

**Cross – modal Working Memory; Discrimination of Pattern and Frequency in the Visual
and Tactile Modality**

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DECLARATION

I, Chrysi Anastasaki confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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ABSTRACT

The function of Working Memory implicates integration of stimuli from different senses which hold different properties. Several studies have exhibited how Vision and Touch have an impact on each other and how cardinal aspect of stimulation, such as Pattern and Frequency share processing codes. Seeking to evaluate whether humans deploy domain-general or domain-specific mechanisms, this thesis compares the relationship between Visual and Tactile modalities and between Pattern and Frequency in each modality and cross-modal comparisons. A psychometric test – Delayed Discrimination Task– employs visual flickering and vibrotactile stimulation to measure the cognitive performance (accuracy) of 11 participants in two modalities (Vision, Touch) and two tasks (Pattern – Frequency). The results did not indicate a statistical dependency between variables – apart from a marginal significance of cross-modal interaction—this dissociation advocate for modality-specific mechanisms in WM for Vision and Touch. The marginal association between features of stimulation is discussed for its possibility to suggest domain-general codes of featural processing. Although this work comes with certain limitations, delineation of these cardinal mechanisms has an impact on the apprehension of mental aptitudes such as sensory and motor skills. It expands in topics of brain organization, cerebral plasticity and cognitive dysfunction. In future studies, the combination of psychometric tests and neuroimaging can infer more robust results across conditions and participants.

Main Text Word Count : 9757

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ABBREVIATIONS

ANOVA – Analysis of Variance

APA- American Psychological Association

ATOM – A Theory of Magnitude

CMT – Constructive Metaphor Theory

CXWM – Cross-modal Working Memory

DCAL – Deafness Cognition and Language Research Center

DLPFC – Dorso-Lateral Pre-Frontal Cortex

DMTS – Delayed Discrimination Task

DT – Discrimination Test

DV – Dependent Variable

DG – Domain-General

DS – Domain-Specific

EEG – Electroencephalography

fMRI - Functional Magnetic Resonance Imaging

IPS - Intra - Parietal Sulcus

ITR- Inferior Temporal Region

IV – Independent Variable

LH – Left Hemisphere

LTM – Long term Memory

OC – Occipital Cortex

OL – Occipital Lobe

PET – Positron Emission Tomography

PFC – Pre-Frontal Cortex

PL – Parietal Lobe

PPC – Posterior Parietal Cortex

RH - Right Hemisphere

RT – Reaction Time

S1- Primary Somatosensory Cortex

S2 – Secondary Somatosensory Cortex

SC – Superior Colliculus
SMG - Supra Marginal Gyrus
SPSS – Statistical Package for Social Sciences
STM – Short - term Memory
SWM – Somatosensory (Tactile) Working Memory
TF- Tactile Frequency
TP- Tactile Pattern
TS – Test Score
V1 – Primary Visual Cortex
VF – Visual Frequency
VP – Visual Pattern
VWM – Visual Working Memory
WM – Working Memory
STS - Superior Temporal Sulcus

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INTRODUCTION

Cognition is the term used to describe the process of knowledge acquisition and comprehension. This field has shared interests with neuroscience and the implementation of different experimental methods such as behavioural, neuroimaging and pharmacological techniques in order to nuance how humans process information and what influences their behaviour. The brain – and the rest of the central nervous system- play a protagonist role in this exploration as it is the governing body of the processes responsible for perception and action. Every cerebral function has neural mechanisms which support its operation and a behavioural impact which is the reflection of these mechanisms in the external self and the environment. (Sternberg & Sternberg, 2012).

Working Memory is considered a cognitive system with a limited capacity which temporarily stores and processes information. The senses are the modes of delivering stimuli with different properties in WM. The focus of this thesis is the Visual and Tactile that they have defining features of Pattern and Frequency. The exact mechanisms of this type of processing in WM are not yet fully understood. However, a variety of studies have suggested the interrelation between Visual and Tactile Modalities and between stimulation with spatial (Pattern) and temporal (Frequency) value. These findings have created the challenge of defining cross-modal WM memory as a domain-general or domain-specific system. These findings have associated the discrimination of Pattern and Frequency with either individual or standard codes of processing those features.

This thesis analyzed the data of the cognitive performance of participants who completed a behavioural test. This psychophysical method is used in this thesis to infer how perceptual

mechanisms possibly shape behaviour. The study of a unified perceptual experience in psychobiology entails mental aptitudes such as motor and sensory skills, language acquisition, decision making or others. The delineation of the putative mechanisms of the WM in different sensory modalities and different traits of stimuli renders an insight on how cerebral organization intertwines with behaviour, cognitive dysfunctions or topics such as brain plasticity.

Hence, this work is divided into two parts: The first part (Chapter 1) is the literature review where the core debates and ideas of this topic are analyzed to acquaint the reader with following research objectives. The second part (Chapters 2-5) presents a research paradigm which explores a dual aspiration; understand the mechanisms of WM concerning Visual and Tactile modalities and concerning the discrimination of Pattern and Frequency as features of stimuli. The discussion part following the methodological analysis provides the interpretation of the evidence and states the limitations of this study.

PART 1: LITERATURE REVIEW

1. THEORETICAL BACKGROUND; BIOLOGICAL AND BEHAVIOURAL ISSUES IN CROSS-MODAL WORKING MEMORY AND THE DISCRIMINATION OF STIMULI

Every day humans are repeatedly asked to internalise and comprehend information. This process is made possible through the communication of neurons (Gazzaniga, 2009). Neurons conduct signals known as action potentials. These signals have to travel from one neuron to the next to get anywhere. A synapse is a place where two neurons link (Purves, 2012). This activity enables messages to be conveyed from the brain to the body (top-bottom) or from the body to the brain, (bottom-up process) and the outcome of this interaction produces behaviour (Augustine, 2008). While external behaviour can be examined with cognitive tests (e.g., how people responded to a stimulus), neuronal activity can be examined with neuroimaging methods such as functional imaging (fMRI), or EEG (electroencephalography) (Sternberg & Sternberg, 2012).

A piece of information (usually object or event) which evokes the human perception and elicits a response, it is considered a stimulus or in the plural, stimuli. Different stimuli can enter the cognitive realm through the sensory system and with the compensation of mental functions such as attention, perception and memory (Eysenck & Brysbaert, 2018). These five fundamental senses are sight, hearing, touch, smell and taste, and there is an organ or a body part which is liable for their function (Sternberg & Sternberg, 2012). This thesis will measure WM tasks in Vision and Touch; therefore, it is crucial to recognise their anatomical structure and function.

Vision is the function that acknowledges the stimulus of light. The lenses and the pupils obtain the stimuli (light) and direct it towards the retina. The latter is a complex layer of

photoreceptors which converts light (the stimulus) into nerve impulse signals that can be processed by corresponding nerves in the cerebral cortex. (Augustine, 2008). Visual stimuli are processed in the Visual Cortex, which is part of the Occipital Lobe (OL) (Fig.3). The Primary Visual Cortex (V1) located in the Visual Cortex is structured in neat subareas, and it is engineered to recognise, amongst others; orientation, direction and boundaries of stimuli (Purves, 2012).

Touch is categorised as a mechanical sense and is made possible through designated tactile receptors located in skin structures as well as in body hair. Applied pressure permits the sensation of touch. A stimulation in parts of the tactile mechanoreceptors generates a potential that is conveyed via dedicated nerves to the spinal cord and the brain in the Primary Somatosensory Cortex (S1) (Augustine, 2008). S1 is divided into multiple sections, and each one of them corresponds to a specific location of the body. Plausibly, certain areas have augmented sensitivity (e.g., the hands) compared to others; thus, they acquire a disproportionately large place of reference in the S1 (Gazzaniga, 2009).

FIGURE 1:

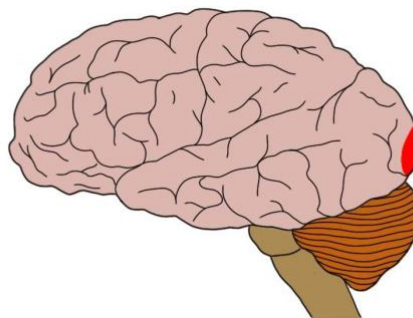


Figure 1: Illustration of the location of the Primary Visual Cortex (in red). Retrieved from: <https://www.neuroscientificallychallenged.com/blog/know-your-brain-primary-visual-cortex>

FIGURE 2:

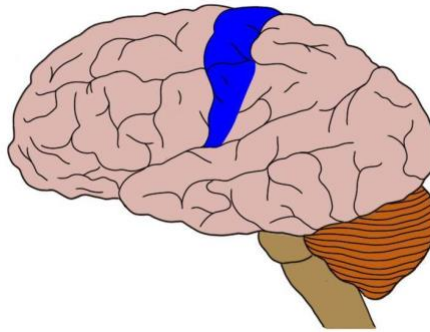


Figure 2: Illustration of the location of the Primary Somatosensory Cortex (in blue). Retrieved from: <https://www.neuroscientificallychallenged.com/blog/know-your-brain-primary-somatosensory-cortex>.

1.1. THE CONCEPT OF WORKING MEMORY

The word Memory describes the process of information acquisition. It is a faculty of the brain which facilitates three stages: encoding (where information enters the cognitive space), consolidation (storage of information) and retrieval (the act of remembering) (Jonides et al., 2007). Consequently, memory is also divided into two distinctive types: Short-term memory (STM) for information which is held for a short period and Long-term memory (LTM) for information, which is consolidated, and it can be recalled (Baddeley, 1999). Traditionally, the study of cerebral lesions and their impairments revealed separate cerebral areas which are responsible for STM and LTM. Amongst others, regions such as the hippocampus, the amygdala and the temporal lobes play a significant role in LTM while the Pre-Frontal Cortex and others play a role in STM (Baddeley & Mehrabian, 1976).

Atkinson and Shiffrin (1968) created a model (Fig 1). which stratified memory storage layers. According to this model, information enters perception through the senses. If the task receives enough attention, this information reaches STM and ultimately (if there is enough rehearsal) moves to LTM as solidified knowledge. This model set the base for subsequent research of the architecture of memory systems (Baddeley & Mehrabian, 1976).

