What Do Working Memory Tests Measure? The Relationship Between the *n*-Back, Digit Span and Symbol Span Tests

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Declaration

A research project submitted in partial fulfilment of the requirements for the degree of MA by coursework and research report in the field of Psychology in the Faculty of Humanities, University of the Witwatersrand, Johannesburg, 15 March 2023.

I declare that this research project is my own, unaided work. It has not been submitted before for any other degree or examination at this or any other university.

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Abstract

Working memory is critical for important cognitive functions, including learning and decision-making. Although the *n*-Back task has been widely used as a measure of working memory, it is not clear whether this task is in fact tapping the same (or similar) constructs as other established working memory tests. This study therefore investigated performance of 47 multilingual South African university students on three working memory measures, namely the *n*-Back task, the Digit Span subtest, and the Symbol Span subtest, in order to assess the relationships between these tasks. Additionally, there was interest in evaluating the extent to which demographic factors influence working memory performance. This study thus examined the extent to which number of languages spoken, proficiency (in speaking, comprehension and reading), biological sex and socioeconomic status affects test scores. Kendall's Tau correlation analysis revealed a significant correlation between specific Digit Span conditions and 3-Back Accuracy scores, while regression analyses indicated that performance on Digit Span Sequencing significantly predicted 3-Back Accuracy scores. In terms of the demographic variables, several of the proficiency scores significantly predicted performance on the Digit Span Sequencing and 3-Back Accuracy scores. These results are interpreted within the theoretical and empirical frameworks guiding this study. Through describing the relationships (or lack thereof) between these variables, this study contributes to a greater understanding of the *n*-Back task, and, perhaps more importantly, to those aspects that remain to be explored and explained.

Keywords: working memory, *n*-Back task, Digit Span, Symbol Span, multilingualism, proficiency, sex-effects, socioeconomic status

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Chapter 1: Theoretical and Conceptual Background

1. Introduction

The term 'working memory' refers to a cognitive system that is dedicated to temporarily storing and manipulating a limited amount of information for the purpose of performing cognitive tasks, such as comprehension, reasoning and learning (Baddeley & Hitch, 1974). In simpler terms, it may be understood as "the ability to work with information" (Alloway & Copello, 2013, p. 105). Working memory capacity is measured based on performance on working memory tests. One working memory test that is increasingly used is the *n*-Back task. However, this task has not been subjected to many behavioural tests of construct validity, and so it is unclear whether the *n*-Back task is tapping into the same constructs as other established working memory tests (Gajewski et al., 2018; Jaeggi et al., 2010; Kane et al., 2007). Therefore, the current study sought to explore the relationships between the *n*-Back task and two other working memory measures. Since performance on working memory tests may be influenced by individual demographic factors (e.g., sex, socioeconomic status, number of languages spoken and proficiency level), they were also evaluated.

In this chapter, several working memory models are discussed to provide an integrative understanding of working memory theory and its interaction with cognitive constructs. Thereafter, working memory, as it relates to this study, is defined. The three neuropsychological tests used to operationalize working memory in this study are briefly described, namely (1) the Digit Span subtest, (2) the Symbol Span subtest, and (3) the *n*-Back task, and the demographic variables are discussed. Finally, the rationale and aims of the current study are presented.

2. Literature Review

As mentioned above, working memory constitutes a cognitive system dedicated to the storage and processing of information (Baddeley & Hitch, 1974). What makes working memory such an important cognitive system to study is that it plays such an integral role in complex cognitive activities, such as comprehension, reasoning, and problem-solving

(Cowan, 2014; Korovkin et al., 2018). For example, when hearing a sentence, the listener needs to ‘hold in mind’ information from the beginning until the end of the sentence. When there are deficits in working memory capabilities, parts of the sentence are lost before it can be formulated into a complete thought (Cowan, 2014). Similarly, performing mental arithmetic requires one to maintain, and simultaneously manipulate, the numbers in one’s mind to reach the answer. Essentially, working memory serves as the interface between attention, perception and memory (Baddeley, 1998), and is involved in the simplest to the most complex everyday tasks. In fact, it has been argued that working memory “is so central to human cognition that it is hard to find activities where it is not involved” (Ericsson & Delaney, 1999, p. 259). The importance of working memory is particularly important when one learns something new. New information that is not yet integrated with other knowledge imposes a high working memory load. Once this knowledge is processed and stored into long-term memory, working memory load is reduced. Deficits in working memory have also been associated with a range of disorders, including learning disorders (e.g., Maehler & Schuchardt, 2009; Wiguna et al., 2012) and psychiatric disorders, such as Alzheimer's disease, Schizophrenia, and Multiple Sclerosis (e.g., Dienel & Lewis, 2019; Huang et al., 2019; Kouvatsou et al., 2019; Zokaei & Husain, 2019).

Given the important role of working memory in cognition, it is widely researched in cognitive neuroscience (Cowan, 2014). Several theoretical models are proposed to describe how it is structured, how it interfaces with other cognitive systems, and how it underpins maintenance and processing operations. Since the term 'working memory' developed from the concept of short-term memory (STM; Baddeley et al., 2019; Chai et al., 2018; Cowan, 2008), it is useful to review STM and its history, as this provides further context on the defining characteristics of working memory.

3. Historical Overview

The term ‘short-term memory’, and later working memory, can be traced back to the philosopher John Locke (1690), who distinguished between contemplation (e.g., keeping an idea "actually in view") and memory (e.g., the "storehouse of ideas" that can be "revived") (p. 37). He further asserted that the human mind is unable to maintain several ideas simultaneously. Two centuries later, James (1890) differentiated between items currently in consciousness as 'primary memory' and stored items as 'secondary memory'. This differentiation between memory capacities (i.e., short-term versus long-term capacity) played an influential role in early experimental psychology (e.g., Ebbinghaus, 1885/1913).

More recent developments in the concept of STM have been partially attributed to the work of Miller (1956), who investigated limits in STM capacity, specifically, the number of items that can be retained in memory. In this study (Miller, 1956), participants were presented with a list of seen or spoken items; immediately afterwards, they were asked to repeat the list, verbatim. The number of items correctly recalled was limited to about seven ‘chunks’. To illustrate the concept of ‘chunks’, consider the following: a random list of digits (e.g., 293685) might be encoded as six chunks, i.e., one chunk per digit (2-9-3-6-8-5). In contrast, digits ‘654123’ might be encoded as only two chunks (e.g., 654-123), as they might be classified as a descending and ascending triplet (Cowan, 2014). Therefore, ‘chunks’ do not constitute predefined units, but rather relate to individual strategies (Miller, 1956).

The discovery that the human information processing system is limited to approximately seven ‘chunks’ resulted in the development of several STM theories. For example, the selective attention experiments conducted by Broadbent (1958) resulted in a theory on selective filtering. In this theory, information enters a sensory store, and through an attention filter, is refined to only a few items in a temporary holding store. Finally, a limited amount of information is processed into long-term memory. Essentially, Broadbent (1958) suggested that a STM-type store existed, which served as a transient buffer between sensory input and long-term memory.

By the end of the 1960s, the notion that the human processing system consisted of a unitary memory system was largely rejected, as evidence for dissociable memory stores continued to accumulate (e.g., Brown, 1958; Peterson & Peterson, 1959). Nevertheless, these distinct memory components were often depicted as a unidirectional flow chart. For instance, in Broadbent’s (1958) model, information passes unidirectionally through the proposed memory components. Atkinson and Shiffrin (1968) rejected this sequential information processing pattern, arguing that memory is a more complex system that involves several interacting mechanisms. They proposed the ‘Multi-store Model’, which depicted the interactive nature between (1) a modality-specific sensory register, (2) a short-term store of limited capacity, and (3) a substantially larger, permanent long-term store. Although progressive in emphasising the interactive (as opposed to unidirectional) nature of memory components, their model maintained that STM is a unitary store, into which all sensory information entered. However, this implied that any damage to STM would negatively affect long-term encoding. This was not supported by neuropsychological evidence (e.g., Bower, 2000), which revealed that impairments in STM did not necessarily hinder encoding into long-term memory .

For this reason, Baddeley and Hitch (1974) challenged the notion of a unitary STM store. They noted several dissociating attributes, where *verbal* storage was most disrupted by simultaneous *verbal* processing, while *visuospatial* storage was most disrupted by simultaneous *visuospatial* processing. They proposed that STM is, in fact, a multicomponent system, consisting of a control system (dependent on attention) and several distinct storage systems. It was the functional aspect of STM (the mental ability to simultaneously store and process information) that became known as 'working memory' in the Multicomponent Model, proposed by Baddeley and Hitch (1974). A main divergence of the Multicomponent Model from STM theories was the perspective that STM is not a single system. Rather, it could be differentiated into separate parts operating together: instead of all information entering a single short-term store, different systems exist for different types of information.

Baddeley and Hitch (1974; Baddeley, 2000) thus divided working memory into several distinct domain-general and -specific stores, which are overseen by executive functions. The simplest and most widely-researched component is the ‘phonological loop’ (RepovŠ & Baddeley, 2006), which plays an important role in processing and storing auditory-verbal information, such as heard and spoken speech. The phonological loop includes a passive phonological store, where information is momentarily captured as memory traces, and an active articulatory control process that rehearses this information to prevent deterioration (Baddeley, 2003; Baddeley & Hitch, 1974; Schaeffner et al., 2020). Here, working memory span corresponds to the amount of information that can be recalled before the first item fades from the store. Due to the extensive research on the phonological loop, this component of the working memory model is theoretically well-developed and supported by empirical findings. It has, for example, been studied in different sample groups (e.g., Bajre & Khan, 2019; Jarrold et al., 1999), relating to limited span (e.g., the maximum number of items an individual can hold in mind is dependent on stimuli type, i.e., verbal versus visuospatial), the phonological similarity effect (e.g., items sounding most similar within a given sequence influence the number of items recalled), the irrelevant sound effect (e.g., irrelevant words significantly impair recall of target verbal material), the word length effect (e.g., word length reduces immediate memory for word sequences), and articulatory suppression (e.g., repeating a random word inhibits articulatory rehearsal, so that target items cannot be effectively rehearsed and recalled). The verbal nature of these techniques and associated impairments suggest a distinct phonological component in working memory (Buchsbaum, 2013; RepovŠ & Baddeley, 2006).

The second component of working memory is the 'visuospatial sketchpad', i.e., a visuospatial version of the phonological loop, which stores and processes both visual and spatial information. Comparable to the phonological loop, the visuospatial sketchpad consists of a passive system, referred to as the 'visual cache', for the storage of visuospatial information, and an active system, termed the 'inner scribe', which refreshes this information through rehearsal (Logie, 1995; Logie & Pearson, 1997). Several working memory studies suggest a visuospatial component that is distinct from verbal processes (e.g., Mohammed et al., 2020; RepovŠ & Baddeley, 2006; Sims & Hegarty, 1997). These support the proposition that visuospatial memory constitutes an independent component of working memory (Baddeley & Hitch, 1974). Moreover, these provide evidence for further fractionation into visual and spatial subsystems, i.e., where visual memory pertains to fixed colour and geometric properties, whereas spatial memory includes physical or imagined movement (Baddeley, 2012; Logie & Pearson, 1997; Pickering, 2001; RepovŠ & Baddeley, 2006).

The central executive, which co-ordinates the abovementioned stores, is regarded as the most intricate component of the working memory model (Baddeley, 1996). This component is responsible for several functions in working memory, which includes: (1) focusing attention on immediate tasks, (2) dividing or prioritising attention to salient stimuli, (3) switching between tasks, and (4) interfacing with long-term memory (Baddeley, 2012). Essentially, the central executive is involved in attentional processes, and allows one to focus attention on specific stimuli, while disregarding others. It is also the central executive that initiates rehearsal processes to prevent decay of information from the phonological and visuospatial stores (Adams et al., 2018). Importantly, different tasks require varying activation of the central executive. When the phonological loop and visuospatial sketchpad require simple storage (such as keeping digits/symbols in mind), this engages a domain-specific skill. However, when information needs to be both stored and manipulated (or when two tasks need to be coordinated, simultaneously), the domain-general central executive is required for additional processing (Gajewski et al., 2018; Schaeffner et al., 2020). The concept of a central executive component operating over sub-goal hierarchies is supported by empirical evidence (Buehler, 2018; Hills et al., 2010). For example, the same control process (i.e., central executive) appears to be used across and within domains, to mediate search-related problem solving, even when these domains are associated with independent sub-components, i.e., verbal versus visuospatial (Hills et al., 2010).

