has two wheels (F)
10. An acoustic guitar has a square shaped sound hole (for sound to resonate) (F)
11. The key lock on a door is above the handle (F)
12. A bicycle saddle is narrower at the front than behind (T)
13. A baseball bat is thicker at the end than the grip (T)
14. A penguin has longer legs than a duck (F)
15. A goat is larger than a hare (T)
16. A worm is larger than a woodlouse (T)
17. A canoe is widest in the centre than the ends (T)
18. A grapefruit is larger than an orange (T)
19. A £1 coin is larger than a 2p coin (F)
20. A golf ball is larger than a snooker ball (F)
21. A 5p coin is larger than a 1p coin (F)
22. A match is larger than a toothpick (F)
23. A ladle is larger than a tablespoon (T)
24. A cigar is larger than a cigarette (T)

Size Are these objects higher than wider or wider than higher? 11 T / 11 F

1. Soap (width) – A bar of soap is more wide than tall (T)
2. Traffic-light (high) – A traffic-light is more wide than tall (F)
3. Bottle (high) – A bottle is more wide than tall (F)
4. Crate (width) – A crate is more wide than tall (T)
5. Vase (height) – A vase is more wide than tall (F)
6. Sofa (width) – A sofa is more wide than tall (T)
7. Wardrobe (high) – A wardrobe is more wide than tall (F)
8. Boot (high) – A boot is more wide than tall (F)
9. Television set (width) – A TV is more wide than tall (T)
10. Egg (high) – An egg wider is more wide than tall (F)
11. Typewriter (width) – A typewriter is more wide than tall (T)
12. Bell (high) – A bell is more wide than tall (F)
13. Can of tuna (width) - A can of tuna is more wide than tall (T)
14. Tankard (high) – A tankard is more wide than tall (F)
15. Fridge (high) A fridge is more wide than tall (F)
16. Bench (width) – A bench is more wide than tall (T)
17. Dining chair (height) – A dining chair is more wide than tall (F)
18. Bed (width) – A bed is more wide than tall (T)
19. Lid of a pot (width) – A lid of a pot is more wide than tall (T)
20. Keyboard (width) – A keyboard is more wide than tall (T)

Appendix 5.3: Participant familiarity sheet-checker
Participant number…………………………………………………………

Below are a list of items which were listed in the previous task. Please look through and put an X next to any of these items which are unfamiliar to you/ if you do not know the item.

Item	**Rating**	**Item**	**Rating**
Apricots		Fire exit	
Banana		Cadburys	
Raspberries		First aid sign	
Strawberries		EU flag	
Tangerine		Donald Trump	
Terracotta		Second class stamp	
Milk		Ambulance	
Spaghetti		Grass	
Radish		Pinetree	
Ham		Grape	
Post Box		Brick	
UK Passport		Tangerine	
Turmeric		Petal	
Paprika		Hay	
Spinach		Marshmallow	
Celery		Pebble	
Walnuts		Glass	
Coffee bean		Scouring pad	
Milk chocolate		Paper	
Brown bread		Bubble wrap	
Tomato		Tree bark	
Red onion		Tractor	
No entry sign		The number eight	
Apple		Tennis ball	
Recycle symbol		Symbol for degrees	
Bicycle saddle		Rugby ball	
Baseball bat		Wheelbarrow	

Penguin
Duck
Goat
Hare
Worm
Orange
£1 coin
2p coin
5p coin
Tablespoon
Bar of soap
Traffic light
Bottle
Crate
Vase
Sofa
Bell
Barrel
Tankard
Fridge
Bench
Handle

Guitar sound hole
Key lock
Woodlouse
Canoe
Grapefruit
Golf ball
Snooker ball
1p coin
Ladle
Cigar
Cigarette
Wardrobe
Boot
TV
Egg
Typewriter
Can of tuna
Keyboard
Dining chair
Bed
Lid of a pot

Appendix 5.4: Demographic Questions

Participant Number…………………………………….

Age…………………………………………………..   Sex…………………

Where were you born (closest major city)? ……………………………………

Closest city to where you went to primary school (or equivalent, at age 5-11):

……………………………………………….……………………………

Closest city to where you went to secondary school (or equivalent, at age 11-16):

……………………………………………………………………………………

Appendix 5.5: The Bucknell Auditory Imagery Scale (BAIS)

Bucknell Auditory Imagery Scale (BAIS-V)

The following questions measure auditory imagery, or the way in which you "think about sounds in your head." For the following items you are asked to do the following:

1. Read the item and consider whether you think of an image of the described sound in your head.

2. Then rate the vividness of your image using the following "Vividness Rating Scale" between 1-7 on the following scale for each question.

1 = No image	2	3	4 = Fairly as vivid	5	6	7 = Vivid as actual sound

Feel free to use all of the levels in the scale when selecting your ratings.

1. For the first item, consider the beginning of the song "Happy Birthday."
The sound of a trumpet beginning the piece._____

2. For the next item, consider ordering something over the phone.
The voice of an elderly clerk assisting you._____

3. For the next item, consider being at the beach.
The sound of the waves crashing against nearby rocks. _____

4. For the next item, consider going to a dentist appointment.
The loud sound of the dentist's drill.______

5. For the next item, consider being present at a jazz club.
The sound of a saxophone solo.______

6. For the next item, consider being at a live baseball game.
The cheer of the crowd as a player hits the ball._____

7. For the next item, consider attending a choir rehearsal.
The sound of an all-children's choir singing the first verse of a song. ______

8. For the next item, consider attending an orchestral performance of Beethoven's Fifth.
The sound of the ensemble playing. ______

9. For the next item, consider listening to a rain storm.
The sound of gentle rain. ______

10. For the next item, consider attending classes.

The slow-paced voice of your English teacher.______

11. For the next item, consider seeing a live opera performance.
The voice of an opera singer in the middle of a verse.______