Baddeley and Hitch (1974) proposed a different model which launched the concept of Working Memory (Fig. 2). They named WM the cognitive system, which temporarily (within seconds) maintains and processes information. In this model, distinctive ‘buffers’ are devoted to managing the administration of specific tasks. These segments explained how concrete representations are formed so that they can be stored later in LTM and form knowledge (Baddeley, 2012).

Specifically, the Phonological Loop is responsible for the comprehension of language by recognizing sound, speech or words (Baddeley, 2003). Secondly, the Visuospatial Sketchpad synthesizes mental representations for the identification of objects, shapes, colours or similar elements (Baddeley, 2003). Both of the above ‘buffers’ are coordinated by the Central Executive; a function responsible for navigation and allocation of information to the appropriate areas (Baddeley, Allen & Hitch, 2011, Chai et al., 2018). The fourth component is the Episodic Buffer. It is responsible for the exchange of information between STM and LTM, and it merges information from previous buffers. This function creates an ‘imprint’ of a representation which has a meaningful time sequence. This justifies the reason why memories are not fragmented pieces of information, but they have meaningful coherence (Baddeley, 2002).

FIGURE 3:

The multi-store model of memory
(Atkinson & Shiffrin, 1968)

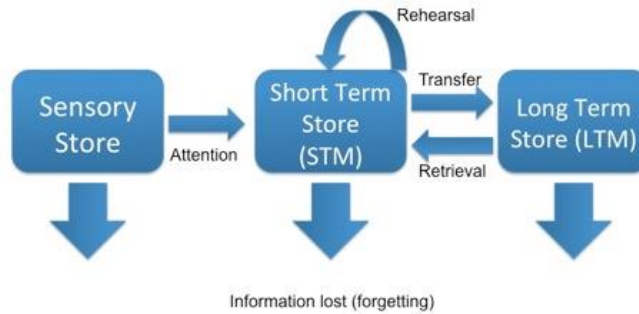
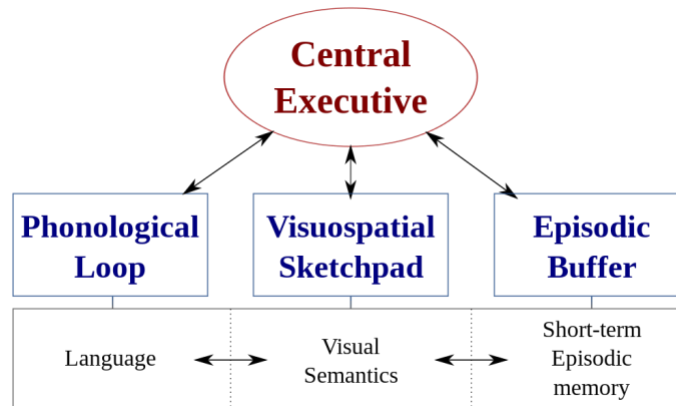


FIGURE 4:



Figures 3 and 4: The initial Multi-store model of memory by Atkinson & Shiffrin in 1968 (Fig.1) was gradually overshadowed by the model which describes the Working Memory function by Baddeley & Hitch (1974) (Fig 2). Retrieved from:

<http://www.psychteacher.co.uk/memory-AS/page94/multistore-model.html> (Fig. 1) and

<https://psynso.com/baddeleys-model-working-memory/> (Fig. 2)

Parallelly, Cowan's (1999) model replaced the distinguished 'buffers' of WM (Baddeley & Hitch, 1974) with a centralised system which stores representations to use them whenever it is mandatory. This model recommended that WM is an 'embedded' process which relies on flexible attention and LTM. Working Memory has not been a separate entity in this model but rather a conglomeration of novel and existing knowledge which forms representations according to the sporadic information (Cowan, 2010). An abstract way of describing WM was established, but it did not extend towards specified sorts of cognition, such as Visuospatial WM (Cowan, 1999). This constraint made it challenging to test this model with the same feasibility as Baddeley's (Cowan, 2010). Nonetheless, it offered a unique viewpoint and touched upon understudied matters such as WM capacity and object familiarity (Cowan, 2016).

A variety of theories have tried to mark on a theoretical level the role of WM in cognition. While others labelled it as a 'Primary Memory' where information is processed before they are stored in the 'Secondary Memory' (LTM), others considered that it serves as 'storage-processing device', or a 'workspace' (Camos, 2017). Mainly, WM has been categorised as an executive function, which allows flexible behaviour while manipulating information or ingesting knowledge for long term contextual influences (Spaak et al., 2017). Thus, WM tasks necessitate some degree of Prefrontal activation as it has been observed in neuroimaging inquiry (Postle, 2006 and Bunge et al., 2000). The wealth of proposed models that have tried to describe WM highlight the probable existence of multiple cellular mechanisms and functions which shape WM, so the examination of this topic has not settled issues surrounding this cognitive domain (Barak & Tsodyks, 2014).

1.2. FUNCTIONAL ORGANIZATION OF WM MECHANISMS AND CROSS-MODAL INTERACTIONS IN THE VISUAL AND TACTILE MODALITY

Elementary processing of stimuli during WM tasks has been traditionally considered unimodal (one modality) meaning their processing would occupy one sensory area (e.g., Visual stimuli would be processed in the visual cortices). Studies from Gruber & von Cramon (2003) and Smith & Jonides, (1997) on WM suggested that the evidence of laterality in tasks such as object recognition in the Left Hemisphere and spatial comprehension in the Right Hemisphere should lead to distinct WM mechanisms.

Moreover, Shah & Miyake (1996) tested on selective interference tasks to examine domain-specific evidence. In their study, the presentation of the same type of cognitive test (spatial memory task) twice leads to the dropped performance. Antithetically, the presentation of two separate cognitive tasks (Visual WM and Verbal WM) did not have a cost in performance. Domain-specific WM mechanisms have been susceptible to interference when they encounter identical tasks since they have to ‘fractionize’ a specific resource centre. Conversely, Domain-general mechanisms have not been interrupted because they rely on a general pool of resources to execute tasks which allowed participants to perform well enough on all the tasks.

Other studies have proposed general domain resources for WM. This is mainly due to the association of the Working Memory with the PFC, an area where information from different cortical areas merge to form complex perception (Postle, 2006 and D’Esposito, 2007). Cowan’s and More’s (2007) suggested through their studies that the dexterity of the WM system to manage without detriment all kinds of information (such as the retention of sets of shapes, letters and digits while new sets have been introduced) means that there are domain-general resources.

Kane et al. (2004), dissociated WM from specific tasks and decided that it was involved in tasks of fluid or general intelligence which claimed abstract or general comprehension.

Progressively, the growth of sensory neuroscience put under the microscope the receptive field of neurons, an endeavour which informed WM structure. Specifically, the place which surrounds a neuron and allows stimuli to be perceived by increasing or decreasing its firing rate is called the receptive field (D'Esposito, 2007). Neurons react only to stimuli which are presented within this area. In some situations, the receptive fields of the neurons of a distinct area (e.g., Visual Cortex) become receptive to stimuli expected to be processed in another area (Somatosensory Cortex) (multimodal function) (Cohen et al., 1997, Klemen & Chambers, 2012, D'Esposito & Postle, 2015).

On other instances, the receptive fields of neurons in a specific area have been activated for diverse types of stimuli (e.g., Visual or Tactile stimuli) to allow assimilation of information (supra-modal function). An area which comprises this type of neurons is the Superior Colliculus which has been found receptive to both Visual and Tactile stimuli. Furthermore, a variety of pre-frontal areas such as the dorsolateral PFC, the Superior Temporal Sulcus (STS) in the association cortex and the sensory cortices have all shown that their neuronal activity is not related to just one type of stimuli (Klemen & Chambers, 2012, Stein & Stanford, 2008).

Visual and Tactile Interactions in Cross-Modal Working Memory

Activities from daily life such as that people can touch an object to feel its shape and then describe its figure based on visual-mental imagery that they retained have indicated that information can be passed from one modality to the other (Constantinidis, 2016). Increasingly, a

variety of studies which have used different methods have exposed an overlap of WM mechanisms in the Visual and Tactile modality (Pasternak & Greenlee 2005).

A study by Taylor-Clarke et al. (2008) proposed that Visual cues modulate the activity of the somatosensory cortices (S1 and S2). Specifically, they found increased activation of neurons of the somatosensory cortex after the presentation of visual cues for a tactile task. These results are in line with the work by Heller, (1982), Kennet et al., (2004) and Haggard et al., (2007) which observed that visual cues of somatosensory stimuli (watching a part of a body while stimulating it), raised the performance in tactile modality tasks. Moreover, Gallace & Spence (2008) insinuated that pictorial representations of visual imagery are present during the processing of spatial information in the tactile domain. Zhou & Fuster (2000) have suggested that somatosensory cells are sensitive to both visual and tactile stimuli.

Zangaladze et al. (1999), displayed the disruption of the discrimination of tactile orientation by applying TMS to the Occipital Cortex of healthy individuals. Additionally, Sathian et al., (1997), suggested the involvement of the visual cortex in the discrimination of tactile grating orientation (an activity which requires Visual-mental imagery). Similar studies looked for Cross-modal interactions in the blind population such as Cohen et al. (1997) that stimulated the Occipital Cortex of blind subjects and noted decreased performance in tactile tasks. Hagen et al. (2002), found activity for tactile motion processing tasks in a predominantly visually stimulated region, the human Middle Temporal Complex (hMT/V5). The cortical system has specialized areas, but that does not prevent the ‘unorthodox’ activation of regions for the processing of other stimuli.

Additionally, Ohara et al. (2006), observed independent sensory processes during cross-modal WM tasks in the Visual and the Tactile modality. They assumed that cross-modal WM uses both modality-specific and general mechanisms. Kawashima et al. (2002), reviewed both intramodal (within the visual or tactile modality) and cross-modal (across modalities) visual and tactile processing and noticed that the order of the stimuli presentation was a determining factor in setting a dual ventral stream of activation. Specifically, the tactile WM for visual information deployed modality-specific regions such as the primary cortices while visual WM during Tactile information processing involved additional cortical areas. Wu et al. (2018), proposed that the sensory cortices might play a crucial role in the decoding of stimuli. However, abstract knowledge has been a product of the association cortices, including pre-frontal Areas. Understandably, cross-modal WM has involved both DS and DG mechanisms for diverse types of information processing.