In 1986, attention-dependent storage was removed from the Multicomponent Model, and later replaced by a domain-general store, i.e., the ‘episodic buffer’ (Baddeley, 2000). The latter helps explain how the central executive and the subsidiary stores interact, i.e., the episodic buffer consolidates both verbal and visuospatial information into logical episodes (e.g., memories), and integrates these into long-term memory (Demir, 2021; Henry, 2010). Consequently, this explains how several sources of information can be processed simultaneously. This component of working memory is supported by empirical evidence that points to an integrating buffer distinct from the central executive and slave-systems (e.g., Alloway et al., 2004).

The Multicomponent Model therefore reflects a hierarchy of buffer stores, and thereby provides an explanation of how cognitive processes can occur at once (Baddeley & Hitch, 2019). Information can enter phonological and visuospatial storage concurrently and interact under simultaneous executive control, while being logically integrated through the episodic buffer. Neuropsychological evidence from dual-task experimental designs provides valuable insight into the fractionation of working memory, the nature of individual stores, and how these relate to each other (e.g., Alloway et al., 2004; Bajre & Khan, 2019; Gray et al., 2017; RepovŠ & Baddeley, 2006; Vallar & Baddeley, 1984; Waris et al., 2017).

Nevertheless, the Multicomponent Model has been subject to criticism. It has, for instance, been described as overly simplistic, as it fails to explain phenomena outside the laboratory. In other words, it does not adequately explain the nature of ‘real’ everyday cognition (Demir, 2021; Engle & Kane, 2004). Consequently, it has been argued that this working memory model cannot be used to make cognition-based predictions, or explain cognitive phenomena, as the components and their interrelationships are not described in enough detail (Andrade, 2001). Furthermore, even though the central executive is considered the most complex component of the working memory model, it is the least studied or understood (Demir, 2021; RepovŠ & Baddeley, 2006). For example, it is unclear whether executive working memory (e.g., updating) is content-general or -specific (Waris et al., 2017). For this reason, it has been suggested that the central executive be redesigned to clearly differentiate the extent to which the central executive (content-general) and/or slave systems (content-specific) overlap in the function of rehearsal (Demir, 2021). Furthermore, it has been argued that the proposed binding functions of the episodic buffer do not constitute a single component, but rather depend on attention from other functions (Gray et al., 2017). This is complicated by having no established methodological process for individually assessing the episodic buffer (Henry, 2010), which Baddeley (2012) considered to be an unresolved issue.

In light of the abovementioned critiques, other working memory theories have been proposed. For example, Cowan (1988) asserts that the Multicomponent Model (Baddeley, 2000; Baddeley & Hitch, 1974) is limited to verbal and visuospatial representations and excludes other types of information, such as tactile stimuli. For this reason, Cowan (1988, 1999) believed that working memory does not constitute a separate entity, but is rather a collection of ‘embedded’ cognitive mechanisms, and consequently, proposed the ‘Embedded-process Model’ (Adams et al., 2022; Cowan, 1999). Essentially, Cowan’s proposed working memory model reflects a single memory store, comparable to long-term memory, which relies heavily on attention. Through focused attention, information in long-term memory can be activated, or “brought into working memory” (Chein & Fiez, 2010, p. 5). Memory components, focus of attention and long-term memory are all ‘embedded’ within each other to enable on-demand processing, irrespective of whether the incoming stimuli is verbal or visuospatial (Cowan, 1988, 1999). While Cowan (1999) acknowledges differential forms of information (i.e., verbal and visuospatial), these are processed in the same way (through focused attention). The central executive, similar to that of Baddeley and Hitch (1974), manipulates information within the focus of attention, as well as within activated long-term memory (Adams et al., 2022; Cowan, 1999). Although these activated long-term memory representations decay over time, they are refreshed through focused attention. Therefore, according to this model, working memory capacity reflects the number of items that can be maintained within focused attention (Cowan, 1988, 1999; Gray et al., 2017).

Cowan’s (1988, 1999) model is similar to the theory proposed by Baddeley and Hitch (1974). Indeed, the Multicomponent Model (Baddeley & Hitch, 1974) and Embedded-process Model (Cowan, 1988, 1999) have been described as “coming closer together”, (Adams et al., 2018; Chein & Fiez, 2010; Gray et al., 2017, p. 18). For instance, introducing the episodic buffer (Baddeley, 2000) sought to account for some of the phenomena that Cowan (1988, 1999) related to the focus of attention. Nevertheless, important considerations remain, such as whether the phonological and visuospatial components of Baddeley and Hitch (1974) are functionally comparable to Cowan's (1988) activated portion of long-term memory (Gray et al., 2017). Furthermore, the Embedded-process Model (Cowan, 1988, 1999) has been criticized for not explaining different types of encoding, or why items with similar features (i.e., verbal or visuospatial) interfere with each other (e.g., Adams et al., 2018).

An alternative approach to working memory, termed ‘Executive-attention Theory’ was proposed by Engle and Kane (2004). According to this theory, working memory is a system that includes: (1) short-term stores, consisting of activated long-term memory traces (in a variety of codes, i.e., verbal or visuospatial), (2) rehearsal strategies for maintaining activation (including chunking or phonological rehearsal), and (3) executive attention. This theory emphasizes the role of executive attention, which underpins the ability to control attention and regulate responses (e.g., decision-making and cognitive control), especially in conflict situations, such as with competing stimuli (Engle & Kane, 2004; Holmboe & Johnson, 2005; Kumar & Singh, 2020). Essentially, immediate memory, (particularly, executive attention) is crucial for maintaining information during interference (Engle & Kane, 2004). Executive control inhibits distractions that could interrupt attention to preserving stimuli representations, as activated in long-term memory. From this perspective, working memory plays a critical role in controlling attention, as opposed to the amount of information that can be stored (Berch, 2008). Greater working memory capacity thus reflects greater attentional control, as opposed to a larger memory store. In line with the Embedded-process Model (Cowan, 1988, 1999), Executive-attention Theory (Engle & Kane, 2004) postulates that the coding, maintenance and rehearsal processes of immediate memory relate to activated traces of long-term memory, and are not separated into domain-specific stores, i.e., verbal and visuospatial, as observed in the Multicomponent Model (Baddeley & Hitch, 1974). However, a limitation of Executive-attention Theory (Engle & Kane, 2004) is that the term ‘executive attention’ is poorly defined, and researchers have consequently used this term to denote different constructs (see Oberauer, 2019). It has also been criticized for inaccurately predicting a strong correlation between working memory and measures of inhibition and fluid intelligence, respectively (e.g., Wilhelm et al., 2013). Furthermore, the precise relationship (and boundary) between executive attention and intelligence are somewhat unclear, and deriving coherent attention control latent factors has proved challenging (Holmboe & Johnson, 2005; Mashburn et al., 2020).

In summary, several theories on working memory exist. These differ in the extent to which they propose dissociable components, and the degree of fractionation within subsystems, mechanisms and processes. Nevertheless, these frameworks tend to agree on the concept of a limited attentional system, dedicated to storing a small amount of easily-accessible information, for the purpose of performing cognitive tasks (RepovŠ & Baddeley, 2006).

4. Working Definition of Working Memory

Given the variations in working memory theory, it is challenging for a single definition to fully incorporate the theoretical arguments presented by different theorists. As such, it is necessary to adopt a tentative definition for the purpose of this study. Baddeley and Hitch's (1974) Multicomponent Model is considered one of the most prominent and widely-cited theories in cognitive neuroscience (Baddeley et al., 2021; Chai et al., 2018), and is further supported by lesion and neuroimaging studies (e.g., Albouy et al., 2019; Cañas et al., 2018; Chai et al., 2018; Geva et al., 2021; Kuznekoff & Titsworth, 2013; Lim et al., 2022). Even though the theories mentioned above differ from the Multicomponent Model, i.e., they emphasize attentional control in working memory, this is not dissimilar to the central executive, as it serves as an attentional controller (Baddeley & Hitch, 1974). Furthermore, despite the criticisms of the Multicomponent Model (Baddeley & Hitch, 1974), it remains one of the most tractable, and therefore, easy to operationalise in research. For this reason, the definition of working memory used in this study is based on the theory by Baddeley and Hitch (1974), which highlights the domain-specific verbal and visuospatial 'slave' storage systems, as well as domain-free executive processes, within working memory (Baddeley & Hitch, 1974).

The different theories highlighted in the previous section illustrate the complex nature of operationalising such an abstract construct as working memory. As such, it becomes increasingly important to investigate whether working memory measures are in fact tapping into the same (or similar) cognitive constructs. This is discussed in the next section.

5. Measures of Working Memory

Recently, there has been interest in distinguishing the components and processes of working memory. One way to assess these is to investigate the relationship between working memory tests to determine if they measure the same (or similar) constructs. The extent to which these tests measure different or overlapping aspects of working memory, however, is unclear. For example, despite its wide-use as a working memory measure, not much is known about the *n*-Back task and its relationship with standardised, diagnostic working memory tests. The current study thus sought to examine the *n*-Back task in relation to two established working memory measures: the Digit Span (verbal) and Symbol

Span (visuospatial) subtests, according to the subcomponents included in Baddeley and Hitch's working memory model (1974).

As mentioned, working memory tasks require different degrees of activation of the central executive. When only STM capacity is challenged, such as keeping a list of words in mind, information is stored, but not manipulated, thus not requiring any central executive involvement. This is referred to as a simple span task. In contrast, when information is stored and additional information is processed simultaneously, such as keeping a list in mind and arranging the items into categories, central executive processing is required (Gray et al., 2017; Myers et al., 2017). This is considered a complex span task. Simple and complex span tasks are used in neuropsychological tests to examine domain-specific skills (e.g., verbal and/or visuospatial) and domain-general executive attention (e.g., verbal and/or visuospatial, together with the central executive; Wilhelm et al., 2013). Importantly, while simple and complex working memory are commonly discussed as being theoretically distinct, in practice, they are always both implicated in complex span tasks (Cockcroft et al., 2016; Unsworth & Engle, 2006). In other words, simple span tasks may rely only on storage, but complex span tasks do not rely only on processing. Rather, complex span tasks always involve both storage (verbal/visuospatial) and processing (central executive involvement).

For this reason, running memory tasks (less reliant on storage), such as the *n*-Back task, discussed below, may serve as a purer measure of the central executive component of working memory, and thereby provide greater insight into the functioning of the central executive (Baddeley & Hitch, 1974). As mentioned earlier, a critique of the Multicomponent Model (Baddeley & Hitch, 1974) concerns whether executive working memory (e.g., updating) is content-general or content-specific. Working memory updating reflects the ability to actively add or subtract (i.e., 'update') new information from the working memory system (Colom et al., 2008; Gajewski et al., 2018). Since the *n*-Back task requires constant updating of the last '*n*' items, working memory updating is believed to be critical for successful performance on this task (Waris et al., 2017; Wells et al., 2018). In a study that used factor analysis methods, the *n*-Back task showed no clear differences according to task content, i.e., verbal versus visuospatial (Waris et al., 2017). This suggests a content-general, central executive component, and the current study aims to provide clearer insight into this.

In addition to gaining a clearer understanding of the working memory processes involved, it is hypothesised that the relationships between these three tests may demonstrate the extent to which they draw on storage and processing. These tests are discussed in more detail below, as well as in the Methods section.

