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Introduction

Working memory is one of the most intriguing concepts in modern cognitive sciences. Its complexity leads researchers to question its existence, and evidence supports either some or no theoretical model to explain it. Under these circumstances, several questions remain about the real structure and consequences of working memory function. The present work attempts to shed light on such a diverse and complex matter based on functional magnetic resonance imaging (fMRI) studies and neuropsychology.

Let us say that I need to hold a telephone number in mind until I dial it, or I need to understand and follow directions about how to go somewhere I have never been before, or I need to follow instructions in a manual to use a new gadget. These are few examples of a human ability that we call working memory (Cowan, 1999). Evolutionarily, it makes sense to think that our ancestors from the Stone Age also had this ability, and it was likely essential for their survival (Coolidge & Wynn, 2005; Read, 2008).

To hold and manipulate all sorts of information in mind, a set of mental processes, known as working memory, is required. A good example of working memory is how we perform multiplication in our mind. The ability to actively maintain numbers in our mind demands focusing attention on one piece of information at a time because of humans' inherent limits of attention (Cowan, 2010). Because we have such limitations, we developed other mental strategies to overcome these mnemonic and attentional limitations, including, for example, grouping separate descriptions of a jungle as a singular mental piece(also known as chunking), overtly or covertly repeating novel directions to avoid forgetting them (also known as rehearsing), and accommodating new descriptions into previously known codes (also known as encoding; Cowan, 1999). Such strategies are not initially used but rather learned through experience and neural maturity, and they can be trained because they rely on neuroplasticity (Diamond, 2013).

The examples above illustrate how this type of operational memory is used and limited by an individual's mnemonic and attentional capacity. Much evidence indicates that working memory comes before other superior cognitive functions, such as language, reasoning, thinking, and planning, during early development (Diamond, 2013; Garon, Bryson, & Smith, 2008). Most human activities also need working memory to be executed properly. Following instructions, reading texts, and cooking food are tasks that are structured by a series of steps that rely on an individual's ability to update what was already done and what still needs to be done. Because of this, problems in working memory can lead to several consequences that impair the functioning of individuals. For example, children with working memory deficits during early development are more likely to show language impairments, learning disabilities, and attention disorders than their peers (Baddeley, 2003; Diamond, 2013). Elderly adults who present impaired working memory because of neurodegenerative diseases tend to present procedural difficulties and impairments in daily activities (Filgueiras, Charchat-Fichman, & Landeira-Fernandez, 2013). Working memory is used in everyday activities. Any complex thought relies on the proper performance of this cognitive function. Its importance spreads through all human cognition and is one of the foundations of creativity, reasoning, and abstract imagery (Diamond, 2013). Despite such importance, working memory is still a mystery to most cognitive scientists, and several questions remain unanswered.

Understanding how the brain is activated during working memory tasks can shed light on how such tasks activate the brain's neural networks. For example, Rottschy et al. (2012) evaluated all modalities of working memory (i.e., verbal, non-verbal, and visuospatial) in a single meta-analysis. Their results showed core activation of distinct areas, including bilateral activation of the dorsolateral prefrontal cortex, supramarginal gyrus, and anterior intraparietal sulcus and bilateral activation of the cingulate cortex (anterior insula and pars opecularis, part of Broca's area). Parietal and frontal regions appear to be activated during working memory tasks. Other meta-analyses also reported similar results (Owen, McMillan, Laird, & Bullmore, 2005; Wager & Smith, 2003). Strong evidence shows fronto-parietal network activation during working memory tasks. The literature suggests that parietal regions are mostly integrative. While the brain is executing a working memory task, those regions integrate perceptive and sensorial inputs in a way that allows processing (Owen et al., 2005). Frontal regions are associated with motor control and thinking; thus, mental processing likely occurs in those regions (Rottschy et al., 2012). According to this view, working memory can be divided into two components within the same network: integration and processing.

Theorists generally agree that working memory has two divided subsystems: one that is domain-general and one that is domain-specific (Baddeley, 2003; Cowan, 2010; Diamond, 2013). The domain-specific subsystem is also divided into phonological and visuospatial domains. These are mirror subsystems. Thus, the mental process that an individual uses to retain serial instructions in mind is likely similar to the one that is engaged when imagining a group of visually different stimuli to mentally manipulate them. This means that both phonological memory and visuospatial working memory share the same functional structure (Baddeley, Allen, & Hitch, 2011). The present work focuses on phonological working memory because evidence supports the notion that it has stronger associations with reasoning, naming, and language (Baddeley, 2000, 2003; Baddeley, Allen, & Hitch, 2011), the last of which is our main interest.