The investigation of cross-modal interactions between Vision and Touch is still open-ended as it has a pivotal contribution in fields such as sensory-motor behaviour, brain plasticity or cognitive development (Shimojo & Shams, 2001). For instance, in a study by Sadato et al., (2004) blind individuals exhibited Occipital activation for Braille reading which is a somatosensory (and not a visual) activity. The future of the cellular mechanisms to deploy certain areas for the processing of others can be valuable in times of deprivation such as injury. On the other hand, a study by Wilson & Swanson (2002) approached the issue of DG vs DS mechanisms debate under the scope of mathematical difficulties. It concluded that deficits in both domain-general and domain-specific mechanisms lead to mathematical challenges. The inspection of the impact of those mechanisms in dysfunctions can comprehend their causal models and successful interventions.

1.3. DISCRIMINATION OF PROPERTIES OF STIMULI; PATTERN AND FREQUENCY

Working Memory is a function which processes with ease and speed goal-relevant information coming from all senses. This operation not only detects but recognizes the properties of stimuli such as their location in space or their direction of movement or even the colour, shape or other features (Gazzaley & Nobre, 2012). Thus, memory perception has shown sensitivity towards finer aspects of stimulation. The term Pattern (space) has been used to refer to spatial characteristics of stimuli while the term Frequency (time) has been used to refer to the temporal dimension of stimuli. Moreover, the term discrimination has described the instant process of determining if two fields are same or different (Julesz, 1962).

It is important to delineate what these terms mean; Pattern is the location of stimuli in space, and it can be perceived through angles, distances, figures, forms or other elements. For example, the Pattern of an object on a screen is its location (Gould & Dill, 1969, Derrington & Henning, 1980, Greenlee & Magnussen, 2000). Haggard & Giovanogli, (2011), suggested that Visual Patterns are vital in forming the ‘Visual Field’ when people look at an array of objects in space. On the other hand, Tactile Patterns refer to the stimuli that can be perceived by Touch in a constant location. That can be a vibration induced in a specific part of the body such as the fingers (Hegner et al., 2007, 2010).

Frequency is defined as the rate of occurrence of stimuli in time, the tempo, the direction of movement, the vibration or even the vibrotactile ‘flutter’ (Singer & Gray, 1995, Hegner et al., 2010, Weber et al., 2013). The Visual Frequency of a stimulus determines its rate of occurrence over time at a specific point, e.g., how fast or slow an object is pulsating or flickering on a screen. Similarly, the Tactile Frequency of a stimulus can be characterized by the type of the

vibration felt by the somatosensory receptors, e.g., electric vibrations on fingers can be fast or slow (Preuschhof et al., 2006, Mauk & Buonomano, 2004) or they can have a particular direction of vibration which is dictated by their frequency (Singer & Gray). Weber et al. (2013) emphasized that the Somatosensory Frequency is necessary to help humans recognize different features of tactile stimuli such as texture (e.g., velvet or silk).

Interrelations Between Pattern (Space) and Frequency (Time) in Stimuli

The ability of the brain to conjunct together the individual features of stimuli and form a cohesive representation has been called binding of information. The latter has enabled the brain to process complex object. Several neurobiological models have tried to answer to the mechanisms of this level of information processing. On a behavioural level studies have shown that when pattern and frequency coexist, they can interfere or influence the performance of each other in relevant tasks (Erez, 2016, Hadjikhani & Roland, 1998). On a cellular level, it is speculated that this process is not accomplished at single cell location but rather on wider population of cells which remain distributed over several cortical areas (Singer & Gray, 1995, Erez, 2016). In neuroimaging studies, Frequency and Pattern discrimination has activated frontoparietal areas such as the PFC and the PPC (Marcos & Genovesio, 2017, Greenlee & Magnussen, 2000). The processing of Frequency has activated areas such as the thalamus, cerebellum, Basal Ganglia (Merchant et al, 2013).

On a theoretical level, Lakoff and Johnson (1980) developed the idea that space (Pattern) is more salient than time (Frequency) since people use linguistic metaphors and analogies of space to describe time more often than the opposite (Constructive Metaphor Theory or CMT). According to Coull et al. (2015), this spatial dominance is obvious when people use metaphorical

vocabulary to create affinity of time using space with expressions such as ‘Tuesday is ahead’. Bottini & Casasanto (2013), tested this asymmetric relationship on children and found that they could easily ignore temporal information when they were making spatial judgements, but they had difficulty in ignoring spatial information when they were deciding about time. Borodinsky et al, 2000 speculated that time is shaped by space since space can be used easily to process information of time although spatial cues are not a requirement for the same task.

On the other hand, Walsh in 2003 supported the Theory of Magnitude (ATOM), which proposed that time and space hold similar value in mental processing. Agrillo & Piffer (2012) showcased a symmetric mechanism for space and time when musicians improved both in temporal skills and spatial skills. Studies on developmental dyscalculia exposed a deficit for both temporal and spatial representations (Skagerlund et al., 2014). Simultaneously, Ramascone (2009), proposed that space and time hold different value for each modality; therefore, their dominance is interchanged depending on the modality of the task. For instance, Vision relies more on spatial observations; therefore, Patterns would play a core role in Visual Task. The opposite would happen in the Tactile domain since it is a mechanical sense, and it relies mainly on Frequencies (Loeffler et al., 2018).

Other studies have inspected the brain areas responsible for the discrimination of properties of stimuli from a multisensory perspective. The study closer to the interest of this thesis by Hegner et al., (2007, 2010) has investigated the neurophysiological correlates of Pattern and Frequency discrimination within the Tactile modality and found out that pattern and frequency shared certain areas of activation, but they essentially relied on different ones. Other studies regarding two modalities studied the discrimination of stimuli of shape. For instance,

Saito et al. (2003), proposed that the visual and tactile modalities share regions in the brain (posterior intraparietal sulcus) for the distinction of shape. Earlier, Hadjikhani & Roland, (1998) examined Visual and Tactile cross-modal WM in the discrimination of shape and proposed that the brain transforms multisensory integration in modality specific processes, but the individual cortical structures communicate through areas which support multisensory integration such as the previously mentioned Superior Colliculus.

It is evident that the study of the interrelation of space and time have come a long way but require more research. The perception of featural information has application in everyday life skills such as the ability to detect complex objects, ignore intruding information, estimate dimensions, or improve performance in skills (Singer & Gray, 1995, Marcos & Genovesio, 2017, Loeffler et al., 2018). The apprehension of this matter on a behavioural and neurophysiological level could to the coding of spatial and temporal representations in the brain (Linden, 2007).

PART 2: RESEARCH

2. OBJECTIVE

The literature review of this thesis presented certain studies and theories in order to present the research aspiration which emerges from those topics. There are two core matters of importance around the system of WM; the first is to explore which mechanisms (domain-general or domain-specific) are used in cross-modal WM memory in the Visual and Tactile modality. The second one is to appreciate the mechanisms involved in the discrimination of properties of stimuli (pattern, frequency) during Visual and Tactile stimulation (in each modality and in cross-modal comparisons).

The putative reason to study this field is that multisensory integration in WM is a cognitive quality which maximizes an organism's strength to perceive an experience. This trait is the foundation for optimal behaviour and life skills while people navigate in contexts which demand perception – actions plans (Quak & Talsma, 2015, Camos, 2017). The depiction of these mechanisms will extend its contribution to topics of cognition such as problem-solving, reasoning, developmental disorders and brain plasticity (Miller et al., 2017). Moreover, this study advances the understanding of the functional organization of the brain, the architecture of human cognition and the coding of spatial and temporal mechanisms (Shimojo & Shams, 2001, D'Esposito, 2007, Nieder, 2017, Erez et al., 2016).

The empirical aim of this thesis is to approach this matter with behavioural testing in relevant tasks and infer results from the observation of an appropriate test which will examine the relationship between the variables. Although the evolution of neuroimaging techniques has

made possible an advanced mode of testing, cellular level mechanisms manifest in behaviour. (Chein et al., 2011, Sieben et al., 2013). Therefore, the attention of this thesis is the behaviour of participants during spatial and temporal stimulation in Visual and Tactile WM.

The experimental method will be a Delayed Discrimination task which will be used as a mean to quantify behaviour in order to analyze it with an appropriate statistical method (Field, 2013 and Cohen, 2013). Quantitative research has been trusted partly for being able to expose the reflection of internal mechanisms in behavioural responses. The presence (or absence) of a type of relationship between the scores of the Visual and Tactile WM tasks in the discrimination of Pattern and Frequency is a valuable indicator of behaviour which can connect to independent or shared neuronal mechanisms (Chein et al., 2011).

2.1. RESEARCH QUESTION AND HYPOTHESIS

The literature review mentioned studies which indicated the possibility of Domain-general or domain-specific mechanisms for the process of Visual and Tactile Spatial and Temporal stimuli in WM tasks. The majority of these studies used discrimination tasks as their basic research design. Therefore, this is also the paradigm that will be used in this research.

Ohara et al. and Wu et al. (2018) assessed the temporal discrimination in the Visual and Tactile modalities and did not report differences in the accuracy of scores between Visual and Tactile modalities. Both advocated for domain-specific mechanisms in Visual and Tactile tasks. On the other hand, D' Esposito (2007), Ku et al. (2002), and Li et al. (2007) and Kawashima et

al. (2002) reconciled both views on WM mechanisms and concluded that both modality-specific and modality-independent mechanisms are involved in Visual and Tactile tasks.

Concerning the matter of the discrimination of the spatial and temporal features of stimuli, one theory has speculated different neural codes for space and time (CMT by Lakoff and Johnson) and other theories have speculated that they share a common neural code (ATOM by Walsh, 2003). Moreover, Singer & Gray (1995) insinuated that stimuli discrimination involved scattered and no single cortical areas which are not yet fully conceded. Agrillo et al. (2012), Skagerlund et al. (2016), Mendez et al. (2011) all agreed that spatial and temporal activities are interrelated during tasks which implicated relevant skills aligning with the shared mechanism theory.

Studies by Hegner et al. (2007, 2010), tested the performance of subjects on tasks that involved the discrimination of Tactile Pattern and Tactile Frequency. They reported insignificant differences in the accuracy of correct responses but longer reaction time for Frequency than Pattern. They also reported a slightly shortened response time when the Frequency was different and slightly longer reaction time when the pattern was different. Longer response time in Frequency might be linked to the fact that temporal discrimination requires the presentation of the whole stimuli (Hegner. 2007). Nevertheless, there is still an enigma between brain connectivity versus the existence of individual hubs for spatial and temporal processing.