5.1 Digit Span Subtest

The Weschler Adult Intelligence Scale, Fourth Edition (WAIS-IV; Wechsler, 2008a) is considered one of the most advanced measures of cognitive ability in adults (aged 16 years and older). There are 10 subtests in the WAIS-IV, but only the Digit Span was used in this study. The Digit Span subtest is considered one of the oldest working memory tasks, dating back to 1887 (Jacobs, 1887). It was designed to measure verbal STM and working memory (Holdnack, 2019; Wechsler, 2008a), and is divided into three parts: (1) Digit Span Forwards, (2) Digit Span Backwards, and (3) Digit Span Sequencing.

The Forwards condition requires participants to immediately repeat a series of digits, in the same order in which it is presented. It requires both focused attention and maintaining information. Since it does not involve a processing aspect (i.e., simple span task), it is considered to be a measure of attention or STM only, primarily tapping the phonological loop (Alloway et al., 2004; Cullum et al., 1998; Gray et al., 2017; Schaeffner et al., 2020; Wechsler, 2008a). Generally, most cognitively healthy individuals can achieve the 'seven plus/minus two' recall range on the Digit Span Forwards (Gignac & Weiss, 2015; Miller, 1956; Reynolds et al., 2022).

In contrast, the Digit Span Backwards requires participants to immediately repeat a series of digits, in the reverse order. Since this involves a processing aspect, in the form of manipulation, this task is considered a true measure of working memory, involving both the phonological loop and the central executive (Schaeffner et al., 2020). It is a commonly used tool to assess working memory capacity in clinical neuropsychology (Coulacoglou & Saklofske, 2017). Research has shown distinct differences in working memory performance between cognitively healthy and cognitively impaired population groups (e.g., mild cognitive impairment and dementia), using the Digit Span Backwards subtest (Eppig et al., 2012; Lamar et al., 2008).

Finally, the Sequencing condition, incorporated in the latest version of the WAIS (Wechsler, 2008a), requires participants to immediately repeat a series of digits in ascending order. This condition necessitates a higher level of cognitive manipulation, since the sequencing component requires constant comparison of the digits held in mind. Knowledge of number values (i.e., 8 is greater than 5) and the ability to note repeated digits is also required. The Digit Span Sequencing is thus also used as a neurocognitive screening tool, and performance on this task has shown to differentiate between cognitively healthy and cognitively impaired groups, beyond Forward and Backward performance (Lumpkin & Sheerin, 2018; MacDonald et al., 2001; Werheid et al., 2002).

Psychometrically, the WAIS-IV technical manual reports the Digit Span subtest scores to have an average internal consistency reliability of .93, i.e., a very high level of internal consistency, which suggests that each condition is measuring the same construct (Wechsler, 2008b). Subsequent studies have found the Digit Span subtest to display internal consistency above .89 (Young, Sawyer, et al., 2012), and the Digit Span Forwards, Backwards and Sequencing test scores are reported to have high internal consistency reliabilities of .81, .82 and .83, respectively (Gignac et al., 2019). The Digit Span subtest has been used to examine the neural and cognitive mechanisms underpinning working memory and its capacity limitations (Pavlov et al., 2022). In the South African context, this subtest has been used to assess cognitive functioning associated with ageing (Peltzer & Phaswana-Mafuya, 2012), HIV-associated neurocognitive disorder (Singh et al., 2010), psychological resilience (Bemath et al., 2020), and bi- or multilingualism (Cockcroft et al., 2017).

5.2 Symbol Span Subtest

The Wechsler Memory Scale, Fourth Edition (WMS-IV; Wechsler, 2009a) is a useful test for assessing different memory functions in individuals, between 16 and 90 years old, and is commonly used alongside the WAIS-IV in clinical assessments (Dzikon, 2020; Holdnack & Drozdick, 2010; Wechsler, 2008a, 2009a). As part of this test battery, the Symbol Span subtest was designed as a visual analogue to the Digit Span subtest, measuring visuospatial instead of verbal working memory. The Symbol Span subtest uses geometric symbols to restrict the extent to which the phonological loop is activated during the test. According to the WMS-IV test manual, the Symbol Span subtest has a test-retest reliability of .83, which indicates that scores maintain a high level of consistency over time (Wechsler, 2009b). Subsequent studies show that this subtest has a modest test-retest reliability (.72), and acceptable international consistency (.76 - .92; Young, Caron, et al., 2012). Performance on this subtest examines both memory for the symbol, as well as its location in the stimulus array (Emrani et al., 2019; Liang et al., 2016). Therefore, it does not include a ‘pure’ measure of visuospatial STM, in the same way that the Digits Forwards taps verbal STM.

Some research suggests that the Symbol Span may be more sensitive in detecting emergent cognitive impairment than analogous verbal working memory tests (Emrani et al., 2019; see also Tang et al., 2021). It is theorised here that the Symbol Span is more cognitively demanding than the Digit Span Backwards and Sequencing, as the cognitive skills required for the Symbol Span are less automated, whereas recalling digits is routinely practiced in everyday life. This hypothesis is supported by recent studies in the neurosciences (e.g., Moberly et al., 2018). Additionally, it is common for individuals to assign verbal labels to nonverbal visual stimuli (Ellis & Muller, 1964; Santa & Baker, 1975; Taylor et al., 2016; Vivanti et al., 2016), which suggests the recruitment of verbal cognitive operations. This influence of verbal labels on the organization of non-verbal shapes in memory implies that visual working memory (i.e., Symbol Span) test performance may be underpinned by a more extensive arrangement of neurocognitive operations.

5.3 n-Back Task

While the Digit Span and Symbol Span subtests are typically used in clinical neuropsychology, often for diagnostic purposes (e.g., Hale et al., 2002; Leung et al., 2011; Lumpkin & Sheerin, 2018; Young, Caron, et al., 2012), the *n*-Back task (Gevins & Cutillo, 1993) is commonly used in neuroimaging and experimental research to explore the neural networks or cognitive operations underpinning working memory (e.g., Lamichhane et al., 2020; Miró-Padilla et al., 2020). In the *n*-Back task, participants are presented with items (e.g., digits) and are required to indicate whether a particular item matches the one presented *n*-items prior (e.g., 1-digit back, 2-digits back, 3-digits back, etc.). Common versions are 2-back and 3-back tasks, which requires participants to recall stimuli presented two or three trials earlier (Meule, 2017). The *n*-Back task differs from many other working memory tests, as participants do not need to recall information, but recognize it (Kane et al., 2007; Pelegrina et al., 2015). As mentioned, this task therefore measures 'running memory' and necessitates several cognitive processes. Each item '*n'* needs to be encoded and temporarily stored in working memory. With incoming stimuli, each item must be continually updated; simultaneously, items not immediately relevant must be inhibited, and items ultimately irrelevant must be eliminated from working memory. The task requires the participant to both count (specific to the '*n*') and match upcoming and stored items. It is also useful in measuring working memory performance as processing load increases, in that a higher *'n'* increases working memory load (Nikolin et al., 2021).

Since maintenance and manipulation of stimuli are processed simultaneously, the *n*-Back task is said to be a relatively pure measure of domain-general central executive processes (Wilhelm et al., 2013). However, precisely which aspects of working memory are measured with this task remains unclear. In addition to this, not much is known about the *n*-Back task's relationship with well-established, standardised measures of working memory, such as the Digit Span and the Symbol Span subtests. As described above, simple and complex span tasks are said to broadly measure the same basic processes (e.g., maintenance, rehearsal, updating), but rely on these processes to varying degrees (Unsworth & Engle, 2006). As such, simple span tasks (Digits Forwards) largely measure maintenance, while complex span tasks (Digits Backwards, Sequencing; Symbol Span) measure controlled memory retrieval and processing (Wilhelm et al., 2013). In other words, simple memory span tasks operationalize short-term storage, while complex memory span tasks, more fittingly, entail working memory. Theoretically, both complex span tests and the *n*-Back task appear to tap related aspects of working memory. In both kinds of tasks, stimuli are typically presented verbally or visually, participants are required to hold relevant items in mind for a few seconds while preventing interference from non-target items, and, finally, respond after the necessary retention interval (Redick & Lindsey, 2013). This implies that the *n*-Back task would also measure working memory. However, correlations between the *n*-Back task and complex working memory measures are surprisingly weak and often not statistically significant (Kane et al., 2007; Redick & Lindsey, 2013), which suggest that these tasks do not tap the same construct. In fact, some studies have proposed that the *n*-Back task is more highly correlated with simple span tasks (e.g., Digit Span Forwards) than with complex span tasks (Jaeggi et al., 2010; Scharinger et al., 2017). Findings that the *n*-Back task correlates more strongly with tasks of STM (simple span tasks) refute *n*-Back validity as a measure of 'true' working memory. This poses an important concern: if we are unable to rely on the *n*-Back task as a measure of working memory, we are unable to rely on inferences drawn about working memory in studies using the *n*-Back task (Gajewski et al., 2018).

Given the discrepancies in task correlations, the first part of the current study assessed the relationships between the *n*-Back, Digit Span and Symbol Span tasks, as this could provide valuable insight into what common working memory processes these tests measure (Redick & Lindsey, 2013). Importantly, one explanation for the variation in research findings could relate to individual differences in working memory performance, such as demographic variables. This formed the second part of the study and is discussed further in the next section.

6. Demographic Factors and Working Memory Performance

Individual differences in working memory play an important role in the ability to construct, preserve and update integrated information (Wilhelm et al., 2013). Demographic factors may influence performance on working memory tests, and so this is important to investigate, i.e., to gauge whether task performance is, in fact, due to working memory ability, or due to other variables (Steffl et al., 2019). Demographic factors of (1) number of languages spoken and level of proficiency, (2) biological sex, and (3) socioeconomic status are elaborated below.

6.1 Number of Languages Spoken and Level of Proficiency

It has been proposed that speaking more than one language can influence cognitive performance. Specifically, a growing body of evidence suggests that individuals who speak two languages possess an executive functioning advantage over monolingual individuals

(Bialystok, 1988; De Cat et al., 2018). This ‘bilingual advantage’ has been attributed to the fact that bilinguals constantly need to resolve the simultaneous activation of their two language repertoires, perpetually inhibiting one of their languages (Poarch & van Hell, 2012). Bilinguals also need to routinely assess and update their immediate social context to switch to the language relevant to the speakers they are engaged with (Antón et al., 2019). This consistent training of execute control mechanisms is hypothesised to aid superior executive functioning, including working memory performance. For example, a study on Spanish-Basque young adults (mean age of 22 years) found that bilingual participants performed significantly better in both verbal and visuospatial working memory tasks that require storage and simultaneous processing of information (Antón et al., 2019). In other words, while no between-group differences were found for the forward conditions of the Digit Span and Corsi tasks (storage only), bilinguals were found to outperform monolinguals in the backward conditions of these tasks (storage and processing). This has been replicated in a multilingual sample of South African young adults (age range between 18.11 and 22.11 years), who outperformed monolinguals in both verbal and visuospatial working memory (Cockcroft et al., 2017). These findings further support the argument that bilingual advantages extend beyond effective inhibition, i.e., managing two (or more) languages influences central executive functioning, and consequently, cognition across an array of task demands (Blom et al., 2014; Cockcroft et al., 2017).

However, some researchers have questioned the research protocols employed in these studies, including small sample sizes, inadequately matched participants, lack of attention to confounding factors (e.g., cultural differences), and failure to publish null results (Antón et al., 2014; Paap et al., 2015). As a result of this, some researchers have argued that bilingual advantages, if they do exist, are restricted to specific circumstances, and cannot be generalised to all executive functions (Paap et al., 2015). For instance, no bilingual advantage in working memory performance was observed between monolingual and bilingual English-Spanish speaking young adults (mean age of 19.45 years; Ratiu & Azuma, 2015). More recently, the relationship between bilingualism and working memory has been reported as an overall advantage in the visuospatial components of working memory, but less clear in verbal working memory (Liu & Liu, 2021). It therefore remains unclear whether a multilingual advantage exists in working memory, and whether these tentative advantages are domain-general, i.e., an overall advantage in executive functioning (e.g., see Bialystok, 2017) or modality-specific, i.e., verbal and/or visuospatial (e.g., see Espi-Sanchis & Cockcroft, 2022).