12. For the next item, consider attending a new tap-dance performance.
The sound of tap-shoes on the stage.______

13. For the next item, consider a kindergarten class.
The voice of the teacher reading a story to the children.______

14. For the next item, consider driving in a car.
The sound of an upbeat rock song on the radio.______

Part 2: Bucknell Auditory Imagery Scale (BAIS-C)

The following scale is designed to measure auditory imagery, or the way in which you "think about sounds in your head." - **Use the same scale as on the opposite page**

For the following pairs of items you are asked to do the following: Read the first item (marked "a") and consider whether you think of an image of the described sound in your head. Then read the second item (marked "b") and consider how easily you could change your image of the first sound to that of the second sound and hold this image.
Rate how easily you could make this change using the "Ease of Change Rating Scale." If no images are generated, give a rating of 1. Please read "a" first and "b" second for each pair. It may be necessary to cover up "b" so that you focus first on "a" for each pair.

1. For the first pair, consider attending a choir rehearsal.
a. The sound of an all-children's choir singing the first verse of a song.
b. An all-adults' choir now sings the second verse of the song. ______

2. For the next pair, consider being present at a jazz club.
a. The sound of a saxophone solo.
b. The saxophone is now accompanied by a piano.______

3. For the next pair, consider listening to a rain storm.
a. The sound of gentle rain.
b. The gentle rain turns into a violent thunderstorm.______

4. For the next pair, consider driving in a car.
a. The sound of an upbeat rock song on the radio.
b. The song is now masked by the sound of the car coming to a screeching halt. ______

5. For the next pair, consider ordering something over the phone.
a. The voice of an elderly clerk assisting you.
b. The elderly clerk leaves and the voice of a younger clerk is now on the line.______

6. For the next pair, consider seeing a live opera performance.
a. The voice of an opera singer in the middle of a verse.
b. The opera singer now reaches the end of the piece and holds the final note. ______

7. For the next pair, consider going to a dentist appointment.
a. The loud sound of the dentist's drill.
b. The drill stops and you can now hear the soothing voice of the receptionist.______

8. For the next pair, consider the beginning of the song "Happy Birthday."
a. The sound of a trumpet beginning the piece.
b. The trumpet stops and a violin continues the piece.______

9. For the next pair, consider attending an orchestral performance of Beethoven's Fifth.
a. The sound of the ensemble playing.
b. The ensemble stops but the sound of a piano solo is present.______

10. For the next pair, consider attending a new tap-dance performance.
a. The sound of tap-shoes on the stage.
b. The sound of the shoes speeds up and gets louder.______

11. For the next pair, consider being at a live baseball game.
a. The cheer of the crowd as a player hits the ball.
b. Now the crowd boos as the fielder catches the ball._____

12. For the next pair, consider a kindergarten class.
a. The voice of the teacher reading a story to the children.
b. The teacher stops reading for a minute to talk to another teacher. ______

13. For the next pair, consider attending classes.
a. The slow-paced voice of your English teacher.
b. The pace of the teacher's voice gets faster at the end of class. ______

14. For the next pair, consider being at the beach.
a. The sound of the waves crashing against nearby rocks.
b. The waves are now drowned out by the loud sound of a boat's horn out at sea. _____

Appendix 5.6: The Plymouth Sensory Imagery Questionnaire (Psi-Q)

Please try to form the images described below and rate each mental image on the following scale:

0 (no image at all) to 10 (image as clear and vivid as real life)

Please rate every item

Imagine the appearance of:

- A friend you know well
- A cat climbing a tree
- A sunset
- The front door of your house
- A bonfire

Imagine the sound of:

- An ambulance siren
- Hands clapping in applause
- The mewing of a cat
- The sound of a car horn
- The sound of children playing

Imagine the smell of:

- A stuffy room
- A rose
- Fresh paint
- Newly cut grass
- Burning wood

Imagine the taste of:

- Mustard
- Toothpaste
- Lemon
- Sea water
- Black pepper

Imagine touching

- Warm sand
- A soft towel
- The point of a pin
- Icy water
- Fur

Imagine the bodily sensation of:

- Relaxing in a warm bath
- Having a sore throat
- Threading a needle
- Jumping into a swimming pool
- Walking briskly in the cold

Imagine feeling:

- Excited
- Relieved
- Furious
- In love
- Scared

Appendix 5.7: Participant information sheet and consent for sensory questionnaires

Information sheet

(Please copy and paste this information so that you can either print or save it and refer to if necessary).

The aim of this questionnaire is to examine self-reports of imagery within different sensory modalities. It should take you between 20-25 minutes to complete. At the end of the questionnaire, you will be asked to leave your contact details (name and email address) if you wish to be contacted with regards to further research. We will only contact you if you agree to participate in further research.

As you go through the questionnaire, please note that there are no right or wrong answers to the questions. It is not necessarily desirable to experience imagery or, if you do, to have more vivid imagery.

Please note:

Participation is entirely voluntary.

You have the right to withdraw at any time without giving a reason.

You have the right to ask for your data to be withdrawn and for personal information to be destroyed.

The results of this study will be published in appropriate outlets.

Your responses will be confidential.

No individuals will be identifiable from any collated data, written report of the research, or any publications arising from it.

If you have any queries please contact: Zoe Pounder: z.pounder@my.westminster.ac.uk

Consent Form

Please select below if you have read the above information and are willing to act as a participant in the research study.

Yes I agree to participate in this questionnaire

Appendix 5.8: Debrief for sensory questionnaires

Thank you for taking the time to complete our questionnaires. These questionnaires aim to examine self-reported imagery vividness across various sensory modalities in aphantasics who lack visual mental imagery, and non-aphantasics who have normal visual imagery. These results will form the basis of future studies within this area.