The above studies facilitate the formulation of the primary research question of this thesis; Are there domain-general or domain-specific mechanisms for cross-modal WM in the Visual and Tactile modality involved in the discrimination of Pattern and Frequency?

This question has a dual scope; firstly, to investigate DG vs DS mechanisms on modality level, and this is relevant to the scores of subjects in the Visual and Tactile modality. It is hypothesized that the participants' performance in one modality will be correlated with the participants' performance in the second modality for the domain-specific mechanisms scenario. Secondly, this question will investigate DG vs DS mechanisms which refer to the discrimination of Pattern and Frequency in the two modalities. For this goal, it will inspect the relationship of the scores of Pattern and Frequency within a single modality (e.g., VP-VF/TP-TF) and between two modalities (VP-TP, VF-TF, VP-TF, VF-TP). It is hypothesized that the participants' performance in the pattern task will be related to the participants' performance in frequency tasks if the two properties share neural mechanisms.

3. METHODOLOGY

3.1. MATERIALS AND METHODS

The researchers of the Deafness, Cognition and Language Research Center (DCAL) at UCL, initiated a project which aimed to examine whether the auditory cortex plays a role in the Visual and Tactile modality. This project received ethics approval by the UCL research committee. The project involved, amongst other steps, the analysis of behavioural and neuroimaging data from deaf and hearing individuals. One of the steps was the completion of a behavioural test. This test was analyzed in this thesis as part of the research focus. The objective was to train the participants on a cognitive test which they repeated it during an fMRI scanning session. This procedure would increase their confidence and understanding of what is required during their participation in this study.

This thesis analyzed the data which were extracted from the sessions which tested the efficacy of this training. As it is mentioned before, the type of the behavioural test which was chosen is a Delay Discrimination test, a widely used method in psychometric testing (Hegner et al., 2010). The participants sit in a chair and complete a computer-based exercise. During the test, the participants were asked to decide whether two different samples were the same or different by pressing a button at the end of the presentation of the second stimuli. The responses of the subjects were recorded as scores (in percentage from 1-100%). They were statistically analyzed to determine whether there was an inclination which can describe their behaviour and answer to the research questions.

The materials that were used are a laptop, headphones with white noise, earplugs, piezo-electric stimulator with electric piezo wafers, and a folder which contained relevant paperwork. The software which was used was MATLAB (Mathworks, Natick, MA, USA) and the extension Psych Toolbox while the data analysis conducted with the Statistical Package of Social Sciences (SPSS version 26).

3.2. PARTICIPANTS

The sample size consisted of 11 healthy individuals, all adults of different ages, who were English speakers. They were recruited using an online platform where researchers advertise experiments for potential participants. They visited the DCAL at a scheduled appointment to complete the test. They were met at the reception of the building, escorted at the designated room, and signed a consent form. Then, they were given a behavioural information sheet which

explained the purpose of the research. The researcher filled the baseline report form with the participant's detail such as ID number, gender and age.

The participants sat in a chair, looking at the screen of a laptop in order to complete the test. The researcher arranged the set-up of the environment while explaining the procedure and answering any questions. The overall time that an individual spent to complete the experiment ranged from 20 minutes to 1.5 hours. During this time, the researcher took notes on a behavioural log sheet which concerned the experimental session (whether participants wished to stop or how much time they spend on a task, etc.). Some subjects dropped out of the session and stopped their testing for varying reasons, with the main one being the difficulty of the task. Those participants were excluded from further testing or data analysis. The subjects were debriefed, and they were given a payment in exchange of their participation at the end of the session.

3.3. DESIGN

The experimental design precluded two tasks: one in the Visual and one in the Tactile Modality. The participants had to compare whether two different samples have the same features of Pattern and Frequency. The term Pattern refers to spatial information and describes where an object is located (Hess & Plant, 1985). The term Frequency refers to the temporal information, which is the occurrence in time or how fast or slow the stimuli move (Hegner et al., 2010). During the completion of these tasks, the subjects stared at a small flashing dot at the centre of the screen to maximise their concentration.

In the Visual Modality, the stimuli were delivered with sinusoidal gratings (Gabor patches) in pairs of 4, on a laptop's screen (Figure 6). In the Visual Pattern task, the participants had to choose whether the stimuli were in the same or different location on the screen by contrasting two samples. In the Visual Frequency task, they had to memorise how fast the gratings' temporal movement changed their direction in the screen. Each grating's lines flickered vertically and horizontally, and their rate of moving changed according to the frequency parameters (low or high) of each sample.

In the Tactile Modality, the stimuli were delivered with electric vibration. Piezo wafers were attached to each of the four fingers (all except the thumb) on an individual's left hand (Figure 5). The stimulation was given to any 2 out of 4 fingers for every sample. During the Tactile Pattern task, participants had to memorise at which fingers the vibration had occurred. Different finger vibration meant a difference in Pattern. In the Tactile Frequency task, they had to memorise the type of vibration change in terms of how fast or slow they felt this on their fingers. During the tactile modality task, headphones with white noise were provided, so that any other noise would be eliminated, and the participants would not get distracted from the vibration.

FIGURE 5

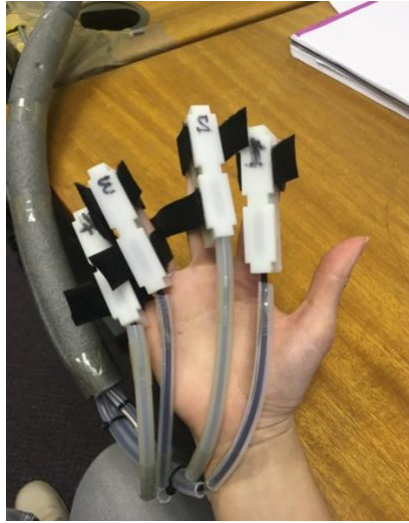


FIGURE 6



Figures 5 & 6: The stimulation equipment for the Tactile Modality. The piezoelectric charge is given at any 2 out of 4 fingers each time and the difference in frequency results in different vibration types (fast, slow etc.). The vibration at different fingers describes the different Patterns.

FIGURE 7

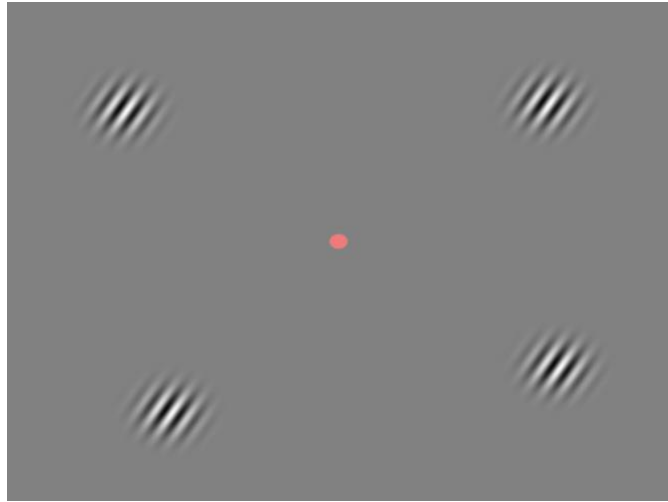


Figure 7: The task of the visual modality involves the display of moving gratings on a laptop's screen. Each grating's lines flickered vertically and horizontally. The red dot is flashing as the grating change and participants are given instructions to focus on the dot.

3.4. EXPERIMENTAL PARADIGM

The experimental paradigm included eight individual runs which were consisted of a maximum of 8 blocks. Each block consisted of 8 trials. There was a maximum of 64 trials in each run. At the beginning of each trial, there was a cue which indicated the modality and the feature that the subjects had to attend (Figure 7). A single trial was structured on five steps; a sample stimuli (1) which lasted for 500ms in the Visual and 1000ms in the Tactile modality. Then there was a Delay (2) (3-5 s), followed by the presentation of the second stimuli (3) of the same type and duration as the first one. This is followed by a Response (4) of 2 seconds when the participants decided whether the two samples are the same or different from each other and pressed the appropriate button. The last stage of a trial is the Time Interval (ITI) (3-5 s) (5) which was followed by either another trial or a Block.

FIGURE 8



Figure 7: Before each Run, there is a Cue (e.g., visual pattern). In the tactile modality, the illustration is changed to indicate touch (a hand). Frequency is symbolized with F.

FIGURE 9:

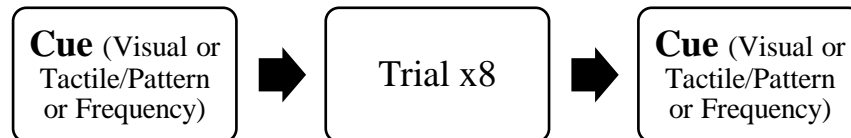


Figure 8: Example of a block. Each block has 8 trials. That summons 64 trials for every Run.

FIGURE 10:

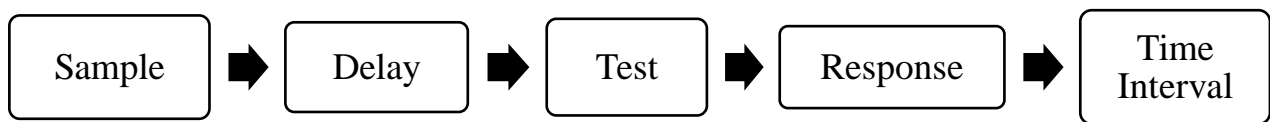


Figure 9: The above figure illustrates the steps included in a single Trial. There were a maximum of 64 trials in each run.

All the participants completed a short training at the beginning of the experimental session which introduced them to the tasks, and they had to pass a short test to ensure that they knew how to follow the instructions. After that, they proceeded with their training in the Visual

Pattern (VP) and Visual Frequency (VF) followed by the Tactile Pattern (TP) and Tactile Frequency (TF) tasks. The last part of the experimental session consists of the Cross-modal WM tasks, and the data from the performance of the subjects in that session was used for analysis in this thesis. The cross-modal test included the tasks in all four conditions of VP, VF, TP, and TF.