Given these mixed results, the influence of speaking multiple languages on working memory may be more nuanced. For example, working memory performance may be dependent not only on the number of languages spoken, but also on proficiency of these languages. Language proficiency is a core aspect of bilingualism (Xie et al., 2019). Therefore, it has been argued that a high level of bilingual proficiency is necessary to facilitate any potential benefits in cognitive functioning (Mishra, 2015). In other words, an individual might first need to attain a threshold level of linguistic competence in both languages before any bilingual advantages emerge. However, a somewhat contradictory view is that highly proficient bilinguals no longer require memory strategies for comprehension of their second language, thereby decreasing cognitive load and attenuating working memory advantage (Yang, 2017). During the initial phases of learning a second language, learning strategies are necessary for effective acquisition of the language, which exercises working memory processes. However, as language proficiency levels increase, there is less need for simultaneous retention and rehearsal of language input, and the associated cognitive demands decrease. As such, it may be that intermediate bilinguals (i.e., those with intermediate proficiency in a second language) present a greater working memory advantage: since these individuals are still in the process of learning a second language, they are engaged in constant cognitive training. Highly proficient bilinguals no longer require these strategies (Yang, 2017).

This also suggests that being bilingual does not guarantee a working memory advantage. Instead, the advantage may be related to the level of proficiency in each language. This underscores the recommendation to study bi-and multilingualism on a continuous scale that accounts for language proficiency and usage, as opposed to categories of 'monolingual' or 'bilingual', to accurately evaluate the degree of multilingualism of an individual and any associated cognitive advantages (Antón et al., 2019; Luk & Bialystok, 2013; R. K. Mishra, 2015). Essentially, this integrates the different aspects of multilingual experience. Consequently, this study investigated whether the number of languages spoken, as well as the level of proficiency in each language, significantly predicted performance on each of the working memory tests, i.e., Digit Span subtest, Symbol Span subtest and *n*-Back task.

6.2 Sex-Related Differences

Biological sex effects on working memory performance have been widely studied, but the findings are inconsistent (Saylik et al., 2018; Voyer et al., 2017). Research has shown that males tend to perform better on spatial working memory tasks than females. For example, one study found that male undergraduate students (average age of 18.6 years) performed more accurately than females (average age of 19.1 years) on spatial and object versions of a *n*-Back task (Lejbak et al., 2011). In support of this finding, young adults (between 20 and 28 years) completed a spatial version of the *n*-Back task in a functional magnetic resonance imaging (fMRI) study (Blokland et al., 2011). Compared to females, males showed significantly stronger activation across several areas of the visuospatial working memory network, particularly in the frontal lobe, which is implicated in working memory (Nissim et al., 2017). Furthermore, a meta-analysis of cognitively healthy samples (age range from 3 to 86 years) concluded that males performed significantly better than females in visuospatial working memory tasks (Voyer et al., 2017).

While there appears to be some consensus regarding a male visuospatial advantage in working memory, a verbal working memory advantage is less clear. A systematic review and meta-analysis on sex differences in verbal working memory reported an overall significant female advantage, although the effect size was almost zero (Hedge's $g = .03$; Voyer et al., 2021). Another study found that males match females (age range from 17 to 31 years) on verbal working memory performance, i.e., females did not perform better than males on verbal working memory tasks (Lejbak et al., 2011). Still another study showed that males outperform females (age range from 19 to 31 years) on verbal working memory tasks (e.g., Zilles et al., 2016).

Apart from modality, other factors may influence sex-based differences in working memory. For example, it has been suggested that differences in working memory performance might only be observed during tasks that impose high working memory load. One study found that young adult males (mean age of 21.38 years) achieved higher task accuracy than females on a verbal task, specifically when the working memory load was high (Reed et al., 2017). Evidently, large discrepancies exist regarding sex influences on working memory. These inconsistent findings indicate that further research on sex and working memory performance is required. Therefore, this study investigated whether sex is associated with performance on each of the working memory tests.

6.3 Socioeconomic Status

Socioeconomic status (SES) is a measure of an individual's social position, and is commonly classified according to family income, educational attainment, parental occupation, or a combination of these (Leonard et al., 2015). Consequently, SES has significant implications for shaping an individual’s immediate environment. Lower SES is often characterised by poor nutrition, limited access to resources, increased exposure to stress and violence, and inadequate cognitive stimulation (Adler & Rehkopf, 2008; Duncan et al., 2017; Evans, 2004; Noble et al., 2015). For this reason, it is suggested that impoverished environments may compromise structural and functional development of the brain, which would, in turn, influence development of cognitive systems (Hackman et al., 2010; Noble et al., 2015). However, the extent to which SES influences working memory is debated.

Some research has found that children from low SES present with differences in neuroanatomical structures underpinning working memory systems (e.g., cortical thickness; Mackey et al., 2015). For example, a study investigating SES and brain morphometry (independent of genetic ancestry) among young people (age range from 3 to 20 years) found the association between income and brain surface area, particularly in regions supporting executive functioning and language, to be logarithmic (Noble et al., 2015). In other words, among individuals from the poorest families, small income differences were associated with relatively large differences in brain surface area. For this reason, it is proposed that low SES, and associated socioeconomic disadvantage, are related to lower working memory performance (Hackman et al., 2014; Leonard et al., 2015; Little, 2017). For instance, one study found that lower SES was associated with poorer working memory in young people aged 6 to 19 years (Rosen et al., 2018). Similarly, another study found that childhood poverty was inversely associated with working memory in young adults (mean age of 17.29 years; Evans & Schamberg, 2009), in that those who experienced greater periods of socioeconomic disadvantage had poorer working memory. This finding was also reported in young adults (mean age of 23.52 years; Evans et al., 2021). A possible way in which SES influences brain development is via stress-related mechanisms that hinder neuroplasticity (Duncan et al., 2017; Evans, 2004). This, in turn, influences cognitive development and may affect the working memory system (Beilock & DeCaro, 2007). Indeed, research on working memory and stress consistently reports impairments in working memory under acute or chronic stress conditions (Naninck et al., 2015; Sheridan & McLaughlin, 2014; Shields et al., 2016). For instance, a laboratory-based study observed that undergraduate university students with high working memory only outperformed those with low working memory under low-stress conditions (Beilock & DeCaro, 2007).

A systematic review on cognitive functioning in young adults (age range between 15 and 24 years) reported that individuals who experienced poverty, homelessness or foster care exhibited more difficulties in working memory capabilities compared to non-disadvantaged youth (Fry et al., 2017). In fact, a large population-based study (*n* = 10 788) found that SES played an even larger role than childhood maltreatment in working memory performance in young adults (age range from 24 to 32 years; Dunn et al., 2016). Results revealed a clear gradient suggesting better memory performance among those individuals whose parents had received more education and were in higher status occupations. In line with this, a more recent meta-analysis found that low SES is generally associated with lower working memory performance, across both simple and complex working memory tasks, for both verbal and visuospatial modalities (Mooney et al., 2021). This disputes the proposition that simple working memory (due to relying more on ‘stored’ knowledge) is more sensitive to low SES than complex working memory (Alloway & Copello, 2013). Rather, it points to impairments in storage, processing and manipulation of information. Indeed, some research has proposed that low SES may have even more profound effects on cognitive processing aspects than simple storage (Mooney et al., 2022).

In contrast to the above, however, some research has found that SES is unrelated to executive function and working memory (e.g., Engel et al., 2008; Vandenbroucke et al., 2016; Wiebe et al., 2008). For example, a study on the relationship between cortical thickness and working memory in children (age range between 9.0 and 10.9 years) found no influence of SES (Krogsrud et al., 2021). Importantly, an alternative view argues that low SES environments do not exert uniformly negative influence on cognitive development, but rather that low SES may enhance specific aspects of cognition. For one, the evolutionary-developmental model posits that individuals growing up in unpredictable surroundings may develop unique, specialized abilities to match these environments (Ellis et al., 2017; Ellis & Del Giudice, 2019). Essentially, functional changes that occur in response to stress may improve forms of attention, memory and learning as individuals become developmentally adapted to navigating ecologically-relevant problems. One study observed that adults (mean age of 33.41 years) raised in unpredictable environments showed superior performance on working memory updating tasks under conditions of uncertainty, compared to adults raised in more predictable conditions (Young et al., 2018). This can be explained in that it is advantageous to track and update information about one's immediate environment when it continually changes, such as detecting threats or acting on fleeting opportunities (e.g., Mittal et al., 2015). It is thus important to conceptualise the influence of low SES as having the ability to *shape*, rather than uniformly impair, working memory (Young et al., 2018). Indeed, early life stress, such as potentially induced by low SES, may regulate working memory development towards contextually adaptive abilities and skills (Ellis et al., 2017).

The relationship between SES and working memory is important to understand, considering that both constructs predict important life outcomes, such as academic attainment (Last et al., 2018). Therefore, investigating whether SES predicts working memory performance remains a relevant undertaking, especially since the South African context is characterised by stark socioeconomic discrepancies. Further understanding the association between SES and working memory will provide insight into how environmental factors may influence the development of specific cognitive systems. This may, in turn, better inform strategies or cognitive training programs aimed at protecting children from vulnerable socioeconomic backgrounds (Leonard et al., 2015).

7. Rationale and Aims

Given its importance in daily cognitive functioning and attainment, working memory has sparked much interest in neurocognitive psychology as well as clinical research (e.g., Chai et al., 2018). An integral part of this type of research is defining and measuring the abstract construct of working memory. However, due to different theoretical conceptualisations of working memory, as well as the wide-range of working memory tests, it is unclear whether these tests are tapping the same (or similar) constructs. By using working memory tests that do not operationalise working memory in the same way, these tests could incorrectly inform clinical groups, and fail to correctly differentiate between the cognitively healthy and cognitively impaired. In particular, several researchers have questioned the validity of the *n*-Back task as a measure of working memory, especially given its wide use (Jaeggi et al., 2010; Kane et al., 2007). The first part of this study thus examined the relationship between three working memory measures: (1) the Digit Span subtest, included in the WAIS-IV (Wechsler, 2008a), (2) the Symbol Span subtest, included in the WMS-IV (Wechsler, 2009a), and (3) the *n*-Back task (Gevins & Cutillo, 1993).

Furthermore, individual differences in working memory capacity are often influenced by demographic factors, such as the number of languages spoken and level of proficiency (Calvo et al., 2016; Yang, 2017), biological sex (Voyer et al., 2017, 2021), and SES (Noble et al., 2015). In the diverse context of South Africa, unique and insightful findings might be observed across population groups. The second part of this study thus investigated the predictive relationship of the abovementioned demographic factors on performance in the working memory tests included in this study.

8. Research Questions

The primary aim of this study was to explore the relationship between the Digit Span subtest, Symbol Span subtest and *n*-Back task, as well as whether performance on these measures were influenced by demographic variables. The study thus investigated the following questions:

1. Is there a significant relationship between the Digit Span subtest, Symbol Span subtest and *n*-Back task?

2. If significant associations arise from research question one above, do the Digit Span and Symbol Span tests predict variance in the *n*–Back task?
3. Do the demographic variables of proficiency in each spoken language, number of languages spoken, sex of participants and SES predict variance in each of the working memory tests (Digit Span Forwards, Backwards and Sequencing; Symbol Span; and *n*–Back task).

The methods and materials used to investigate these research questions are discussed in the following chapter.

Chapter 2: Methods and Materials

To address the research questions presented in Chapter 1, the current study formed part of a larger study examining the effects of multilingualism on working memory in a South African student population (Protocol No: M210626). In this chapter, the research design, sample, instruments and procedure of the study are described. Prior to starting the research process, a pilot study was conducted with three participant volunteers. This served to assess whether task instructions were adequately clear and whether there were issues with the computer-based *n*-Back task. Minor changes were made to the research procedure (e.g., clearer, better formulated instructions were provided to the participants, and adjustments to the order in which the tasks were presented).