If you have any further queries regarding this research, please contact Zoë Pounder at z.pounder@my.westminster.ac.uk

APPENDICES for Chapter 6:
Appendix 6.1: The Goldsmiths Musical Sophistication Index (Gold-MSI)

Score on a scale of 1-7 (1 = completely disagree, 7 = completely agree), please put an X in the appropriate column.

	1 = completely disagree	2	3	4	5	6	7 = completely agree
I spend a lot of my free time doing music-related activities.							
I enjoy writing about music, for example on blogs and forums.							
If somebody starts singing a song I don't know, I can usually join in.							
I can sing or play music from memory.							
I am able to hit the right notes when I sing along with a recording.							
I can compare & discuss differences between two performances or versions of the same piece of music							
I have never been complimented for my talents as a musical performer.							
I often read or search the internet for things related to music.							
I am not able to sing in harmony when somebody is singing a familiar tune.							
I am able to identify what is special about a given musical piece.							
When I sing, I have no idea whether I'm in tune or not.							

Music is kind of an addiction for me - I couldn't live without it.

I don’t like singing in public because I’m afraid that I would sing wrong notes.

I would not consider myself a musician.

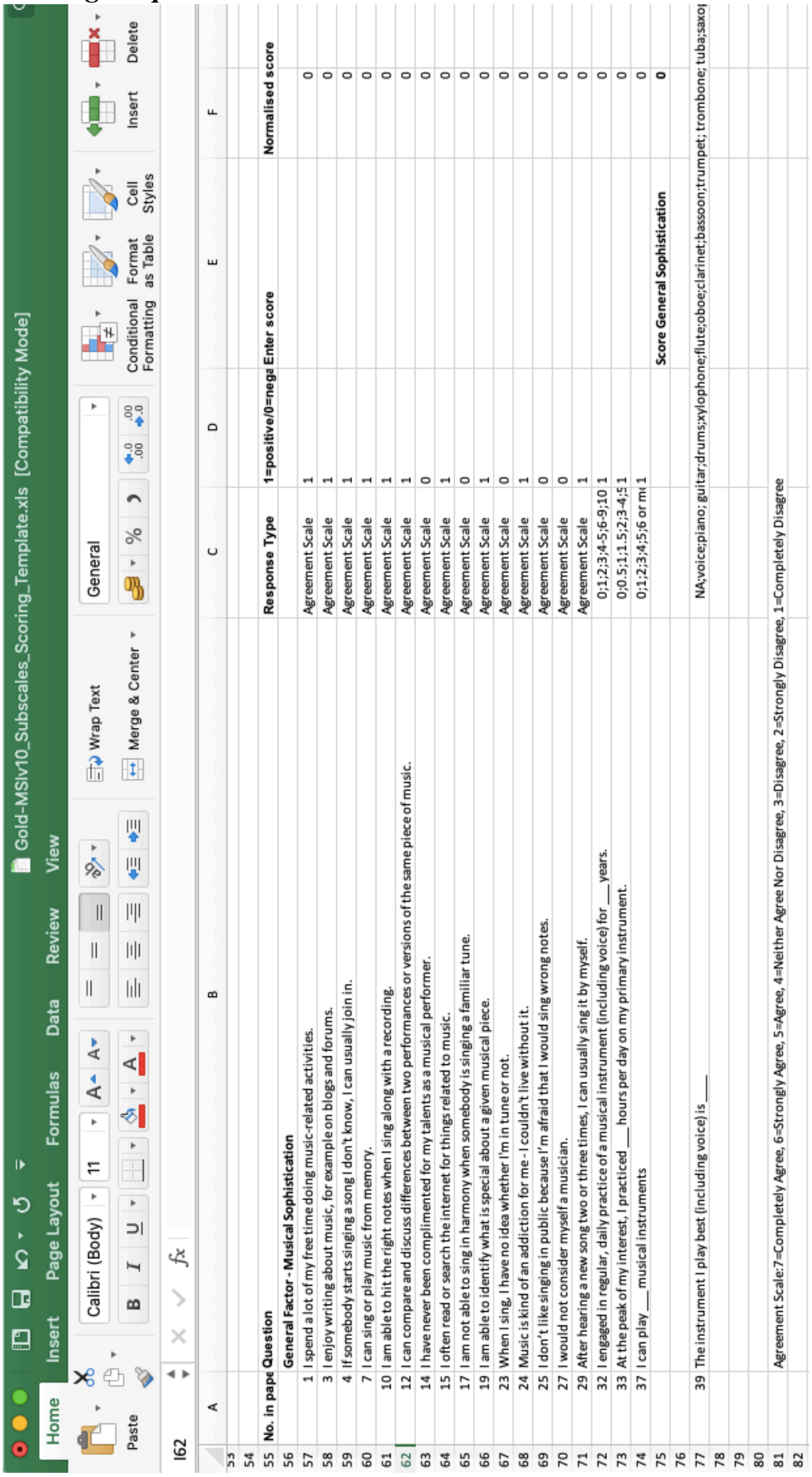
After hearing a new song two or three times, I can usually sing it by myself.

I engaged in regular, daily practice of a musical instrument (including voice) for ___ years.

At the peak of my interest, I practiced ___ hours per day on my primary instrument.