Furthermore, the stimuli of this test were organized in a fixed fashion which allowed 50% same and 50% different stimuli presentation. Below there is a summary regarding stimuli appearance and organization in both modalities and tasks (Tables 1-4). The participants were not aware of this arrangement

TABLE 1:

Visual Frequency Stimuli Organization (500ms stimuli duration on a laptop's screen).

Sample (Stimuli no 1)	Test (Stimuli no 2)	Condition (Is the movement of the gratings on the screen same or different?)
1.5 Hz	1.5 Hz	Same
	0.75 Hz	Different
	3 Hz	Different
3Hz	3 Hz	Same
	1.5 Hz	Different
	4.7 Hz	Different

TABLE 2:

Tactile Frequency Stimuli Organization (500ms stimuli duration on a laptop's screen).

Sample (Stimuli no 1)	Test (Stimuli no 2)	Condition (Is the movement of the vibration on the fingers same or different?)

24 Hz	24 Hz	Same
	14 Hz	Different
	40 Hz	Different
70 Hz	70 Hz	Same
	50 Hz	Different
	110 Hz	Different

TABLE 3:

Visual Pattern Stimuli Organization (500ms stimuli duration on a laptop's screen).

Sample (Stimuli no 1)	Test (Stimuli no 2)	Condition (Are the gratings in the same or different location on the screen?)
Pattern 1	Pattern 1	Same
	Pattern 2	Different
	Pattern 3	Different
Pattern 2	Pattern 2	Same
	Pattern 4	Different
	Pattern 5	Different

TABLE 4:

Tactile Pattern Stimuli Organization (1000ms finger stimulation with electric wafers).

Sample (Stimuli no 1)	Test (Stimuli no 2)	Condition (Is the vibration on the same or different fingers?)
Pattern 1	Pattern 1	Same
	Pattern 2	Different
	Pattern 3	Different
Pattern 2	Pattern 2	Same
	Pattern 4	Different
	Pattern 5	Different

3.5. DATA ANALYSIS

The statistical analysis applied the software SPSS (Statistical Package for Social Sciences). The data analysis and report of the findings followed the guidelines given by Field (2013), Cohen (2013) and Coolican, (2018) on how to conduct and interpret behavioural experiments. The written report followed the guidelines of the publication manual of the American Psychological Association (APA), 7th Edition.

Based on the categorization of data, it was determined that the Independent Variable (IV) would be the Accuracy Score (AS) or Test Score (TS) of the participants while the two Dependent Variables (DV) would be Modality (Visual, Tactile) and Task (Pattern, Frequency). Descriptive Statistics tested the count (n), mean (M), and standard deviation (Std. Deviation) of the data set. The probability of the results is indicated by the *p-value*, which symbolizes the statistical significance of evidence (significance threshold $p < 0.05$). The null hypothesis H_0 contradicts the tested hypothesis and implies that there are not sufficient evidence to accept H_a or the alternative hypothesis, which represents the theory which is studied.

Pearson's Correlation test was chosen for this study as it is the measure of association between two variables. The research question aimed to investigate whether two variables are statistically dependent on each other. Correlation tests have the goal to examine whether one variable (e.g., Pattern) co-occur with another (e.g., Frequency), inferring their association (but not causation) (Field, 2013, Cohen, 2013). Hence, the parametric Pearson correlation coefficient (r) was used to assess the linear correlation between the two quantitative variables of Modality (Vision and Touch) and Task (Pattern and Frequency) (Figures 11-17, Results section). This measure can take a range of values from +1 to -1. A value of 0 indicates that there is no

association between the two variables. Values close to +1 indicate a positive association and values close to -1 indicate a negative association. The relationship between the two variables is considered significant when the *r-value* exceeds 0.7. When the *r-value exceeds* 0.5, it is considered a moderate correlation while a value around 0.3 or below is considered a weak correlation.

Certain assumptions had to be met across all data sets in order to perform a Correlation test (Field, 2013). The first one was normality (harmoniously distributed numbers without extreme fluctuations). All datasets were tested using the Shapiro -Wilk test since the sample size consisted of less than 30 subjects ($n < 30$). Normality was met (Shapiro-Wilk $p < 0.05$) for the data set by removing the scores of two subjects who were outliers (ID no 8 and 10) (Field, 2013, Coolican, 2018). All variables were measured on a continuous scale, and there were two variables for each case in order to achieve bivariate normality. The relationship between these variables as inspected through a scatterplot indicated linearity. The scatterplots provided in the results section were a graphical illustration of the correlation between two variables, while the boxplots were a graphical representation of the data sets.

4. RESULTS

Table 5 provides a summary of the performance of the subjects through their Test Scores in the Visual and Tactile Working Memory Tasks. The value of *n* equals to the sample size of this study ($n = 9$ adults) while the minimum and maximum values represent their upper and lower scores (1% lowest – 100% highest) on each task. The value of the Mean (M) expresses the

average point of each of the data sets, and the Standard Deviation (Std. Deviation) describes how close these values are with each other or their dispersion. The boxplot highlighted no potential outliers. The tables below present the scores of the participants in each condition.

TABLE 5:

Descriptive statistics of the scores in the Visual and Tactile Working.

	N	Minimum	Maximum	Mean	Std. Deviation
Visual Working Memory	9	.79	.92	.8633	.04031
Tactile Working Memory	9	.78	.93	.8444	.05593

TABLE 6:

Summary of the scores of the participants in the Visual Modality tasks.

Modality Tasks	Accuracy Scores of Visual WM Tasks (Percentage 1-100%)
Visual Working Memory All	86.3%
Visual WM Pattern	88.2%
Visual WM Frequency	83.6%

TABLE 7:

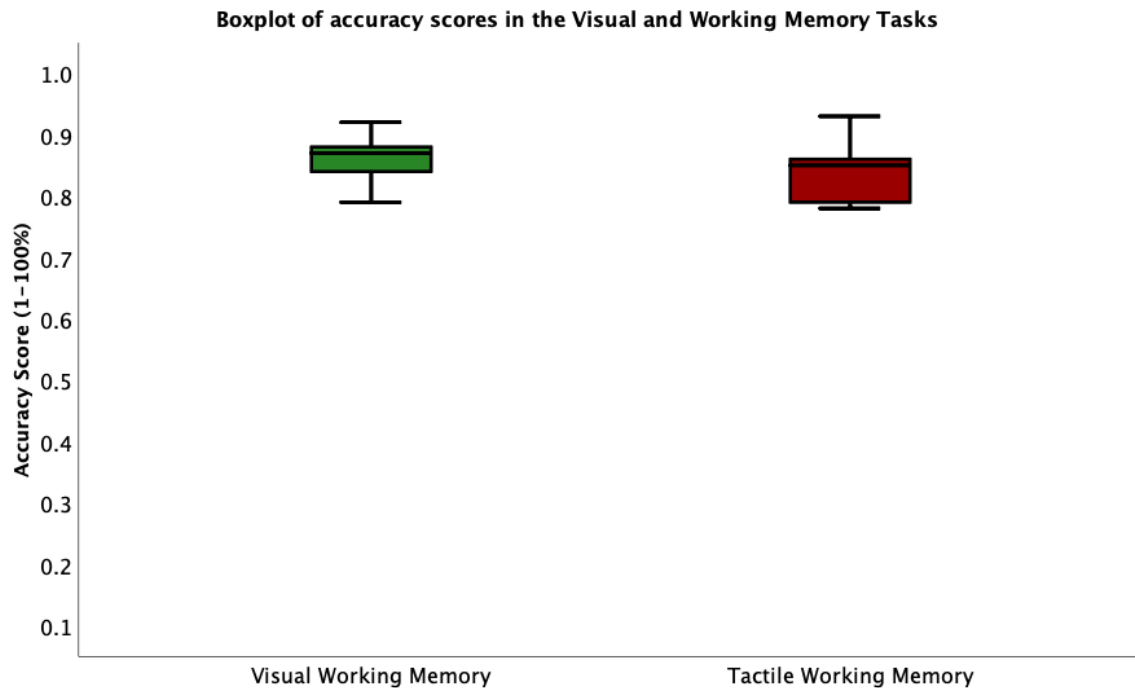
Summary of the scores of the participants in the Tactile Modality tasks.

Modality Tasks	Accuracy Scores in Tactile WM Tasks (Percentage 1-100%)
Tactile WM All	84.4%

Tactile WM Pattern	94.1%
Tactile WM Frequency	74.2%

FIGURE 11:

Boxplot of accuracy scores in the Visual and Tactile modality. No statistically significant difference in scores is observed between the two modalities.

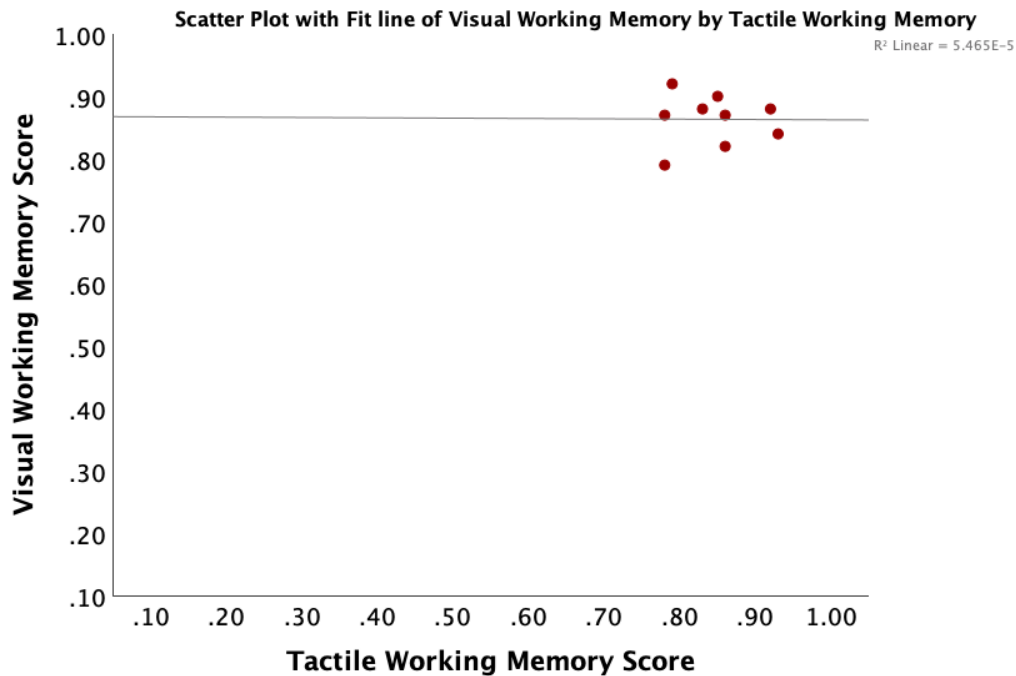


In the Visual Modality (both Pattern and Frequency tasks) the Mean was 0.86 and Std. Deviation 0.040 whilst in the Tactile Modality (both Pattern and Frequency Tasks), the Mean was 0.84 and Std. Deviation 0.055. The assumption of normality was not violated, as assessed by the Shapiro-Wilk's test ($p > 0.05$). Outliers were excluded earlier from the data so there were no extreme values. A paired-samples t-test was used to compare the difference in scores for the two

variables. There was no statistical significance between the accuracy scores in the Visual and the Tactile Working Memory Tasks ($p < .436$).