The present thesis consists of a meta-analysis that is presented in five parts: (1) history of working memory and importance of understanding it from a neuroscientific perspective, (2) the presentation of three of the most important theories to explain working memory function: (*i*) Baddeley, Allen, and Hitch (2011), (*ii*) Cowan (1999, 2010), and (*iii*) Diamond (2013)—Chapter 2, (3) objective and methods of this thesis—Chapter 3, (4) meta-analysis of fMRI studies on phonological working memory and how such studies can help resolve some of the issues in Chapter 2—Chapter 4, (5) conclusions of the present thesis and future directions—Chapter 5. The main goal of the present study is to shed light on working memory, how it works in the brain, and how fMRI evidence supports or does not support one theoretical model or another. Our efforts were directed toward providing further knowledge about this subject and not necessarily providing answers to unanswered questions.

1.1

History of working memory

Modern psychological science has been through paradigm transformations since its inception in 1857 in Leipzig with Wilhem Wundt (Mills, 2000). Psychoanalysis, psychophysics, and behavioral sciences were some of the earlier approaches to explaining psychological phenomena. During the first half of the 20th century, North-American psychologists were thrilled by studies of respondent and instrumental conditioning by such authors as B.F. Skinner, John Watson, and Ivan Pavlov (Mills, 2000). According to psychology's behavioral approach, the mind is a blank slate, and behaviors are imprints of learning that are created through conditioning. For behaviorists, there is no cognitive predisposition. Men are products of their environment. Thus, there is no need to study the human mind. To understand the psychological aspects of an individual, psychology only needs to know the stimuli, the individual history of learning and conditioning, and the result of the stimuli in terms of behaviors (Mills, 2000).

Historically, cognitive sciences were the response of North-American psychologists to the behavioral approach. In the late 1950s, such researchers as Albert Bandura, Aaron Beck, and Albert Ellis suggested that learning can also occur without self-experience (Bandura, 1971; Beck, 1967; Ellis, 1958). Bandura (1971) provided strong evidence of vicarious learning (i.e., learning by observing someone else's experience). Beck (1967) and Ellis (1958) showed how rational thinking enables learning in psychotherapy patients. This evidence suggested that learning is also attributable to cognitive predispositions that can be explained by different mental processes rather than simply environmental influences.

During this historical period, another researcher also showed how it is not possible to learn anything. Human cognition is not limitless, and cognitive capacity is defined by innate limitations. To show how memory is limited, George Miller (1956) proposed an experiment in which the participants had to remember a set of stimuli in the same order in which they were presented. Miller (1956) showed that participants are able to retain an average of seven items for each set in the same dimension (e.g., numbers, words, or phonemes) with possible variations from five to nine items, depending on the person. According to Miller (1956), this "magical number" of seven (plus or minus two) is the product of the ability to chunk information (i.e., to create groups of items in the same dimension). For example, whenever one is trying to memorize a set of numbers, creating tens and hundreds (i.e., chunks of two or three digits) enables better retention then trying to remember number by number.

Several studies were conducted since Miller's "magical number" paper in 1956 to understand how short-term memory works and whether it is the only process that is recruited to retain and recall information. In 1964, Conrad and Hull performed a set of experiments using pitches and sounds and showed that acoustic variations and perception affect short-term memory span performance. Similar results were found by Baddeley (1966a, b), who suggested that articulation and rehearsal of the sound by the participant allowed better retention and repetition in span tasks. In fact, Murray (1968) also showed that the articulation or sub-vocalization of a sound or phoneme can cause confusion when chunking and rehearsing are needed in short-term phonological tasks.

Altogether, this evidence suggested that other mental processes play important roles in retention and retrieving information in span tasks. Baddeley and Hitch (1974) then proposed an innovative theoretical model—the working memory model—to explain how humans use novel information and process it to deal with challenges in the environment. According to these authors, short-term memory (i.e., the one that is accessed by direct span tasks) is modality-dependent (i.e., phonological or visual).The mental manipulation of novel information requires more than just short-term memory. Miller, Galanter, and Pribham (1960) created the term “working memory,” but it was Baddeley and Hitch (1974) who named this way these mental processes involving retaining and manipulating novel information.