I can play ___ musical instruments

Appendix 6.2: Copy of Goldsmiths Musical Sophistication Index (Gold-MSI) scoring template



Gold-MSIv10_Subscales_Scoring_Template.xls [Compatibility Mode]

	A	B	C	D	E	F
54						
55	No. in pape	Question	Response Type	1=positive/0=nega	Enter score	Normalised score
56		General Factor - Musical Sophistication				
57	1	I spend a lot of my free time doing music-related activities.	Agreement Scale	1		0
58	3	I enjoy writing about music, for example on blogs and forums.	Agreement Scale	1		0
59	4	If somebody starts singing a song I don't know, I can usually join in.	Agreement Scale	1		0
60	7	I can sing or play music from memory.	Agreement Scale	1		0
61	10	I am able to hit the right notes when I sing along with a recording.	Agreement Scale	1		0
62	12	I can compare and discuss differences between two performances or versions of the same piece of music.	Agreement Scale	1		0
63	14	I have never been complimented for my talents as a musical performer.	Agreement Scale	0		0
64	15	I often read or search the internet for things related to music.	Agreement Scale	1		0
65	17	I am not able to sing in harmony when somebody is singing a familiar tune.	Agreement Scale	0		0
66	19	I am able to identify what is special about a given musical piece.	Agreement Scale	1		0
67	23	When I sing, I have no idea whether I'm in tune or not.	Agreement Scale	0		0
68	24	Music is kind of an addiction for me - I couldn't live without it.	Agreement Scale	1		0
69	25	I don't like singing in public because I'm afraid that I would sing wrong notes.	Agreement Scale	0		0
70	27	I would not consider myself a musician.	Agreement Scale	0		0
71	29	After hearing a new song two or three times, I can usually sing it by myself.	Agreement Scale	1		0
72	32	I engaged in regular, daily practice of a musical instrument (including voice) for ___ years.	0;1;2;3;4-5;6-9;10	1		0
73	33	At the peak of my interest, I practiced ___ hours per day on my primary instrument.	0;0.5;1;1.5;2;3-4;5	1		0
74	37	I can play ___ musical instruments	0;1;2;3;4;5;6 or m	1		0
75					Score General Sophistication	0
76						
77	39	The instrument I play best (including voice) is ____	NA;voice;piano; guitar;drums;xylophone;flute;oboe;clarinet;bassoon;trumpet; trombone; tuba;saxo			
78						
79						
80						
81		Agreement Scale:7=Completely Agree, 6=Strongly Agree, 5=Agree, 4=Neither Agree Nor Disagree, 3=Disagree, 2=Strongly Disagree, 1=Completely Disagree				
82						

Appendix 6.3: Original list of 49 songs for piloting (Experiment 9)

Information sheet

In this questionnaire, you will be asked to rate how familiar you are with a variety of different songs.

You will be asked to rate these songs on a scale of 1-5. As you go through the list of songs, please note there are no right or wrong answers. This should take you no longer than 10 minutes to complete.

Please note:

Participation is entirely voluntary and all responses are anonymous.

You have the right to withdraw at any time without giving a reason.

The responses provided will be used to inform the creation of a future task.

Consent

Please select below:

Please select how familiar each of these songs are on a scale of 1-5. The artist of the song is provided first, followed by the name of the song.

Rating scale:
1 = I do not know this song
2 = I know of this song but I do not know it well
3 = I can hum or sing only the chorus of this song
4 = I can hum or sing the majority of this song
5 = I can hum or sing this song from start to finish

Song	**1 = I do not know this song**	**2 = I know of this song but I do not know it well**	**3 = I can hum or sing only the chorus of this song**	**4 = I can hum or sing the majority of this song**	**5 = I can hum or sing this song from start to finish**
Madonna – Like a Virgin					
Louis Armstrong – What a Wonderful World					
The La's – There She Goes					
The Beatles – Hey Jude					

Oasis – Don't Look Back in Anger	
Kate Bush – Running Up that Hill	
The Verve – Bitter Sweet Symphony	
Marvin Gaye & Tammi Terrell – Ain't No Mountain High Enough	
Wham! – Wake Me Up Before You Go-Go	
Gabriel – Outta Reach	
Big Mountain – Oooh Baby, I Love Your Way	
Neil Diamond – Sweet Caroline	
Irene Cara – What a Feeling	
The Calling – Wherever You Will Go	
Starship – Nothing's Gonna Stop Us Now	
Whitney Houston – I Wanna Dance with Somebody (Who Loves Me)	
Jerry Lee Louis – Great Balls of Fire	
Take That – Rule The World	
Blue & Elton John – Sorry Seems To Be The Hardest Word	
Judy Garland, Wizard of Oz – Somewhere Over The Rainbow	
Sound of Music – My Favourite Things	

Elton John – Can You Feel the Love Tonight	
Sam Smith – Writing's On The Wall	
Ryan Gosling – City of Stars	
Shirley Bassey – Diamonds Are Forever	
Julie Andrews, Mary Poppins – A Spoonful of Sugar	
Illene Woods, Cinderella – A Dream Is a Wish Your Heart Makes	
Peabo Bryson & Regina Belle, Aladdin – A Whole New World	
Bedknobs & Broomsticks – The Beautiful Briny	
Frank Sinatra – Have Yourself A Merry Little Christmas	
Gabrielle Aplin – The Power of Love	
Mariah Carey – All I Want for Christmas Is You	
Wizzard – I Wish It Could Be Christmas Everyday	
Perry Combo & Mitchell Ayres – It's Beginning to Look a Lot Like Christmas	
Peter Auty – Walking In the Air	
The Ronettes – I Saw Mommy Kissing Santa Claus	

The Jackson 5 – Santa Claus Is Coming To Town	
Ella Fitzgerald – Frosty The Snowman	
Frere Jacques (nursery rhyme)	
Twinkle Twinkle Little Star (nursery rhyme)	
Rock a Bye Baby (nursery rhyme)	
Baa, Baa, Black Sheep (nursery rhyme)	

Appendix 6.4: Final song list based on song response by different age groups
Highlighted code: HIGH PITCH and LOW PITCH

Songs in light grey songs are excluded

QUESTION: Is the pitch of the second underlined syllable higher or lower than the pitch of the first underlined syllable?