FIGURE 12:

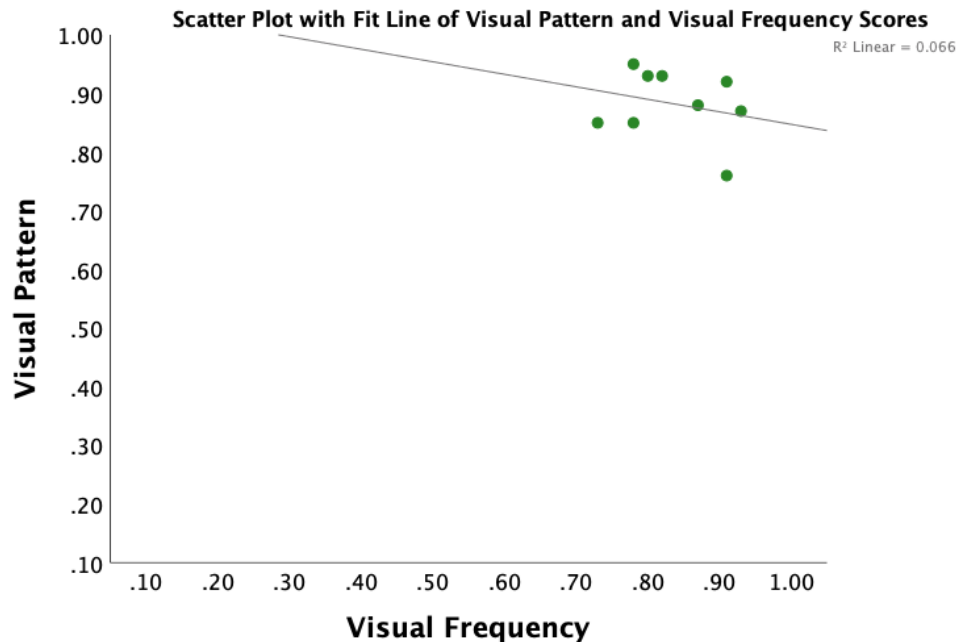
Scatter Plot which illustrates the comparison between Visual and Tactile Working Memory.



A Pearson's correlation was run to assess the relationship between the Visual and Tactile Working Memory tasks. Preliminary analyses showed the relationship to be linear with both variables normally distributed, as assessed by the Shapiro-Wilk's test ($p > 0.05$) and there were no outliers. There was no statistically significant correlation between the Visual and Tactile Modality Working Memory tasks, $r = -0.007$, $p = 0.985$.

FIGURE 13:

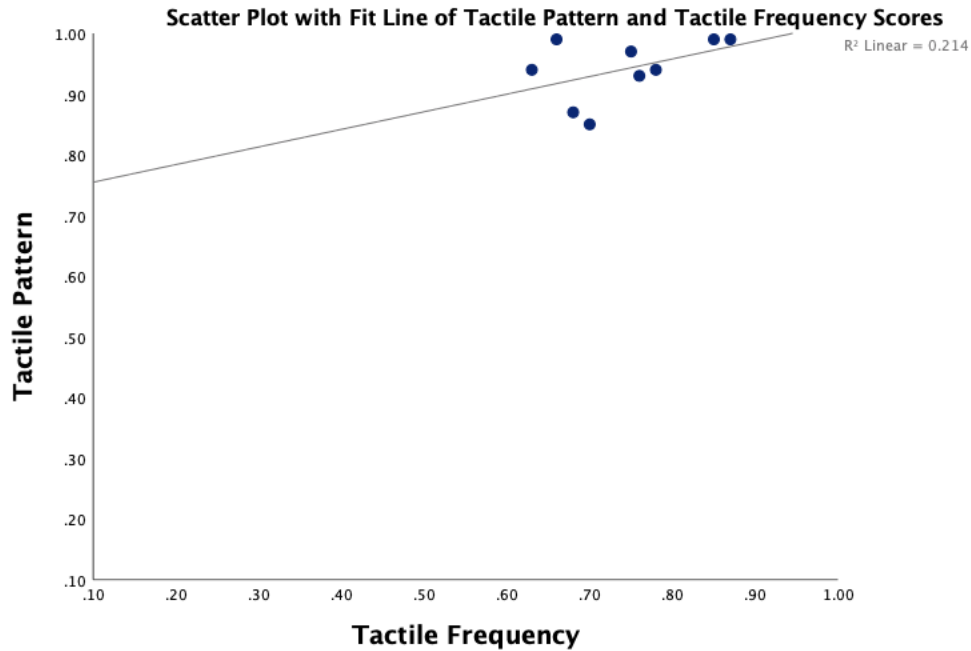
Scatter Plot which illustrates the comparison between Visual Pattern and Visual Frequency.



A Pearson's correlation was run to assess the relationship between the Visual Pattern and Visual Frequency Working Memory tasks. Preliminary analyses showed the relationship to be linear with both variables normally distributed, as assessed by the Shapiro-Wilk's test ($p > 0.05$) and there were no outliers. There was no statistically significant correlation between Visual Pattern and Visual Frequency tasks, $r = -0.256$ $p = 0.506$.

FIGURE 14:

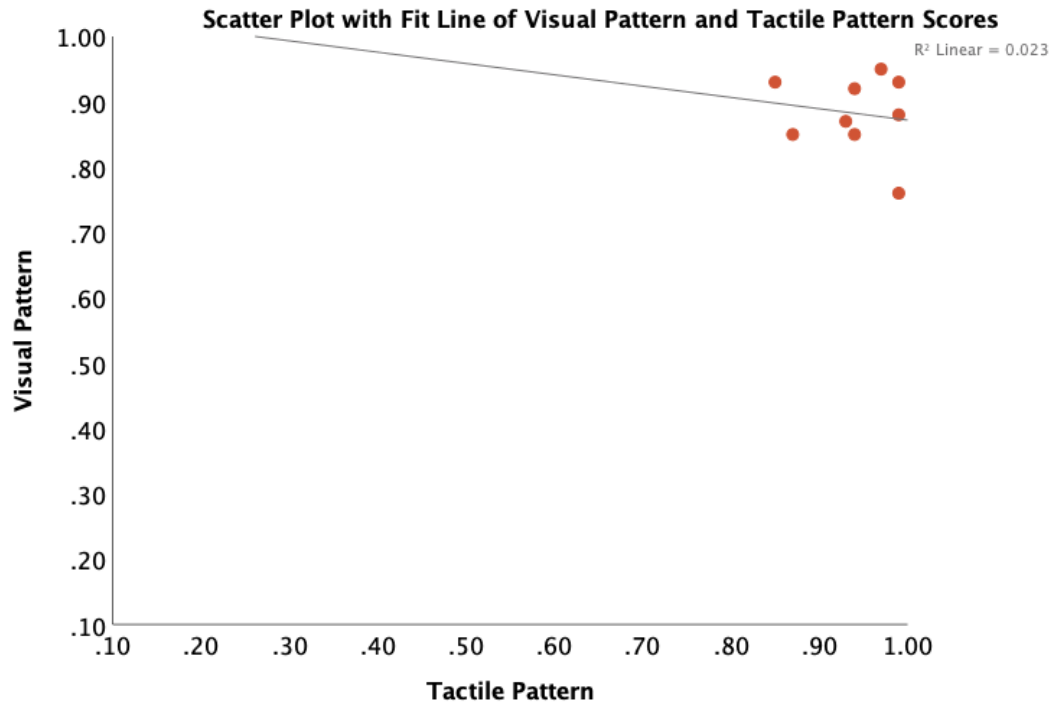
Scatter Plot which illustrates the comparison between Tactile Pattern and Tactile Frequency.



A Pearson's correlation was run to assess the relationship between the Tactile Pattern and Tactile Frequency Working Memory tasks. Preliminary analyses showed the relationship to be linear with both variables normally distributed, as assessed by the Shapiro-Wilk's test ($p > 0.05$) and there were no outliers. There was no statistically significant correlation between Tactile Pattern and Tactile Frequency tasks, $r = 0.463$, $p = 0.210$.