1. Research Design

The study consisted of two parts. The first part investigated the relationships between the three working memory tasks, i.e., the Digit Span, Symbol Span and *n*-Back tasks. The second part of the study investigated the extent to which demographic variables, such as number of languages spoken, proficiency in each language, sex of participants and SES, predicted variance in each of the working memory measures. The study was therefore primarily exploratory in nature. The research design was non-experimental, with no direct manipulation of any of the variables, no control groups, and no random assignment. Instead, a cross-sectional, correlational design was used to investigate associations between underlying working memory constructs following task performance. Accordingly, no direct causal inferences were drawn. The current study adopted a post-positivist critical realism paradigm. As such, the researcher was aware that her own views, perceptions and background would influence her research and subsequent interpretation of the results (Bisman, 2010; Dobson, 2002). While aspiring towards objectivity in the research project, the researcher was aware that bias is immanent in the research process and undertook to address this where possible. This paradigm renders use of both qualitative and quantitative methods, the latter of which was used in this study.

2. Sample and Sampling

The sample used in this study was a non-probability, convenience sample of 48 South African students from the Department of Psychology, School of Human and Community Development, University of the Witwatersrand. However, one participant was later excluded due to missing data on the *n*-Back test, leaving a total of 47 participants. The participants needed to be between 18 and 25 years of age, and proficient in at least three languages (of which English was one, and the others, strictly African languages). In 2018, approximately 78% of South African households spoke an African language (Statistica, 2018). This group therefore differs linguistically from Western industrialized populations (i.e., from which most neurocognitive research is produced), and may shed light on how context and culture produce variability in research findings (Cockcroft, 2020; Henrich et al., 2010; Qu et al., 2021; Rad et al., 2018). Additional volunteers, with the same requirements as specified above, were recruited by a snowball effect.

Since the sample consisted of university students, all participants were assumed to be 'test-wise' and both questionnaire- and computer- literate. Furthermore, since all participants were studying courses in the medium of English, they were deemed sufficiently proficient in the language to complete the working memory assessments, which were presented in English (subjective level of English proficiency was also recorded via the LEAP-Q, as described in section 3.2). Descriptive statistics of the sample (e.g., age range, sex distribution) are presented in Chapter 3.

3. Instruments

Corresponding to the research questions, several instruments were used to collect the following information: (1) participant's demographic data and socioeconomic background, (2) participant's language repertoire, including number of languages and proficiency level of each language, and (3) participant's performance scores in the three working memory tasks. The theoretical bases of the working memory tasks and the rationale for their inclusion were described in the Chapter 1, while methodological aspects, such as administration and scoring, are detailed below.

3.1 Demographic Questionnaire

The demographic questionnaire captured details about the participant's age, sex, educational history, the educational history of their caregivers, and the number of caregivers present in the household during childhood (refer to Appendix A for more on this). Self-reported experience of vision, hearing, language and/or learning impairments was documented, as well as any neurological disorders. For example, traumatic brain injury could compromise working memory performance, and therefore served as an exclusion criterion.

The demographic questionnaire also included the Living Standards Measure (LSM): a series of 23 true/false statements, commonly used as an indicator of SES (SAARF, 2001). This was included to investigate the effects of SES on working memory performance. The items in this index includes assets, such as household appliances (e.g., telephone/microwave oven), entertainment systems (e.g., DVD player/television subscription), and access to municipal services (e.g., flush toilets/tap water). Scoring of the LSM was completed manually using a weighting system. Each weighted score reflected a final LSM score, which corresponds to a scale of socioeconomic group from 1 (lowest) to 10 (highest).

Investigating the construct of SES proves tricky in that this is a latent variable that cannot be measured directly, complicated further by the lack of a widely-accepted definition of precisely what SES is (e.g., Chen et al., 2018; Darin-Mattsson et al., 2017; Oakes & Rossi, 2003). Different measures of SES capture varying degrees of information about the underlying construct (Dickinson & Adelson, 2014). Therefore, composite measures of SES are frequently used by combining several measures, such as income, education and occupation (Shavers, 2007). By combining information from several domains relating to SES, each component can be weighted and used to generate a singular quantity. Composite measures are advantageous as they represent a more comprehensive range of socioeconomic factors. This reduces mismeasurement that might otherwise lead to biased effect estimates (Shavers, 2007). Nevertheless, a drawback of composite measures is that combining constituent information requires rigorous theory on how to correctly weight the respective variables (Profit et al., 2010). Incorrect weightings will render an incorrect scalar outcome, and ultimately, an incorrect socioeconomic measure. These concerns were addressed as best as possible by using a well-established measure of SES, based primarily on living standards. Overall, this demographic information contributed towards addressing research question three: do demographic variables, such as sex and SES, predict variance in each of the working memory tests?

3.2 Language Experience and Proficiency Questionnaire

The Language Experience and Proficiency Questionnaire (LEAP-Q) is a widely-used self-report tool for determining the language profiles of multilingual speakers, aged 14 to 80 years (Kaushanskaya et al., 2020; Marian et al., 2007). It is considered a useful measure for exploring the language experience of multilingual South African students, with factors contributing to first and second language proficiency all supported by moderate to high Cronbach's alphas (.62 - .86; Cockcroft & Laher, 2018). The questionnaire includes information about the number of languages spoken, from least to most well-known. In order to accurately capture the heterogeneity of bilingual experience, measures of exposure (input) and production (output) were included. Specifically, participants indicated how frequently they were exposed to each of the languages they spoke, their preferred language for reading and speaking, and subjective level of proficiency in each language spoken.

For each language, information was captured on the age of acquisition, the age at which fluency was achieved, the age at which reading began, and the age at which reading fluency was achieved. Participants rated their level of proficiency in speaking, comprehension and reading on a scale from 0 ('None') to 10 ('Perfect') for each language. Participants also rated how frequently they were exposed to the respective language through family, friends and a variety of media platforms, such as radio and the internet. This information further contributed towards addressing research question three: does the number of languages spoken and respective proficiency levels predict variance in each of the working memory tests?

3.3 Working Memory Measures

Participants completed a brief neuropsychological (behavioural) battery of working memory tests from the WAIS-IV (Wechsler, 2008a) and WMS-IV (Wechsler, 2009a). These were included to obtain measures of latent construct validity with the *n*-Back task, i.e., assessing which aspects of the tasks correlated with each other. The three tests are described below.

Digit Span Subtest (WAIS-IV; Wechsler, 2008a). The Digit Span subtest is a widely-used verbal working memory task from the WAIS-IV (Wechsler, 2008a), for individuals aged 16 years and older (e.g., Wells et al., 2018). It is divided into three conditions: (1) the Digit Span Forwards task, where the participant heard a sequence of numbers and was asked to recall the sequence in the same order, (2) the Digit Span Backwards task, where the participant recalled a sequence of numbers in reverse order, and (3) the Digit Span Sequencing task, where the participant recalled a sequence of numbers (occasionally including repeated digits) in ascending order. The Backwards and Sequencing conditions included two practice trials each. Thereafter, the sequences gradually increased in length, ranging from two to nine digits. The subtest consists of eight items, each with two trials. Participants received one point for each correct trial, and thus two points if both trials of an item were recalled correctly. In the case that participants corrected their response, the revised response was recorded. The task was discontinued when a participant recalled both trials of the same item incorrectly. The scores of each subtest reflected the number of correct responses, which were summed to generate a maximum total raw score of 48 points. The subtest took approximately 15 minutes to complete.

Symbol Span Subtest (WMS-IV; Wechsler, 2009a). The Symbol Span subtest measures the storage and manipulation of visual information in working memory (e.g., visuospatial working memory; Wechsler, 2009a). Participants were shown an increasing number of linearly arranged symbols, ranging from one to seven, for a total of 26 items. After five seconds of viewing, the display was removed and replaced by a page containing both target and foil symbols, from which the participant was required to identify the designs from the previous page, in the order presented (from left to right). Therefore, this subtest assessed working memory for both the correct object and its location in the stimulus array (Emrani et al., 2019). The Symbol Span subtest included one practice trial. Thereafter, two points were awarded if the participant identified the correct symbols in the correct order. One point was awarded if only the symbols, and not the order, was correct. Zero points were awarded if not all the symbols were identified, or if extra symbols were included in the response. In the instance that participants corrected their response, the revised response was recorded. Once four consecutive imperfect scores were recorded (i.e., one or zero), the task was discontinued. The score for each item was summed to generate a maximum total raw score of 50 points. The subtest took approximately 15 minutes to complete.

***n*-Back task (Gevins & Cutillo, 1993).** The *n*-Back task is widely used in experimental research to assess working memory load, as well as executive processes, such as attentional switching and updating (Gajewski et al., 2018; Weicker et al., 2018). This study used a computerised version of the *n*-Back task, whereby participants were presented with digits displayed, one at a time, on a 17-inch computer screen (font: Arial; font-size: 58; black screen; white text; computer resolution: 1024 x 768 pixels), using OpenSesame (version 3.3.11). For this task, participants needed to determine whether the digit presented on the screen was the same as the one presented '*n*' trials ago (e.g., 1-digit back, 2-digits back, 3-digits back, etc.). Only numbers 1, 2, 3, 4, 5, 6, 8 and 9 were included, with number 7 excluded, given that it is two syllables. If the digit matched the one presented '*n*' trials back (representing a ‘target’), the participant pressed ‘F’ on the keyboard (marked as ‘S’ for ‘same’ on the keyboard). If it was different (representing a ‘non-target’), the participant pressed the ‘J’ key (marked as ‘D’ for ‘different’ on the keyboard). In this study, the task included three working memory load conditions (e.g., 1-, 2-, and 3-back tasks). For example, if the ‘*n*’ for a certain task was ‘3’, and the digits presented were ‘5’, ‘9’, ‘3’, ‘2’, ‘9’, ‘2’, the participant should press ‘S’ only when the second ‘9’ occurs, as ‘9’ was repeated three trials ago. The higher the number (‘*n*’), the more complex the task, as a result of increases in working memory load (Pelegrina et al., 2015). Not only does the '*n*' seem to influence performance on the task, but also response speed.

Instructions for each of the *n*-Back conditions were presented onscreen and restated verbally, using a standard protocol for each participant. Participants started with the 1-Back, followed by the 2-Back, and then the 3-Back task (in this order). Participants completed a practice run to ensure that they understood the requirements for each of the *n*-Back conditions. They were required to score: (1) 85% or above for the 1-Back practice condition (n = 25 stimuli per block), (2) 75% or above for the 2-Back practice condition (n = 25 stimuli per block), and (3) 70% or above for the 3-Back practice condition (n = 25 stimuli per block). Each practice round consisted of up to three attempts (i.e., three 'blocks') to meet the abovementioned criteria. If the requirements for the practice run were not met, the experiment was terminated. Once participants reached the required level of accuracy in the practice round(s), they were directed to the experiment, and asked to respond as quickly and accurately as possible. Individual digits were presented in a fixed central location for 500ms, followed by a 250ms interstimulus interval denoted by a fixation cross, using OpenSesame software. Five blocks of 25 stimuli were presented for each of the load conditions (i.e., 125 trials per condition). The five blocks were separated by brief breaks (10s) where participants were asked to focus on a fixation cross in the centre of the computer screen to reduce mental fatigue. In contrast to the practice run, for the experimental tasks, the participants proceeded to the next block irrespective of accuracy in the preceding block(s). The stimuli in each block were randomly arranged, with a standardized number of targets (33%) and non-targets (67%). Recorded data included accuracy, average reaction time, whether the response was correct, and whether errors were due to commission or omission, for each *n*-Back condition, as well as an overall average. Participants were not restricted in any way relating to the strategies they engaged throughout the task (e.g., tapping/verbal rehearsal). Each experimental condition lasted approximately 15 minutes in duration, equating to 45 minutes in total for this cognitive assessment.