VERSION 1: 17 Certain songs that all 20-70s scored 3 and above for familiarity:

In this list there are: 10 songs where the second syllable is lower // 7 songs where the second syllable is higher

1. Madonna – Like A Virgin (*Like a vir-gin*) 3 semitones
2. The Beatles – Hey Jude 3 semitones
3. Oasis – Don't Look Back in Anger (*Don't Look Back in An-ger*) 7 semitones
4. Wham! – Wake Me Up Before You Go-Go (*wake me up be-fore you go go*) 4 semitones
5. Neil Diamond – Sweet Caroline (*Sweet Caro-line*) 7 semitones
6. Whitney Houston – I Wanna Dance With Somebody
   (*I wan-na dance with some-bod-y*) 4 semitones
7. Judy Garland – Somewhere Over the Rainbow
   (*Some-where o-ver the rain-bow*) 12 semitones
8. Sound of Music – My Favourite Things (*My fa-vour-ite things*) 4 semitones
9. Mary Poppins – A Spoonful of Sugar (*A spoon-ful of su-gar*) 6 semitones
10. Frank Sinatra – Have Yourself A Merry Little Christmas
   (*Have your-self a mer-ry lit-tle Christ-mas*) 8 semitones
11. Mariah Carey – All I Want For Christmas Is You
   (*All I want for Christ-mas is you*) 4 semitones
12. Wizzard – I Wish It Could Be Christmas Every Day
   (*I wish it could be Christ-mas every da-y*) 5 semitones
13. Perry Combo & Mitchelle Ayres – It's Beginning to Look a Lot Like Christmas
   (*It's be-gin-ning to look a lot like Christ-mas*) 9 semitones
14. Ella Fitzgerald – Frosty the Snowman (*Fros-ty the snow-man*) 8 semitones
15. Frere Jacques (*Fre-re Jac-ques*) 4 semitones
16. Twinkle Twinkle Little Star (Twin-kle, twin-kle, lit-tle star) 7 semitones
17. Ba Ba Black Sheep 7 semitones

Gaps: 0 gap = 5 / 1 gap = 7 / 2 gap = 5

Average number of semitones when the second syllable is low: 5.4 - 10 songs in total

Average number of semitones when the second syllable is high: 6.9 - 7 songs in total

7 Less certain songs (but still familiar to most):

1. The La's – There She Goes
2. The Verve – Bitter Sweet Symphony (*A bit-ter sweet sym-pho-ny*)
3. Irene Cara – What A Feeling (*What a feel-ing*)
4. Jerry Lee Louis – Great Balls of Fire
5. Elton John – Can You Feel The Love Tonight (*Can you feel the love to-night?*)
6. Shirley Baddey – Diamonds are Forever (*Dia-monds are for-ev-er*)
7. Peter Auty – Walking in the Air (*Walk-ing in the air*)

7/ 7 /7

Practice/demo examples:

1. Peabo Bryson & Regina Belle Aladdin – A Whole New World (1 syllable gap)
2. The Ronettes - I Saw Mommy Kissing Santa Claus (2 syllable gap)
3. Starship – Nothing's Gonna Stop Us Now (no gap)
4. Shirley Bassey – Diamonds are Forever

Version 2 (of the above songs) with different high/low markings:

1. Madonna – Like a Virgin
2. The Beatles – Hey Jude –
3. Oasis – Don't Look Back in Anger
4. Wham! – Wake Me Up Before You Go-Go
5. Neil Diamond – Sweet Caroline
6. Whitney Houston – I Wanna Dance With Somebody
7. Judy Garland – Somewhere Over the Rainbow
8. Sound of Music – My Favourite Things
9. Mary Poppins – A Spoonful of Sugar
10. Frank Sinatra – Have Yourself A Merry Little Christmas
11. Mariah Carey – All I Want For Christmas Is You
12. Wizzard – I Wish It Could Be Christmas Every Day
13. Perry Combo & Mitchelle Ayres – It's Beginning to Look a Lot Like Christmas
14. Ella Fitzgerald – Frosty the Snowman

15. Frere Jacques
16. Twinkle Twinkle Little Star
17. Ba Ba Black Sheep
18. The La's - There She Goes (less familiar)
19. The Verve – Bitter Sweet Symphony (less familiar)
20. Irene Cara - What A Feeling (less familiar)

10 low second syllable / 7 high second syllable

Gaps: 0 gap = 7 / 1 gap = 6 / 2 gap = 7

When the three above are added there will be 10 songs for each high/low variety.

Appendix 6.5: Informed consent and participant information sheet

Primary researcher: Zoë Pounder

Supervisors: Dr Alison Eardley, Professor Catherine Loveday and Dr Samuel Evans

Introduction
We would like to invite you to participate in our study exploring auditory imagery in individuals who have aphantasia (lack visual mental imagery) and individuals who have typical visual imagery. Before you sign the informed consent form, we would like to ask you to read the following information carefully.

Participant Criteria
If you have any of the following, please notify the experimenter: have impaired hearing, are colour blind.
If you were born and went to school outside of the UK, please also inform the experimenter.

Aim of this study
The goal of this study is to examine performance between individuals with aphantasia and individuals with typical imagery in tasks which involve auditory imagery. At present, research in aphantasia has focused on the visual domain and no studies have yet explored performance within the auditory domain.

Design of the study
The study requires you to attend one testing session. The session will last approximately 1 hour 30 minutes including breaks. During this session, you will undertake four computerised tasks. Each task will have a practice element or demonstration so you understand the nature of the task before starting. You will also be asked to complete a Feedback sheet with regards to the tasks at the end of the session and answer questions with regards to your musical ability.