FIGURE 15:

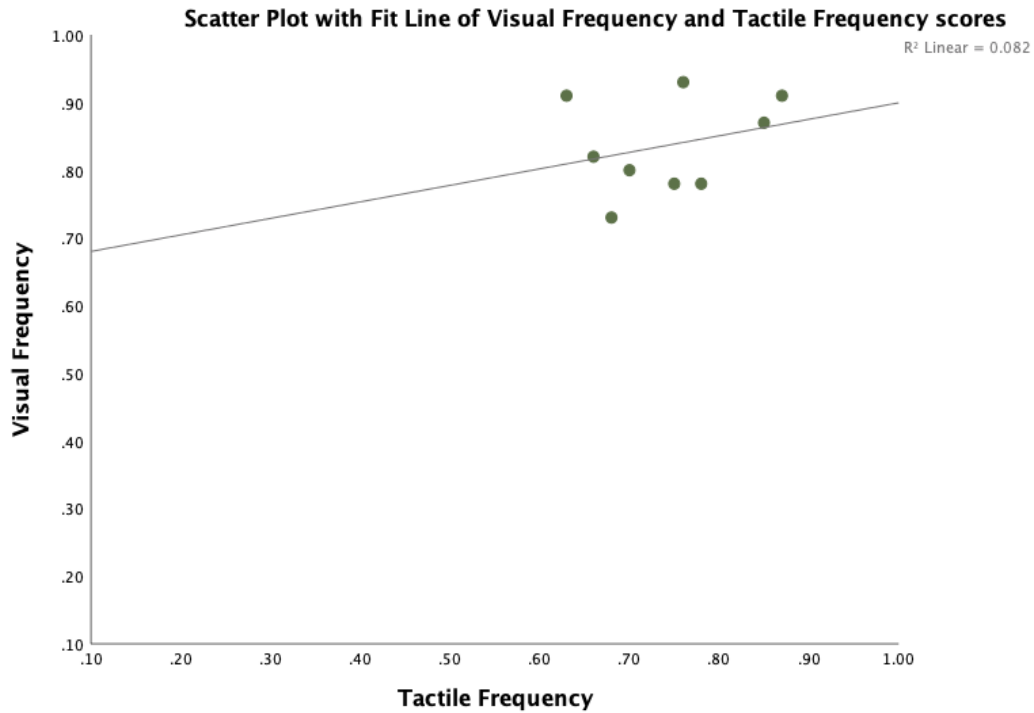
Scatter Plot which illustrates the comparison between Visual Pattern and Tactile Pattern.



A Pearson's correlation was run to assess the relationship between the Visual Pattern and Tactile Pattern Working Memory tasks. Preliminary analyses showed the relationship to be linear with both variables normally distributed, as assessed by the Shapiro-Wilk's test ($p > 0.05$) and there were no outliers. There was no statistically significant correlation between Visual Pattern and Tactile Pattern Working Memory tasks, $r = -0.152$, $p = 0.695$.

FIGURE 16:

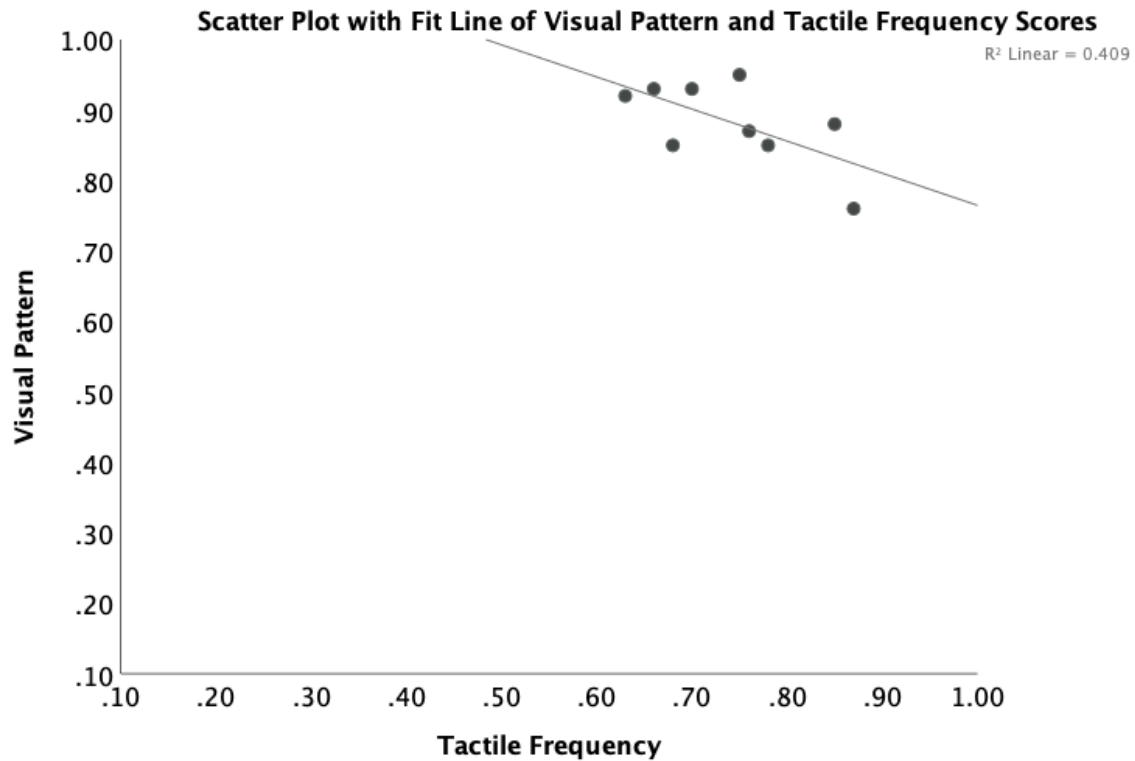
Scatter Plot which illustrates the comparison between Visual Frequency and Tactile Frequency.



A Pearson's correlation was run to assess the relationship between the Visual Frequency and Tactile Frequency. Preliminary analyses showed the relationship to be linear with both variables normally distributed, as assessed by the Shapiro-Wilk's test ($p > 0.05$) and there were no outliers. There was no statistically significant correlation between Visual Frequency and Tactile Frequency tasks, $r = 0.286$, $p = 0.456$.

FIGURE 17:

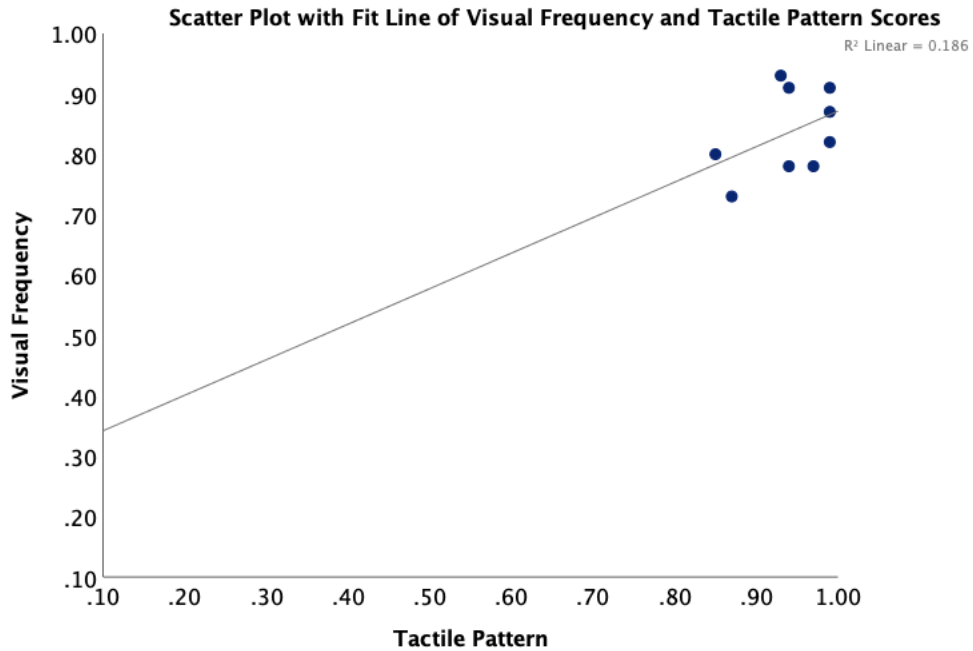
Scatter Plot which illustrates the comparison between Visual Pattern and Tactile Frequency.



A Pearson's correlation was run to assess the relationship between the Visual Pattern and Tactile Frequency in Working Memory tasks. Preliminary analyses showed the relationship to be linear with both variables normally distributed, as assessed by the Shapiro-Wilk's test ($p > 0.05$) and there were no outliers. There was a moderate correlation between the Visual Pattern and Tactile Frequency Working Memory tasks, $r = -0.640$, with an insignificantly marginal p-value ($p = 0.063$). An R^2 measure (0.409) suggested that 40.9% of the total variance in the two variables can be accounted for by the correlation.

FIGURE 18:

Scatter Plot which illustrates the comparison between Visual Frequency and Tactile Pattern.



A Pearson's correlation was run to assess the relationship between the Visual Frequency and Tactile Pattern. Preliminary analyses showed the relationship to be linear with both variables normally distributed, as assessed by the Shapiro-Wilk's test ($p > 0.05$) and there were no outliers. There was no statistically significant correlation between the Visual Frequency and Tactile Pattern tasks, $r = 0.431$, $p = 0.247$.

5. DISCUSSION

In this section, the results of this study are evaluated in juxtaposition with existing literature. The first part of the results assessed the participants' performance in WM tasks under the prism of Modality (Visual – Tactile) in order to explore DG or DS tools. A significant correlation in performance between Visual and Tactile WM hypothesized domain-general structures. However, the results indicate the absence of correlation between the Visual and Tactile modality. Reasonably, the two scores in modality related performance should not be associated. Therefore, the alternative hypothesis of general domain mechanisms cannot be accepted since we fail to reject the initial hypothesis for domain-specific mechanisms. The performance of the participants in the two modalities is considered autonomous in this study. The processing of stimuli in the Visual and the Tactile modality in WM tasks exploit individual primary sensory cortices and not a general pool of resources.

This is in line with other studies which have examined cross-modal interactions between tasks of WM in the Visual and Tactile modality, and they have found domain-specific accounts. For instance, Ohara, Lenz & Zhou (2006) used EEG to approach a neural model that implicated an array of areas which are connected but remain independent for the completion of Visual and Tactile tasks. Wu et al. (2018) suggested that the primary format of stimuli is processed in distinct sensory cortices using domain-specific resources, despite that the higher cognitive associations in abstract format use modality-general processing. Ku et al., (2002), suggested that simple tasks involve modality specific processing, and the maturation of domain-general resources is a superior level for complex cognition. Given the fact that the experiment of this research involved simplistic Visual and Tactile processing, it might be plausible to speculate that

the higher-level cognition was not required; therefore, the subjects recruited domain-specific mechanisms.

Nonetheless, the above results do not preclude the existence of domain-general mechanisms. Numerous researchers such as Ghazanfar & Shroeder (2006) have upheld that senses do not operate in a unimodal manner in real-world circumstances; therefore, their processing potentially encompasses domain-general channels. Shimojo & Shams (2001) discussed that the plasticity of cortical processing puts forward cross-modal interactions and defies the view of modality – specific functions. Li et al., (2014), provided a comparable dual-angle in this topic advising for both domain-general and domain-specific theories.