4. Procedure

Students who expressed interest in participating in the study first received a participant information sheet, which included details about participation (see Appendix B). After students confirmed their willingness to participate, they each received an email with a link to the survey. This constituted the first part of the data collection process, where participants completed the demographic and LEAP-Q questionnaires online, administered through the secure web application, Research Electronic Data Capture (REDCap).

Once the survey was completed, participants were able to select a time and date that was most convenient for them, using the Google calendar online booking system. This constituted the second part of data collection, which involved face-to-face administration of the working memory assessments at the Neuroscience Research Laboratory, Department of Psychology, University of the Witwatersrand. All interviews were conducted one-on-one in a private room. The interview was split into two sessions, separated by a 15-minute break to prevent mental fatigue. Participants either completed the paper-and-pencil tests (i.e., Digit Span and Symbol Span subtests) in the first session, followed by the *n*-Back task in the second session, or vice versa, with task sequence recorded for each participant. The tests were presented in this counter-balanced way to prevent order effects and fatigue influence, although the paper-and-pencil tests were always administered together. Participation timeslot (e.g., morning or afternoon) was also noted for each participant.

The working memory tests were administered as described in the Instruments section. As mentioned previously, all tasks were administered in English, and instructions were standardised for each task. Practice examples for the respective tasks served to confirm that participants understood the instructions and objective of each task, and participants were encouraged to ask questions if anything remained unclear. Overall, each interview slot (i.e., the two test sessions, plus the break) lasted approximately 90 minutes.

5. Ethical Considerations

Ethical clearance was obtained for this study from the Human Research Ethics Committee (HREC Non-Medical; Protocol No: MAPSYC-22-13; see Appendix C). Permission from the University Registrar, Head of School, and Heads of Departments were also obtained. As mentioned, prior to data collection, all participants received an online information sheet that provided a brief description of the study and additional information pertaining to the research process. Consent forms (Appendix D) were also made available through the REDCap platform, which stipulated that participation in the study was entirely voluntary. Since all participants were above 18 years of age, consent could be legally obtained. All individuals who participated in the study received a once-off R150 compensation (constituting the first half of the larger study, of which the full incentive amount was R300) to cover transport expenses related to attending the data collection session.

The tests in this study were not invasive and did not ask questions of a sensitive nature. Nevertheless, the anonymity of participants is important. Since anonymity during data collection was not possible given the face-to-face nature of the study, all information generated from data collection was subsequently anonymised to uphold confidentiality of participants. The data collected was secured on a private computer, and only the researchers have access to participants' original demographic information. Consenting participants were made aware that the data collected throughout the research process contributed towards the completion of this research report. Those participants who expressed interest in the results from this study will be emailed a summary of the findings, although it was made clear to all participants that no personalised results will be shared. Following final submission of this report, the data will be securely stored for potential use in subsequent secondary analyses of future, related research.

6. Data Analysis

Descriptive and inferential statistical techniques were used to analyse the data, using IBM SPSS Statistics, version 28.0.1.0. Descriptive statistics were generated for the sociodemographic characteristics of the sample and the working memory scores. Thereafter, correlation and regression analyses were used to investigate relationships between key variables, in order to address the three research questions. These analyses are discussed in the following chapter.

Chapter 3: Results

This study explored the construct of working memory using a selection of tests. The primary aim was to assess whether the *n*-Back task taps into the same (or similar) constructs as two other established working memory measures, namely the Digit Span and Symbol Span subtests. Secondly, there was an interest in assessing whether demographic variables would predict variance in any of the working memory measures. The preceding chapters provide the context in which the results are presented. An analysis of the proposed relationships between the Digit Span, Symbol Span and *n*-Back tests, as well as the rationale of why demographic variables may influence working memory performance, were discussed in Chapter 1. In Chapter 2, the non-experimental cross-sectional research design, which guided the outlined study, and the methods used for investigating the research questions were described.

In this chapter, the results of the study are presented. Both descriptive and inferential statistical techniques were used to summarize and analyse the data, using IBM SPSS Statistics, version 28.0.1.0. First, descriptive statistics were generated for the sociodemographic profile of the sample and the working memory measure scores. Secondly, correlation analyses between all study variables highlighted preliminary relationships among key variables and served to address the first research question: is there a significant relationship between the *n*-Back, Digit Span and Symbol Span tests? Finally, regression analyses were run to determine: (1) whether the Digit and Symbol Span subtests predicted variance in the *n*-Back variables, and (2) whether the demographic variables predicted variance in any of the working memory variables, in order to answer research questions 2 and 3, respectively. At each step, the results of statistical analyses are presented in tables and attention is drawn to key findings.

1. Descriptive Statistics

This section is divided into three subsections. The first subsection describes the type of data associated with each variable, and the methods used to assess whether the data was suitable for parametric analysis. Before analysing the relationships between the key variables, it was useful to understand their distributions in the sample. Therefore, the second subsection presents the sociodemographic characteristics of the sample, and the final subsection presents the Digit Span, Symbol Span and *n*-Back variables, as indicated below.

1.1 Assessing Data Suitability for Parametric Analysis

Data was assessed for parametric analysis using several methods. Three primary assumptions for parametric statistical analysis include random independent sampling, absence of extreme outliers, and approximately normal distribution of test scores. Although the sample was a convenience sample of volunteers, the order of the working memory tests was randomized, and each participant only completed each test once. The Digit Span subtest produced continuous scores on each of the three conditions (Forwards, Backwards and Sequencing) in which the maximum possible score was 16 points for each condition, and thus, a maximum of 48 points overall. The Symbol Span subtest, also producing continuous scores, had a potential maximum of 50 points. Similarly, the maximum score for each *n*-Back condition was 125 points. In terms of the demographic variables, the minimum number of languages spoken was three languages, i.e., a requirement for participation in this study. The proficiency scores were measured on a Likert-type scale, where participants self-rated their speaking, comprehension and reading proficiencies from 0 (indicating 'None') to 10 ('Perfect'). Finally, the SES scores obtained from the LSM questionnaire (SAARF, 2001) varied on an ordinal scale, from 1 (representing the 'lowest') to 10 (indicating the 'highest'). In order to assess whether any extreme outliers were present, boxplots were generated for each variable. Outliers pose the risk of drawing the mean of a given variable towards more extreme values, which is particularly problematic with small sample sizes (Leys et al., 2019). However, the presence of outliers in data does not necessarily mean that these should be excluded (André, 2022; Oyeyemi et al., 2015). Removing outliers that are rightful values of the distribution of interest is not appropriate and will similarly distort subsequent conclusions. For this reason, only observations that were flagged by the SPSS software as being influential (extreme) outliers were excluded during this initial step of data analysis. Based on this, one observation was excluded on first language speaking proficiency, and two on second language comprehension proficiency. Finally, to determine variable distributions, the Shapiro-Wilk test (appropriate for sample sizes <50; Mishra et al., 2019), skewness and kurtosis coefficients were assessed, and a histogram was computed for each variable. Several of the variables returned a significant Shapiro-Wilk test statistic, as well as skewness beyond ±1, and kurtosis beyond ±3 (Appendix E, Table 1). Additionally, histograms (Figures E1 - E22) for each variable revealed that several of these were not approximately normally distributed. Therefore, it was decided that, overall, non-parametric analyses, where possible, were most appropriate, given the distributions of the variables.

1.2 Sociodemographic Profile of Sample

A consideration of the sociodemographic characteristics of the sample is important in contextualizing the findings reported here. For this reason, descriptive statistics were first used to explore the profile of the 47 participants in terms of age, sex, and whether they attended primary school or not. Additionally, the number of caregivers present in the household, marital status of parents, as well as parental education levels are also reported (Table 1). Most of the participants were female (n = 30, 64%), and the mean age (n = 46, M = 21.51 years, SD = 1.22 years) was approximately 22 years old. Eighty-seven percent of participants attended preschool. The majority of participants grew up with two (60%) or more (25%) caregivers in the household. Most participants' parents were married (30%), with the majority of fathers having completed secondary schooling (49%), and most of the mothers having received tertiary education (47%). No participants reported any language or learning disabilities. Likewise, no participants reported any neurological disorders.

Table 1

Participants' Sociodemographic Profiles

Demographic variable	Frequency		Percent (%)	
Sex				
Male	17		36.2	
Female	30		63.8	
Primary school attendance				
Yes	41		87.2	
No	5		10.6	
Caregiver number				
1	7		14.9	
2	28		59.6	
>2	12		25.5	
Parent marital status				
Married	14		29.8	
Living together	6		12.8	
Widow/widower	9		19.1	
Divorced/separated	11		23.4	
Other	7		14.9	
Parental education	Paternal	Maternal	Paternal	Maternal
No schooling	1	0	2.1	0.0
Primary school not completed	1	0	2.1	0.0
Primary school completed	2	3	4.3	6.4
Secondary school completed	23	21	48.9	44.7
Tertiary education completed	18	22	38.3	46.8
Other	2	1	4.3	2.1

Notes. $n = 47$, except for primary school attendance, where $n = 46$.

In terms of SES, the mean SES score of 8.17 (Table 2) reveals that the participants were towards the high-end of the SES range, although the standard deviation of 1.07 indicates several participants from lower and higher SES groups. The LEAP-Q captured a range of self-report data about the participant's language profiles. Thirty-six percent of participants reported speaking five languages, followed by 34% speaking four languages, and 30% speaking three languages (mean and mode provided in Table 2).

Table 2

Descriptive Statistics for Socioeconomic Status and Number of Languages Spoken

Variable	Mean	*SD*	Mode	Range
Socioeconomic status	8.17	1.07	8	6 – 10
Number of languages spoken	4.06	0.82	5	3 – 5

Notes. n = 47. *SD* = standard deviation.

The particular languages spoken by participants varied considerably, as is typical among South Africans (Statistica, 2018; Table 3). While the specific languages spoken by participants was not explicitly under investigation, this information is useful in contextualising the language profiles of the participants involved.

Table 3

Frequencies of Languages Spoken by Participants

Languages by frequency	First language	Second language	Third language	Fourth language	Fifth language
1	isiZulu (19)	English (31)	isiZulu (13)	Sesotho (10)	Afrikaans (4)
2	English (8)	isiZulu (8)	Sesotho (12)	Afrikaans[a] (8)	isiXhosa (3)
3	isiXhosa (4)	isiXhosa (2)	isiXhosa (8)	Setswana (4)	IsiZulu (2)
4	Sepedi (4)	Setswana (2)	English (6)	isiXhosa (3)	Sesotho (2)
5	Setswana (4)	IsiNdebele (1)	IsiNdebele (2)	isiZulu (3)	Setswana (2)
6	Sesotho (3)	Sepedi (1)	Setswana (2)	English (2)	Siswati (2)
7	Xitsonga (3)	Sesotho (1)	Siswati (2)	IsiNdebele (1)	Tshivenda (1)
8	Other (2)	Other (1)	Other (2)	Other (2)	Other (1)
Total	47	47	47	33	17

Notes. n = 47. The frequency for each language is provided in parentheses.

[a] While effort was made to exclude European languages as far as possible, this was difficult in the case of Afrikaans, since this is a common second language implemented in South African schools (Taylor & von Fintel, 2016; Wildsmith-Cromarty & Balfour, 2019).

In addition to the number of languages spoken, self-report data was also collected for three categories of proficiency (e.g., speaking, reading and understanding), rated on a scale from 0 (‘None’) to 10 (‘Perfect’). Although some participants reported speaking up to five languages, since the sample size became progressively smaller for each additional language spoken, only proficiency in the first, second and third languages were analysed. The means, standard deviations and ranges for these are presented in Table 4.

Table 4

Descriptive Statistics for Proficiency in Speaking, Reading and Comprehension

Proficiency	Mean	*SD*	Range
First language			
Speaking [a]	8.70	1.13	5 – 10
Comprehension	8.87	1.12	5 – 10
Reading	7.83	1.83	2 – 10
Second language			
Speaking	8.15	1.67	1 – 10
Comprehension [b]	8.73	0.84	6 – 10
Reading	8.13	1.62	4 – 10
Third language			
Speaking	6.04	2.04	1 – 9
Comprehension	6.77	2.05	1 – 10
Reading	5.98	2.25	1 – 10

Notes. n = 47. *SD* = standard deviation.