Confidentiality of the data
Your privacy will be assured by coded gathering and analysis of the data. The data will only be available to current members of the research team, and not be given to a thirdparty. All data will be stored in compliance with the Data Protection Act 2018 and General Protection Regulations (GDPR) 2018. The data will be preserved for a maximum of 15 years.

Participant's rights:

- It is important that you know that your participation in this experiment is completely voluntary, and that you can stop at any moment, without reason.
- As a participant, you have the right to ask questions at any time, even during the experiment. It is also possible that you have questions after having finished the experiment. In that case, please contact Zoë Pounder at z.pounder@my.westminster.ac.uk

Results of the study

The results of this study are likely to be disseminated at national and/or international conferences and published in scientific peer-reviewed journals. These results will also be written up for the purposes of Zoë Pounder's PhD thesis.

Further information

Zoë Pounder (z.pounder@my.westminster.ac.uk) and supervisor Dr Alison Eardley (a.eardley@westminster.ac.uk) will be glad to answer your questions about the study at any time.

By signing below you are agreeing that:

1. You have read and understood the information sheet and have had the opportunity to ask questions which have been answered satisfactorily.
2. You are taking part in this research study voluntarily and have been made aware of your rights to withdraw at any time without providing an explanation.
3. You understand once you have taken part in the study, you are still able to withdraw your data at any point until the research has published/submitted as part of my research project, or has been anonymised.
4. You are aware your identity and the information provided will be treated confidentially and in accordance with the University of Westminster ethical guidelines and British Psychological Society code of human research ethics.
5. Your data will be securely stored in compliance with the Data Protection Act 2018 and General Data Protection Regulations (GDPR) 2018.

6. Your data will be anonymised and will not be identifiable from subsequent research papers that arise from this study.

With my signature, I confirm my participation to this study, and volunteer for a research subject.

Name of participant: ………..……………………………………………………

Signed ……………………………………………… Date …………………

Appendix 6.6: Debrief Sheet: Auditory Imagery Study

Thank you for participating in this study investigating aspects of auditory imagery. The tasks you have undertaken comprise of various aspects of auditory imagery and required you to recall and/or hold information as well as manipulate this auditory information. The data gathered will be used to examine how performance in individuals with aphantasia differs from those participants who have typical imagery. At present, no studies have investigated the auditory domain in individuals with aphantasia, with much of the research undertaken in the visual domain. Research suggests that both visual imagery and auditory imagery have several characteristics in common. By investigating the auditory domain, it may provide new insights into aphantasia and open further avenues for investigation.

Results of the study

The results of this study are likely to be disseminated at national and/or international conferences and published in scientific peer-reviewed journals. These results will also be written up for the purposes of Zoë Pounder's PhD thesis.

For further information

If you have any further queries regarding this research, please contact one of the research team at the University of Westminster:

Zoë Pounder: z.pounder@my.westminster.ac.uk
Dr Alison Eardley (a.eardley@westminster.ac.uk)

Appendix 6.7: Familiarity rating list for songs in the lyric task

Participant number……………………………………………………………………………….

Please put an X in the box rating how familiar these songs are (continues on the next page).

	Artist (first) and Song (second)	**Familiarity Rating: How familiar are these songs?**				
		1 = I do not know this song	**2 = I know of this song but I do not know it well**	**3 = I can hum or sing only the chorus of this song**	**4 = I can hum or sing the majority of this song**	**5 = I can hum or sing this song from start to finish**
1	Madonna – Like A Virgin					
2	The Beatles – Hey Jude					
3	Oasis – Don't Look Back in Anger					
4	Wham! – Wake Me Up Before You Go-Go					
5	Neil Diamond – Sweet Caroline					
6	Whitney Houston – I Wanna Dance With Somebody					
7	Judy Garland – Somewhere Over the Rainbow					
8	Sound of Music – My Favourite Things					

9	Mary Poppins – A Spoonful of Sugar					
10	Frank Sinatra – Have Yourself A Merry Little Christmas					
11	Mariah Carey – All I Want For Christmas Is You					
12	Wizzard – I Wish It Could Be Christmas Every Day					
13	Perry Combo & Mitchelle Ayres – It's Beginning to Look a Lot Like Christmas					
14	Ella Fitzgerald – Frosty the Snowman					
15	Frere Jacques					
16	Twinkle Twinkle Little Star					
17	Ba Ba Black Sheep					
18	Bittersweet Symphony – The Verve					
19	There She Goes – The La's					
20	What A Feeling – Irene Cara/ Flashdance					

Appendix 6.8: Randomised consonant vowel syllables

Sounds	original	V1	V2	V3	V4	V5
1	ba	ka	ma	va	ja	ra
2	ca	ya	na	ca	ra	wa
3	da	za	ja	ya	ha	ma
4	fa	la	ra	za	ga	ca
5	ga	sa	fa	sa	wa	ja
6	ha	ba	ka	pa	va	ka
7	ja	ma	ta	ka	ma	va
8	ka	ja	ba	da	pa	da
9	la	da	pa	la	ta	na
10	ma	ta	wa	ra	na	ha
11	na	ca	da	ta	ba	ga
12	pa	ga	va	ha	ya	ta
13	ra	ha	ca	ja	ca	za
14	sa	ra	la	ga	za	ya
15	ta	pa	sa	ma	da	sa
16	va	va	ga	ba	fa	fa
17	wa	na	ha	fa	ka	la
18	ya	fa	za	wa	la	ba
19	za	wa	ya	na	sa	pa