Ku et al., (2015), during a single pulse Transcranial Magnetic Stimulation (spTMS) study, found that both S1 and the PPC were active in WM tasks suggesting that both the association and sensory cortices play a part in WM and represent domain-general and domain-specific mechanisms. Additionally, Christophel et al. (2017), suggested that WM tasks implicate the activation of a variety of regions including sensory, parietal and prefrontal areas. The involvement of disparate areas could be the sign of different representational ‘stages’ where single domains unite their contribution and create a distributed network which ultimately regulates ones behavioural response to the stimulus.

The outcomes of the data in this test account for domain specificity over generality, and this could be a reflection of the discrete cerebral mechanisms which govern behaviour. However, with all things considered, it cannot be overlooked that the processes of cross-modal WM in Vision and Touch might necessitate both domain-specific and domain-general mechanisms, and any of these two hypotheses does eliminate the other. The reconceptualization of the function of

cross-modal WM in Vision and Touch and the conciliation of domain-specific and domain-general mechanisms is sustained by reviewing both evidence (Camos, 2017). Indeed, a variety of aspects such as stimuli characteristics, the anatomical structure of neuronal receptive fields or others modulate the response to a stimulus which generates domain-general or domain-specific mechanisms (Christobel et al., 2017).

The second part of the research question explored localized vs distributed mechanisms of WM under the discrimination of Pattern and Frequency within and across the two modalities (VP-VF, TP-TF, VP-TF, VF-TP). A significant correlation would indicate the association of the dimensions and the indication of a common code of processing of these variables. Although the majority of the findings in this study did not reveal a type of statistical dependency, there is only one correlation which approached significance between Visual Pattern and Tactile Frequency. Bigger sample size would be optimal to ascertain if these effects can be trusted, but for now, it is not possible to conclude from this data set a definite relationship between Pattern and Frequency. Statistically, we fail to reject the initial hypothesis of a separate code for space and time, and we cannot accept the alternative hypothesis of common mechanisms. However, observing the marginal co-occurrence of Visual Pattern and Tactile Frequency, it is advantageous to discuss this topic under non-conclusive remarks but taking into account both aspects of this matter.

Firstly, the results inform an insignificant difference in the accuracy of the participants in the visual and tactile tasks of Pattern and Frequency. Hegner et al. 2007 did not observe a differentiation in performance in tactile pattern and frequency but did not examine the visual modality. A further test could solve whether there a mechanism - either general or specific - is a defining factor of accuracy performance in discrimination tasks. Secondly, the predominant lack

of a relationship between pattern and frequency in each modality and across the two modalities indicates the discrimination of features in one task does not co-occur with the discrimination of features in another. On a neurophysiological level, it might be speculated that there are independent codes which contribute to pattern and frequency discriminability. The above finding is close to the theories which suggest different neural mechanisms for space and time, such as the constructive metaphor theory (CMT) by Lakoff and Johnson, (1980). Loeffler et al. (2018) presented a series of studies where space and time could not be correlated.

Thirdly, the marginal co-occurrence of Visual Pattern with Tactile Frequency can allude to domain-general mechanisms which are embraced by the theory of the ATOM (Walsh, 2003). Certain studies such as Agrillo & Piffer (2012) showcased how musicians transferred quickly from spatial to temporal tasks and when they improved in temporal tasks, they also improved in spatial tasks. Skagerlund & Trauff (2014, 2016), indicated that children with dyscalculia were challenged in both spatial (Pattern) and temporal (Frequency) tasks.

Singer and Gray (1995) noted that the ability of the brain to deploy a diffused area of cells for stimuli perception rather than a single region not only serves the purpose of brain plasticity but also implies that the discrimination of different stimuli can be achieved in different times. This means that when an episode of cognitive demand requires the discrimination of both features, the cognitive system will not exhaust its resources to one single feature. Further tests can be done to associate these theories to other aspects of WM such as selective attention, capacity or interference in order to understand better how the cognitive organization affects behaviour.

Considering all the above sentiments together the discrimination of Pattern and Frequency might depend on individual ‘hubs’ of processing or it can benefit from distributed brain areas where neurons for spatial and temporal processing are ‘sprinkled’ across the cerebral cortex, and they become attuned to a task according to a variety of factors. Indicatively, several parameters such as the physical nature of the stimuli, the individual representations, the strategies that a person deploys to solve a task and the neuronal populations which run for each task could control the discrimination of stimuli and assign different mechanisms for tasks (Hegner et al., 2007).

Nieder (2017) assumed that there is not a sole type of Working Memory for the discrimination of different properties of stimuli. The possible lack of a single region could preserve the valuable ability to distinguish patterns and frequencies in case of neural degeneration or injury (Merchant et al., 2013). The neurophysiological study of brain signals behind these abilities could shed light on the criteria of establishing multisensory or uni-sensory areas which govern each discrimination mechanisms (Ghazanfar & Shroeder, 2006). Lastly it should be noted that despite the possibility of shared or independent mechanisms for pattern and frequency discrimination, space and time might still overlap with each other in tasks which include both features. The degree of their overlap is another future inspection (Mendez et al., 2011).

5.1. LIMITATIONS

At this section, this work ponders its limitations. First and foremost, this study could not control for a more robust sample size ($n = 11$, which was reduced to $n=9$ to avoid outliers). This

main limitation has the potential to cast doubts on the generality of results. The 11 participants who completed the test were not a large number with the power to conclude inferences.

Although, small sample sizes are not a defining feature of a study as long as the interpretation of results remains transparent, (Hackshaw, 2008) it is a reason for the absence of robust results in this thesis. The second limitation is linked to the experimental design of this test. Specifically, laboratory research does not speak for real-life conditions and cannot measure human behaviour in natural habitat. The fact that this experiment is staged under particular conditions with a certain level of difficulty and a certain level of isolation from environmental distractions does not mean that the results would be the same if the researchers attempt to test the participants in different conditions (Constantinidis, 2016, Cohen, 2013).

A third limitation is associated with the chosen statistical analysis. Pearson's correlation has the potential to unveil associations, but it does not fathom prediction or accountability in the comparison of variables. It might be informative to know the dependency between two variables, but this does not mean that one can cause the other (Field, 2013). Therefore, a high score in the Visual modality might be associated negatively or positively with a high or low score in the Tactile modality and vice-versa, but there is no causality in this relationship. In other words, the correlation detects their co-occurrence, but it does not justify its observation. Furthermore, Pearson's Correlation test can reveal tendencies, but it does not constitute the whole spectrum of statistical tests that can be performed in order to come closer to robust statistical power. This fact, in association with limited sample size, could bias the results (Green & Salkind, 2016).

Moreover, the fourth limitation in this experiment elicits from considering the Test Score as the solemn 'testbed' of this study. Adding potential Independent Variables such as the

Reaction Times would scrutinize further the performance of the participants and offer a more spherical view on the results of this test. At the same time, this study does not contemplate how components such as age, language and sleep might influence the subjects' performance., Manning et al. (2006) and Master et al. (2010), both found reduced ability for Pattern recognition in elderly population although, in this thesis, the participants' age is spread across adulthood.

Further limitations assess less critical details. For example, it is unknown whether the participants have secured a solid grasp of what is Pattern or Frequency in this behavioural test. Based on their prior knowledge, they can be more or less primed to recognize and discriminate these features. It is acknowledged that at the beginning of the test, they have to pass a short test which confirms their ability to understand the instructions. However, their notions of what consists Pattern and Frequency remain unverified and might bias their decision making. In a study by Tomassini et al. (2011), participants measured the duration of stimuli using the metric of speed. The encoding of duration was made by using another measurement than the one that was asked. This could lead to confounding variables that can interfere with the subject's judgement and decision making.

Last but not least, this thesis assessed a less researched topic which is relevant to studies in Visual and Tactile experiments of WM. It was challenging to find studies matching the same behavioural test and using the same Variables (Visual, Tactile, Pattern, Frequency) to investigate a research question. Although this is a welcome challenge, it explains the reason why a lot of neurophysiological studies are appraised compared to less behavioural data.

CONCLUSION

In conclusion, the rudimental role of WM is to create a temporary cognitive capacity to process information while maintaining optimal cognitive performance. As it was presented through multiple studies, the sensory systems of Vision and Touch and the properties of Pattern and Frequency in stimuli can be studied in conjunction in order to understand how humans perceive complex multisensory information. Essentially, the theoretical background showcased that the processing of Vision and Touch and the processing of Pattern and Frequency (in stimuli which belong to those modalities) deploy specific mechanisms which have not yet been fully understood.

Thus, to assess the performance of the participants in the Visual and Tactile Modality during cross-modal WM tasks which required the discrimination of Pattern and Frequency, a behavioural test was deployed. Moreover, the statistical analysis strived to detect a dependency between modalities and between tasks. A negative or positive correlation would indicate that any two values co-occur. An association would mean that there are shared internal mechanisms, and a dissociation would mean that there are independent mechanisms.

The results in this study indicated the absence of a statistically significant relationship between modalities (Vision and Touch) and between dimensions (Pattern-Frequency) about each individual modality (VP-VF or TP-TF) and about cross-modal comparisons (VP-TP, VF-TF, VF-TP). However, a marginal significance yielded the possibility of statistical dependency of cross-modal tasks (Visual-Pattern with Tactile Frequency). A minimal sample size adds the lack of likelihood to render robust inferences. Still, it does not restrict the avenue to present views of both edges in this debate. It is sensible to emphasize the possibility of both domain-specific and

domain-independent mechanisms and aim to understand the standards of their deployment. This focus could discover the criteria for establishing one area as multisensory and expand on the discovery of the potential cognitive codes of spatial and temporal processing.

All in all, this study is essentially an invitation to explore the relationship between sensory types of WM and the relationship between the properties of stimuli, such as space and time. This endeavour adds to the novel scope of multimodal and multidimensional research intending to decipher how humans reach holistic perceptual experiences, which aspects impact their reasoning and how sensory deprivation can be tackled. These studies abandon the study of the secluded, performance in WM tasks and provide behavioural data which approximate more realistically the multisensory world. Future research will surmount any concerns and offer optimal provisions for the testing of similar hypotheses, highlighting the contribution of sensory neuroscience in multimodal cognition and the coding of stimulation. The advancement of behavioural psychometric testing and its synergy with other techniques such as neuroimaging can offer secure viewpoints on this subject.

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