[a] = 46. [b] = 45.

1.3 Descriptive Statistics of Working Memory Variables

The main aim of this study was to examine the relationship between the *n*-Back task, Digit Span subtest, and Symbol Span subtest. The descriptive statistics for all 47 participants' performance in these tasks are presented in Table 5.

Table 5

Descriptive Statistics of Working Memory Measures

Working Memory Tests	Mean	*SD*	Range
Digit Span Subtest			
Forwards	9.02	1.91	4 – 13
Backwards	7.83	2.06	4 – 14
Sequencing	8.28	1.66	5 – 12
Total	25.13	3.93	15 – 32
Symbol Span Subtest	29.53	6.65	12 – 40
***n*-Back Task**			
1-Back accuracy	120.47	2.91	114 – 125
1-Back reaction time (ms)	689.07	155.60	398.32 – 1117.92
2-Back accuracy	111.74	7.32	95 – 122
2-Back reaction time (ms)	756.30	193.71	418.14 – 1333.00
3-Back accuracy	98.72	8.42	83 – 121
3-Back reaction time (ms)	783.67	182.45	346.92 – 1274.71

Notes. *n* = 47. *SD* = standard deviation, ms = milliseconds.

2. Inferential Statistics

The inferential analyses consisted of two parts. Firstly, correlations between working memory and demographic variables were examined to assess the initial relationships among key variables. Secondly, regression analyses were used to determine the extent to which (1) Digit and Symbol Span performance predicted variance in the *n*-Back task, and (2) demographic variables predicted performance on each of the working memory measures. These are discussed below.

2.1 Correlations

Tables 6 and 7 contain pairwise correlations among the variables under study, including the working memory scores; number of languages spoken; proficiencies in speaking, reading, and comprehension for the first three languages; biological sex; and SES scores. These correlations provided a preliminary understanding of the association between key variables, i.e., to aid in the interpretation of the more complex relationships revealed through multiple regression analyses.

Kendall’s Tau correlation was run to determine (1) the relationships between the Digit Span, Symbol Span, and *n*-Back variables (as presented in Table 5); and (2) the strength and direction of association between the interval demographic variables (as presented in Tables 2 and 4) and working memory variables. Kendall's Tau correlation coefficient is a nonparametric measure of the direction and strength of association between two variables. Data must be measured on at least an ordinal scale, which was the case for all variables included here. These correlations are presented in Table 6.

Table 6

Kendall's Tau Correlations Between Working Memory and Interval Demographic Variables

	DSF	DSB	DSS	DST	SS	1BA	1BR	2BA	2BR	3BA	3BR	#langs	1LS	1LC	1LR	2LS	2LC	2LR	3LS	3LC	3LR
DSB	.34**	–																			
DSS	.24*	.05	–																		
DST	.71**	.58**	.44**	–																	
SS	.26*	.14	.09	.21	–																
1BA	.07	−.03	−.05	.01	.08	–															
1BR	−.01	−.06	−.08	−.07	−.05	−.05	–														
2BA	.21	.09	.20	.24*	.12	.23*	−.07	–													
2BR	.05	−.06	−.15	−.07	.04	−.03	.50**	−.08	–												
3BA	.22*	.14	.27*	.29**	.14	.11	−.08	.36**	−.06	–											
3BR	.06	−.05	−.16	−.09	.09	−.04	.34**	.14	.64**	.06	–										
#langs	.04	−.17	−.13	−.08	−.03	−.13	−.12	−.05	−.14	.00	−.09	–									
1LS	−.13	.02	−.32**	−.18	−.08	−.11	.06	−.06	.02	−.34**	.04	.14	–								
1LC	−.19	−.11	−.31*	−.24*	−.09	−.14	.10	−.11	.00	−.43**	−.04	.17	.77**	–							
1LR	−.13	.02	−.34**	−.17	−.12	.02	−.01	.01	−.08	−.20	−.04	.00	.57**	.51**	–						
2LS	−.13	−.01	.00	−.08	−.02	.17	.10	.09	.16	−.02	.16	−.06	.08	−.06	−.10	–					
2LC	.00	−.05	−.06	−.06	.05	.18	−.07	.11	.01	−.05	.03	−.03	.13	.09	.11	.64**	–				

Table 6 Continued

	DSF	DSB	DSS	DST	SS	1BA	1BR	2BA	2BR	3BA	3BR	#langs	1LS	1LC	1LR	2LS	2LC	2LR	3LS	3LC	3LR
2LR	−.02	−.03	.06	−.01	−.03	.12	.01	.07	−.02	−.15	−.01	.00	.16	.13	−.06	.70**	.62**	–			
3LS	−.08	−.07	−.08	−.09	−.08	−.24*	−.09	−.02	−.02	.01	.11	.37**	.22	.22	.08	.08	.02	−.08	–		
3LC	−.01	.11	−.18	−.02	.04	−.14	−.04	−.01	.05	.01	.09	.19	.21	.22	.17	.05	.06	−.07	.71**	–	
3LR	.09	−.02	.06	.07	−.02	−.04	.04	.08	.00	.08	.08	.36**	.06	.07	.04	.17	.00	.09	.57**	.51**	–
SES	.02	.05	.22	.13	−.03	.08	−.11	−.02	−.04	.11	.01	.01	−.18	−.31*	−.28*	.20	.19	.10	−.09	−.17	−.08

Notes. n = 47, except for 1LS (n = 46) and 2LC (n = 45). DSF = Digit Span Forwards, DSB = Digit Span Backwards, DSS = Digit Span Sequencing, DST = Digit Span Total, SS = Symbol Span, 1BA = 1-Back Accuracy, 1BR = 1-Back Average Reaction Time, 2BA = 2-Back Accuracy, 2BR = 2-Back Average Reaction Time, 3BA = 3-Back Accuracy, 3BR = 3-Back Average Reaction Time, #langs = number of languages spoken by participant, 1LS = first language speaking proficiency, 1LC = first language comprehension proficiency, 1LR = first language reading proficiency, 2LS = second language speaking proficiency, 2LC = second language comprehension proficiency, 2LR = second language reading proficiency, 3LS = third language speaking proficiency, 3LC = third language comprehension proficiency, 3LR = third language reading proficiency, SES = socioeconomic status.

*$p < .05$. ; **$p < .01$.

Only significant pairwise correlations that related to the research questions are described here. The variable 3-Back Accuracy showed significant, weak positive correlations with Digit Span Forwards (*r*(45) = .22, *p* = .041) and Digit Span Sequencing (*r*(45) = .27, *p* = .014). In terms of the demographic variables, Digit Span Sequencing correlated with first language speaking (*r*(44) = −.32, *p* = .008), comprehension (*r*(45) = −.31, *p* = .011), and reading (*r*(45) = −.34, *p* = .003) proficiency. Similarly, 3-Back Accuracy scores correlated with first language speaking (*r*(44) = −.34, *p* = .003) and comprehension (*r*(45) = −.43, *p* < .001) proficiency. Finally, 1-Back Accuracy scores correlated weakly and negatively with third language speaking proficiency (*r*(45) = −.24, *p* = .037).

A point-biserial correlation was run to determine the relationship between the categorical variable sex and all of the working memory variables mentioned (Table 7). Sex was dichotomised (male/female). None of the correlations between sex and the working memory variables were statistically significant.

Table 7

Point-biserial Correlations Between Working Memory Variables and Sex

Variable	DSF	DSB	DSS	DST	SS	1BA	1BR	2BA	2BR	3BA	3BR
Sex	−.09	−.06	−.12	−.12	−.22	−.26	.15	−.20	.12	.02	.16

Notes. n = 47. DSF = Digit Span Forwards, DSB = Digit Span Backwards, DSS = Digit Span Sequencing, DST = Digit Span Total, SS = Symbol Span, 1BA = 1-Back Accuracy, 1BR = 1-Back Average Reaction Time, 2BA = 2-Back Accuracy, 2BR = 2-Back Average Reaction Time, 3BA = 3-Back Accuracy, 3BR = 3-Back Average Reaction time.

**p* < .05. ; ***p* < .01.

To investigate this further, an independent samples *t*-test was run with a 95% confidence interval for the mean difference to compare the performance of males and females on each of the working memory measures. In order to evaluate the assumptions of this analysis, normality of data for each group was assessed using the Shapiro-Wilk test, skewness and kurtosis coefficients. These, as well as visual inspection of histograms and normal Q-Q plots, indicated that the working memory scores for each subtest were approximately normally distributed for both males and females. Inspection of boxplots revealed no significant outliers. There was homogeneity of variance, as assessed by Levene's test for equality of variances, for Symbol Span (p = .399) and *n*-Back Accuracy (p = .612). However, homogeneity of variance was violated for Digit Span Total (p = .023), and thus diagnostic outputs for equal variances not assumed were used for this variable. None of the results were significant, suggesting that males and females performed equivalently on all of the working memory tests. The means, standard deviations, *t*-statistics and *p*-values are presented in Table 8. Due to lack of homogeneity of variance, outputs for equal variances not assumed were assessed for Digit Span Total, which consequently demonstrated different degrees of freedom.

Table 8

t-Test Results Comparing Male and Female Total Working Memory Scores

Variable	Males	Females	*t*	*df*	*p*
	M (SD)	*M (SD)*			
Digit Span Total	25.76 (4.68)	24.77 (3.47)	0.77	26.11	.450
Symbol Span	31.47 (7.73)	28.43 (5.80)	1.53	45	.134
n-Back Accuracy	333.59 (14.12)	329.43 (15.21)	0.92	45	.361

Notes. n = 47. *SD* = standard deviation, *df* = degrees of freedom.

2.2 Simple and Multiple Regression Models

In order to more closely investigate the relationships revealed by the correlation analysis, two sets of regression models were run to assess (1) whether the Digit Span Forwards and Sequencing predicted variance in 3-Back Accuracy scores, and (2) whether the respective proficiency scores predicted performance on the Digit Span Sequencing and specific *n*-Back variables. Since participants completed the working memory tests during different timeslots across the data collection period, it was important to first establish whether performance on the working memory measures was influenced by the time of day that participants completed the tests – in other words, whether participants who completed the tests in the morning performed significantly differently to those who completed them in the afternoon. An independent samples *t*-test was run to compare performance on the working memory tests (using total scores) at the different timeslots, with a 95% confidence interval for the mean difference. Shapiro-Wilk test, skewness and kurtosis coefficients, as well as visual inspection of histograms and normal Q-Q plots, indicated that the working memory scores for each subtest was approximately normally distributed for both morning and afternoon timeslots. Inspection of boxplots revealed no significant outliers. There was homogeneity of variance for Digit Span (p = .218), Symbol Span (p = 1.000) and *n*-Back Total Correct (p = .797). The results were not statistically significant, suggesting that time of day did not influence performance on any of the working memory tests. The means, standard deviations, *t*-statistics and *p*-values are presented in Table 9.

Table 9

t-Test Results Comparing Working Memory Scores for Morning and Afternoon Timeslots

Variable	Morning	Afternoon	*t*(45)	*p*
	M (SD)	*M (SD)*		
Digit Span Total	24.50 (3.62)	25.78 (4.21)	-1.12	.268
Symbol Span	29.92 (6.43)	29.13 (6.99)	0.40	.690
n-Back Total Correct	330.67 (14.72)	331.22 (15.23)	-0.13	.900

Notes. n = 47. *SD* = standard deviation.