Appendix 6.9: Bamford-Kowal-Bench (BKB) sentences

No

1 The clown had a funny face.

2 The car engine's running.

3 She cut with her knife.

4 Children like strawberries.

5 The house had nine rooms.

6 They're buying some bread.

7 The green tomatoes are small.

8 They're looking at the clock.

9 He played with his train.

10 The postman shut the gate.

11 The bag bumps on the ground.

12 The boy did a handstand.

13 A cat sits on the bed.

14 The lorry carried fruit.

15 The rain came down.

16 The ice cream was pink.

17 The ladder's near the door.

18 They had a lovely day.

19 The ball went into the goal.

20 The old gloves are dirty.

21 He cut his finger.

22 The thin dog was hungry.

23 The boy knew the game.

24 Snow falls at Christmas.

25 She's taking her coat.

26 The police chased the car.

27 A mouse ran down the hole.

28 The lady's making a toy.

29 Some sticks were under the tree.

30 The little baby sleeps.

31 They're watching the train.

32 The school finished early.

33 The glass bowl broke.

34 The dog played with a stick.

35 The kettle's quite hot.

36 The farmer keeps a bull.

37 They say some silly things.

38 The lady wore a coat.

39 The children are walking home.

40 He needed his holiday.

41 The milk came in a bottle.

42 The man cleaned his shoes.

43 They ate the lemon jelly.

44 The boy's running away.

45 Father looked at the book.

46 She drinks from her cup.

47 The room's getting cold.

48 A girl kicked the table.

49 The wife helped her husband.

50 The machine was quite noisy.

51 The old man worries.

52 A boy ran down the path.

53 The house had a nice garden.

54 She spoke to her son.

55 They're crossing the street.

56 Lemons grow on trees.

57 He found his brother.

58 Some animals sleep on straw.

59 The jam jar was full.

60 They're kneeling down.

61 The girl lost her doll.

62 The cook's making a cake.

63 The child grabs the toy.

64 The mud stuck on his shoe.

65 The bath towel was wet.

66 The matches lie on the shelf.

67 They're running past the house.

68 The train had a bad crash.

69 The kitchen sink's empty.

70 A boy fell from the window.

71 She used her spoon.

72 The park's near the road.

73 The cook cut some onions.

74 The dog made an angry noise.

75 He's washing his face.

76 Somebody took the money.

77 The light went out.

78 They wanted some potatoes.

79 The naughty girl's shouting.

80 The cold milk's in a jug.

81 The paint dripped on the ground.

82 The mother stirs the tea.

83 They laughed at his story.

84 Men wear long trousers.

85 The small boy was asleep.

86 The sun melted the snow.

87 The father's coming home.

88 She had her pocket money.

89 The lorry drove up the road.

90 He's bringing his raincoat.

91 The lady goes to the shop.

92 A sharp knife’s dangerous.

93 They took some food.

94 The clever girls are reading.

95 The broom stood in the corner.

96 The woman tidied her house.

97 The children dropped the bag.

98 The dog came back.

99 The floor looked clean.

100 She found her purse.

101 The fruit lies on the ground.

102 Mother fetches a saucepan.

103 They washed in cold water.

104 The young people are dancing.

105 The bus went early.

106 They had two empty bottles.

107 A ball’s bouncing along.

108 The father forgot the bread.

109 The girl has a picture book.

110 The orange was quite sweet.

111 He’s holding his nose.

112 The new road’s on the map.

113 The boy forgot his book.

114 A friend came for lunch.

115 The match boxes are empty.

116 He climbed his ladder.

117 They heard a funny noise.

118 The jug stood on the shelf.

119 The ball broke the window.

120 They're shopping for cheese.

121 The family bought a house.

122 The pond water's dirty.

123 Police are clearing the road.

124 The bus stopped suddenly.

125 She writes to her brother.

126 The footballer lost a boot.

127 The three girls are listening.