Since Baddeley and Hitch (1974) introduced the working memory model, several researchers have sought to understand the mental processes that underlie this psychological construct. However, Baddeley’s studies (e.g., Baddeley, 1966a, b, 2000; 2003a, b; Baddeley, Allen, & Hitch, 2011; Baddeley, Gathercole, & Papagno, 1998; Baddeley, Papagno, & Vallar, 1988) started a new field within cognitive sciences: working memory tasks and processes. To date, although Baddeley’s model has been reviewed and discussed, a final form has not been reached, but it is still the most adopted theoretical model to explain behavioral results in psychology.

1.2
Neuroscience of working memory and fMRI meta-analyses

Neurosciences and neuropsychology are growing fields of research in modern psychology. Since the development of neuroimaging techniques, such as fMRI, positron emission tomography, and magnetoencephalography, from the 1990s until today, psychological researchers have investigated how humans process mental tasks in the brain (Yarkoni, Poldrack, Nichols, Van Essen, & Wager, 2011). The basic idea of neuropsychology is that each and every psychological construct (e.g., memory, attention, thinking, planning, motor preparation, and control) has a neurobiological basis (i.e., a neural network in the brain that is responsible for processing and executing a task or behavior; Damasio, 2006). Because all psychological constructs have a neurobiological basis, the same must be true for working memory.

D'Esposito and Postle (2015) defined working memory as a mental process that accounts for coordinating and processing information when multiple goals are active and guides behavior based on information that is not present in the immediate environment. According to recent data, working memory uses content that is already known from long-term memory to manipulate internal representations through attentional control that generates encoding. Encoding is the ability to convey sensory or semantic information into mental short-term representations that are ready to be mentally manipulated but not necessarily consolidated in long-term memory (Jensen & Lisman, 2005).

Working memory appears to be an embedded set of mental processes that are basically divided into memory and attention (Cowan, 1999, 2010; Cowan, Blume, & Saults, 2013). Memory is divided into three main processes: sensorial memory (sensorial information storage, which happens in ~250 ms),short-term memory (responsible for encoding sensorial information into mental representations), and long-term memory (responsible for activating and retrieving stored represented information). During working memory tasks, attention is divided into two main processes: attentional focus (responsible for activating specific parts of long-term memory where task-relevant represented information is stored) and the central executive or attentional control (responsible for holding in the mind the task's goal and maintaining focused attention on the correct portion of long-term memory; Cowan, 1999).

Recent fMRI studies (e.g., Jensen & Lisman, 2005) have provided evidence that long-term memory storage in the brain is linked to the type of encoding that is represented in the mind (e.g., auditory information is stored in the auditory cortex, a part of the temporal lobe; semantic-encoded information is stored in regions of Wernicke's and Broca's areas). These encoding-dependent regions of storage also appear to be activated during working memory tasks. Long-term memory is likely used to represent and manipulate short-term information (D'Esposito & Postle, 2015). The prefrontal cortex plays an important role in working memory tasks. Evidence from fMRI studies suggests that activation of the prefrontal cortex is pivotal for attentional control. Some authors have suggested that parietal and temporal regions are responsible for encoding, representing, and retrieving mnemonic information and embedding mental processes. Frontal regions are responsible for focusing attention and maintaining or shifting it during working memory tasks (D'Esposito & Postle, 2015).

Despite the growing literature, fMRI studies have not yet determined whether the neural networks that are responsible for encoding the same sensorial input are similarly activated during working memory tasks using different types of representation. The aim of the present dissertation is to address this issue by relying on fMRI meta-analytical methods. This study sought to compare pitch and sound stimuli (non-vocalized) with letters or syllables and words/nonwords. Although such stimuli are similar in terms of encoding, they have an hierarchical organization. Words have both semantic meanings and phonological representations. Syllables and letters are restricted to phonological representations, with a few exceptions (e.g., one-syllable words).Sounds and pitches have only auditory representations and are difficult to vocalize and are thus difficult to rehearse. If fMRI results for each of these types of stimuli are subtracted from one another, then the result would reveal a pure region of auditory storage and pure region of the central executive. This research is unique because all other meta-analyses of working memory have sought to unveil the neurobiological foundations of working memory in terms of neural networks (e.g., Owen et al., 2005; Rottschy et al., 2012; Wager & Smith, 2003) and not the specific location of a single function.