128 The coat lies on a chair.

129 The book tells a story.

130 The young boy left home.

131 They're climbing the tree.

132 She stood near her window.

133 The table has three legs.

134 A letter fell on the mat.

135 The five men are working.

136 The shoes were very dirty.

137 He listens to his father.

138 They went on holiday.

139 Baby broke his mug.

140 The lady packed her bag.

141 The dinner plate's hot.

142 The train's moving fast.

143 The child drank some milk.

144 The car hit a wall.

145 A tea towel's by the sink.

146 The cleaner used a broom.

147 She looked in her mirror.

148 The good boy's helping.

149 They followed the path.

150 The kitchen clock was wrong.

151 Someone's crossing the road.

152 The postman brings a letter.

153 The dog jumped on the chair.

154 They're cycling along.

155 He broke his leg.

156 The milk was by the front door.

157 The shirts hang in the cupboard.

158 The ground was too hard.

159 The buckets hold water.

160 The chicken laid some eggs.

161 The family like fish.

162 Sugar's very sweet.

163 The baby lay on a rug.

164 The washing machine broke.

165 They're clearing the table.

166 The cleaner swept the floor.

167 A grocer sells butter.

168 The milkman drives a small van.

169 The bath water was warm.

170 He's reaching for his spoon.

171 She hurt her hand.

172 The boy slipped on the stairs.

173 They're staying for supper.

174 The girl held a mirror.

175 The cup stood on a saucer.

176 The cows went to market.

177 The boy got into trouble.

178 They're going out.

179 The football hit the goalpost.

180 He paid his bill.

181 The teacloth’s quite wet.

182 A cat jumped off the fence.

183 The baby has blue eyes.

184 Mother made some curtains.

185 They sat on a wooden bench.

186 The oven’s too hot.

187 The girl caught a cold.

188 The raincoat’s hanging up.

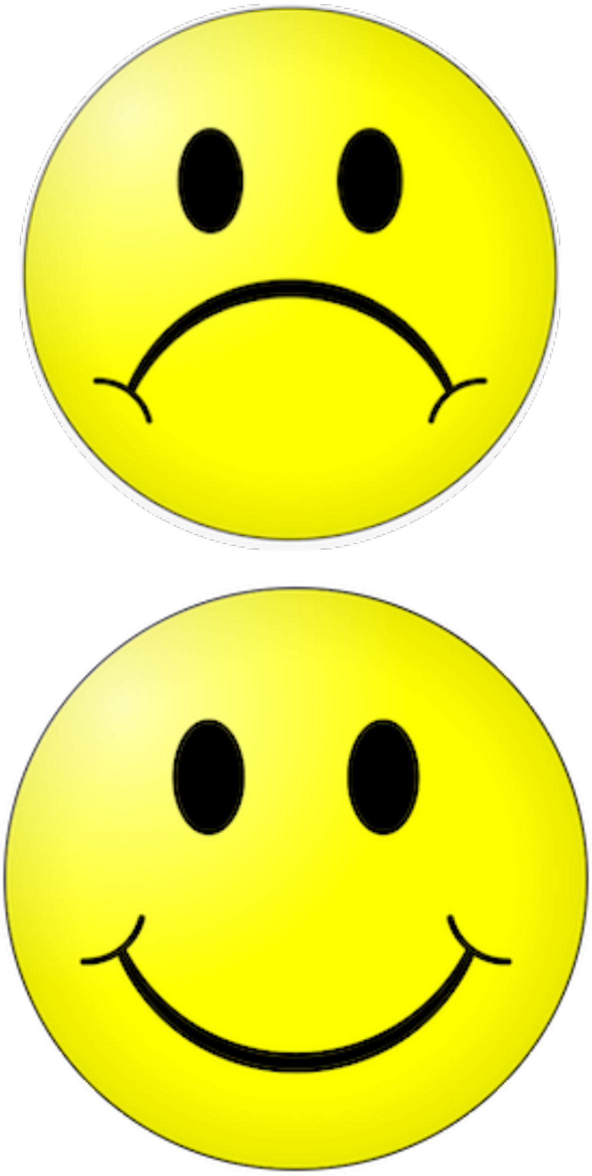
189 She brushed her hair.

190 The two children are laughing.

191 The man tied his scarf.

192 The flower stands in a pot.

Appendix 6.10: Visual feedback presented to participants during the training phase of the categorical perception paradigm.



Appendix 6.11: Analysis of entire participant sample (location matched and including all aphantasic participants who self-report auditory imagery)

Average β values (i.e gradient of the curve) were calculated on MATLAB for each set of speakers. One aphantasic participant was removed from the analysis from speaker pair TD-ZN in the /ka/ and /ma/ continuum as the participant's responses indicated they had confused which speaker was which. No other participants were excluded in the analysis. An independent t-test of slope gradients across groups showed no significant difference in categorical perception function in speaker pair DH-AE ($t(58) = 1.02$, p = .31, $d = .25$), TD-ZN ($t(57) = 0.91$, p = .37, $d = .22$) or AE1-PS ($t(58) = 0.95$, p = .35, $d = .25$).

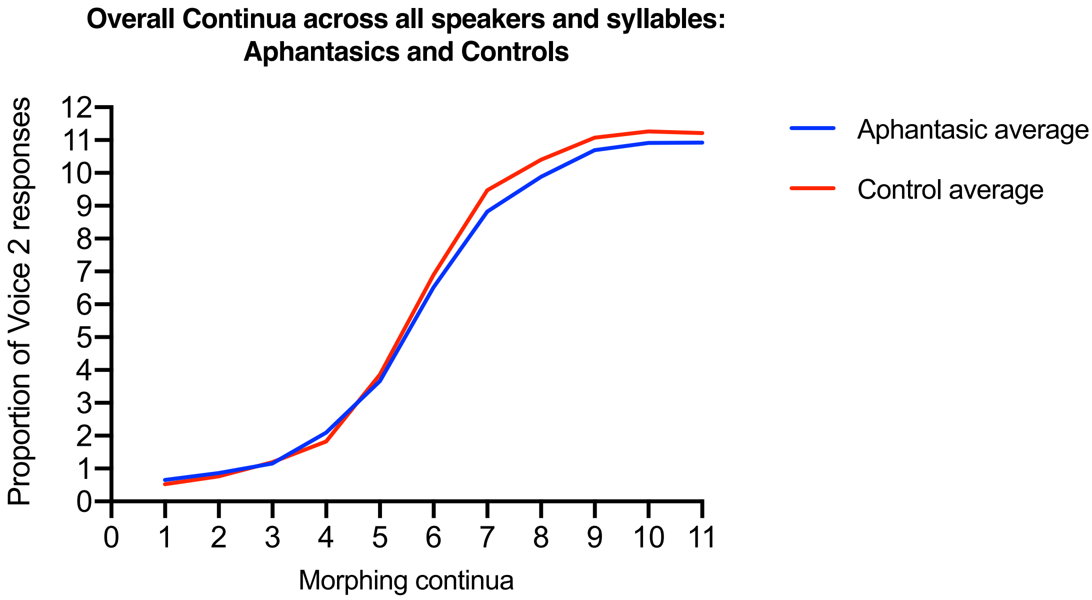


Figure 1: Graph to show overall averaged categorical functions between aphantasic and controls

Slope gradients were averaged across speakers to form a grand average of β-values for the two participant groups. An independent t-test of slope gradients for aphantasics and controls showed no significant difference ($t(58) = -0.41$, p = .69, $d = .11$) between groups. The continua gradient slopes for AE1-PS (for syllables /la/ and /na/, see Figure 6.7c) suggest that these continua produced flatter and more noisy categorical function curves by each participant group. To ensure that the inclusion of these two continua did not impact on the results (i.e. there remains no significant difference between groups), an independent t-test of combined slope gradients for speakers DH-AE and TD-ZN showed no significant difference ($t(58) = 1.15$, p = .25, $d = .28$) between aphantasics and controls.

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