Regression Analyses Investigating Working Memory Variables. To investigate whether Digit Span Forwards and Sequencing predicted variance in 3-Back Accuracy scores, post-regression outputs were examined to assess whether assumptions of multiple linear regression were met. The first assumption is that the independent variables be measured on a continuous scale. Since performance on the Digit Span Forwards and Sequencing was measured on a continuous scale, the first assumption was satisfied. The second assumption stipulates that a linear relationship should exist between the variables. This was assessed by scatterplots, which revealed that all relationships appeared either linear or non-existent. The third assumption, i.e., independence of observations, was assumed by the nature of the research design. Since each participant only completed each working memory task once, there was no concern with repeated measures from the same individual, and therefore, no concern regarding independence of errors. The fourth assumption of homoscedasticity was assessed by plotting the standardized residuals against the predicted values, which revealed adequate homogeneity of errors (Appendix F, Figure F1). The fifth assumption requires an approximately normal distribution of residuals. This was assessed by generating a histogram of standardised residuals, which indicated that the data errors were approximately normally distributed (Figure F2). Sixth, to detect the presence of any outliers, several diagnostic outputs were computed, including the standardized residuals, Cook's distance, Leverage points, and Mahalanobis' distance. As discussed earlier, while outliers may influence statistical outputs, removing outliers that are rightful values of the distribution of interest is not appropriate and may distort conclusions. For this reason, observations that were flagged as outliers by at least two of the abovementioned diagnostic outputs were identified as the most likely to disproportionally influence regression coefficients. Using these criteria, no observations were excluded for this regression model. Finally, multiple regression also requires that the independent variables are not so highly correlated as to show multicollinearity of data. Variables that show very strong intercorrelations ($r \geq .70$) may suggest possible multicollinearity (Dormann et al., 2013), and on this basis, one of the variables should be excluded from subsequent regression analysis. In this case, Digit Span Forwards and Sequencing were only weakly correlated with each other ($r(45) = .24$, $p = .034$). Furthermore, inspection of variance inflation factors revealed no factor above two, suggesting that multicollinearity was not a serious concern.

As indicated in Table 10, the regression equation predicting variance in 3-Back Accuracy scores from performance on the Digit Span Forwards and Sequencing was statistically significant ($F(2,44) = 4.72$, $p = .014$, $R^2 = .18$). However, only Digit Span Sequencing added statistically significantly to the prediction ($\beta = .32$, $t(44) = 2.24$, $p = .030$). This suggests that higher scores on the Digit Span Sequencing conditions significantly predicted higher accuracy in the 3-back condition (the most difficult condition of the *n*-Back task). The R^2 value indicates that 18% of the variance in 3-Back Accuracy was explained by scores on the Digit Span Sequencing.

Table 10

Results of Multiple Regression Analysis for Dependent Variable 3-Back Total Correct

Variable	*B*	*SE*	*β*	*p*	95% CI	
					LB	UB
Digit Span Forwards	0.90	0.63	0.20	.159	−0.37	2.16
Digit Span Sequencing	1.61	0.72	0.32	.030	0.16	3.05

Notes. *n* = 47. *B* = unstandardised *B*, *SE* = standard error, *β* = standardised beta coefficient, CI = confidence interval, LB = lower bound, UB = upper bound.

Regression Analyses Assessing Working Memory and Demographic Variables. For the second set of regressions (examining the influence of the demographic variables on working memory performance), three regression models were computed to determine: (1) whether first language speaking, comprehension and reading proficiency predicted variance in Digit Span Sequencing scores, (2) whether first language speaking and comprehension proficiency predicted variance in 3-Back Accuracy scores, and (3) whether third language speaking proficiency predicted variance in 1-Back Accuracy scores. Since the proficiency scores served as the independent variables and were measured on an interval scale, the first assumption of regression analysis was satisfied. The assumptions of linearity between variables, independent observations, homoscedasticity, normally distributed residuals, and no extreme outliers were assessed, as previously mentioned .

To assess whether first language speaking, comprehension and reading proficiency predicted variance in the Digit Span Sequencing, it was necessary to perform multiple regression analysis, since there were three independent variables present. However, speaking and comprehension proficiency were very highly correlated ($r(44) = .77$, $p < .001$), suggesting that this may cause multicollinearity of data. Since comprehension is considered a higher cognitive function (Barnes et al., 2016; Wu et al., 2020), the speaking proficiency variable was excluded from the subsequent multiple regression analysis, preserving comprehension and reading proficiency as independent variables. The latter two were moderately correlated ($r(45) = .51$, $p < .001$). Inspection of variance inflation factors revealed no factor above two, suggesting that multicollinearity was not a serious concern. As for the remaining assumptions, there was linearity between variables, and independent observations. Two outliers were excluded from the regression model. There was homoscedasticity, and residuals were approximately normally distributed (Figures F3 and F4). As seen in Table 11, this regression equation was statistically significant ($F(2,42) = 5.92$, $p = .005$, $R^2 = .22$). However, neither comprehension nor reading proficiency added individually to the prediction ($p > .05$).

Table 11

Results of Multiple Regression Analysis for Dependent Variable Digit Span Sequencing

Variable	*B*	*SE*	*β*	*p*	95% CI	
					LB	UB
1L Comprehension Proficiency	−.63	.33	−.32	.064	−1.29	0.04
1L Reading Proficiency	−.21	.17	−.20	.241	−0.56	0.14

Notes. $n = 47$. 1L = first language, *B* = unstandardised *B*, *SE* = standard error, *β* = standardised beta coefficient, CI = confidence interval, LB = lower bound, UB = upper bound.

For this reason, two separate simple regression analyses were run. For the model including comprehension proficiency as the independent variable, all assumptions were met (Figures F5 and F6), with two outliers excluded from the regression model. As seen in Table 12, the regression equation was statistically significant ($F(1,43) = 10.33$, $p = .002$, $R^2 = .19$).

Table 12

Results of Linear Regression Analysis for Dependent Variable Digit Span Sequencing

Variable	*B*	*SE*	*β*	*p*	95% CI	
					LB	UB
1L Comprehension Proficiency	−0.86	0.27	−0.44	.002	−1.40	−0.32

Notes. n = 47.

1L = first language, *B* = unstandardised *B*, *SE* = standard error, *β* = standardised beta coefficient, CI = confidence interval, LB = lower bound, UB = upper bound.

Similarly, all assumptions were met for the model in which reading proficiency served as the independent variable (Figures F7 and F8), with two outliers excluded from the regression model. As seen in Table 13, the regression equation was also statistically significant ($F(1,43) = 10.09$, $p = .003$, $R^2 = .19$). These results suggest that as first language comprehension and reading proficiency increased, performance on the Digit Span Sequencing condition decreased.

Table 13

Results of Linear Regression Analysis for Dependent Variable Digit Span Sequencing

Variable	*B*	*SE*	*β*	*p*	95% CI	
					LB	UB
1L Reading Proficiency	−0.50	0.16	−0.44	.003	−0.82	−0.18

Notes. n = 47. 1L = first language, *B* = unstandardised *B*, *SE* = standard error, *β* = standardised beta coefficient, CI = confidence interval, LB = lower bound, UB = upper bound.

The next regression model assessed whether first language speaking and comprehension proficiency significantly predicted 3-Back Accuracy scores. As described above, speaking proficiency was excluded due to very high intercorrelations between the two independent variables, preserving comprehension proficiency as the sole predictor. One outlier was removed from the model. All other assumptions were met (Figures F9 and F10).

As seen in Table 14, this regression equation was statistically significant ($F(1,44) = 18.73$, $p < .001$, $R^2 = .30$), which suggests that comprehension proficiency in a participant's first language significantly predicted 3-Back Accuracy scores. The R^2 value indicates that first language comprehension proficiency explained 30% of the variance in 3-Back Accuracy scores.

Table 14

Results of Linear Regression Analysis for Dependent Variable 3-Back Total Correct

Variable	*B*	*SE*	*β*	*p*	95% CI	
					LB	UB
1L Comprehension Proficiency	−4.81	1.11	−0.55	<.001	−7.05	−2.57

Notes. $n = 47$. 1L = first language, *B* = unstandardised *B*, *SE* = standard error, *β* = standardised beta coefficient, CI = confidence interval, LB = lower bound, UB = upper bound.

Finally, for the regression model investigating 1-Back Accuracy scores from third language speaking proficiency, while most assumptions were met (Figure F11), visual inspection of the histogram revealed non-normally distributed residuals (Figure F12), which indicates that the significance levels for the regression coefficient must be treated with caution. As seen in Table 15, this regression equation was not statistically significant ($F(1,45) = 3.98$, $p = .052$, $R^2 = .08$), suggesting that third language speaking proficiency did not significantly predict variance in 1-Back Accuracy scores.

Table 15

Results of Linear Regression Analysis for Dependent Variable 1-Back Total Correct

Variable	*B*	*SE*	*β*	*p*	95% CI	
					LB	UB
3L Speaking Proficiency	−.41	.20	−.29	.052	−.82	.004

Notes. n = 47. 3L = third language, *B* = unstandardised *B*, *SE* = standard error, *β* = standardised beta coefficient, CI = confidence interval, LB = lower bound, UB = upper bound.

In this chapter, the results of the statistical analyses were provided to address the research questions presented in Chapter 1. Descriptive data analyses provided an overview of the data, while inferential statistics showed the statistical relationships between the variables, answering research questions one to three. There were significant but weak correlations between Digit Span Forward and Sequencing, and 3-Back Accuracy. The results of the regression analyses demonstrated that these relationships were significantly predictive. The proficiency variables were the only demographic variables that correlated significantly, although weakly and negatively, with several of the working memory scores. Several of these relationships were significantly predictive. These results are interpreted and discussed in the following chapter.

Chapter 4: Discussion

The primary aim of this study was to assess whether the *n*-Back task is a valid measure of working memory. This question was addressed by investigating the convergent validity between the *n*-Back, and Digit Span and Symbol Span subtests. An additional study aim was to examine whether performance on these tests was influenced by demographic variables. As outlined in Chapter 1, the study thus investigated: (1) whether there was a significant relationship between the *n*-Back (1-, 2- and 3-back loads), Digit Span (Forwards, Backwards and Sequencing) and Symbol Span tests, (2) whether the Digit Span and Symbol Span subtests predicted variance in the *n*-Back task, and (3) whether demographic variables (number of languages spoken, proficiency in each of these languages, sex of participants and SES) predicted variance in each of these working memory tests. In the previous chapter, the results of the study were provided in line with the abovementioned research questions. Regarding the relationships between the working memory measures, 3-Back Accuracy scores showed significantly weak, positive correlations with Digit Span Forwards and Sequencing. Further, Digit Span Sequencing (but not Forwards) scores significantly predicted variance in 3-Back Accuracy scores. In terms of the demographic variables, only some of the proficiency scores correlated significantly, but weakly (and generally, negatively) with Digit Span Sequencing, 1- and 3-Back Accuracy scores. First language comprehension and reading proficiency scores significantly predicted performance on the Digit Span Sequencing. Additionally, first language comprehension proficiency significantly predicted performance on 3-Back (but not 1-Back) Accuracy scores. Demographic variables, such as number of languages spoken, sex of participants, and SES, did not correlate significantly with any of the working memory tests.

In the following chapter, these results are discussed in terms of the relationship between the three working memory tests, and the extent to which these tests were influenced by demographic variables. These interpretations are drawn from the preliminary statistical analyses and are informed by the theoretical and empirical literature included in Chapter 1. The theoretical and practical contributions of this study will then be discussed, alongside theoretical and methodological limitations that may have biased the results, followed by suggestions for future research in this area of study.

1. Relationships Between the *n*-Back, Digit Span and Symbol Span Subtests

The first part of this study investigated the relationships between the *n*-Back task and Digit and Symbol Span subtests. The *n*-Back task (Gevins & Cutillo, 1993) has been widely used to study cognitive processes (Lamichhane et al., 2020). Complexity in this task increases with higher numbers of '*n*' (e.g., 2-back, 3-back, etc.), in that the items continually change from targets to comparison items, and eventually to distractors that can be discarded. Since this task requires cognitive maintenance, continuous updating and information processing, it appears to match the criteria of a working memory measure, and is thus commonly used to investigate working memory (Gajewski et al., 2018; Kane et al., 2007). However, precisely which aspects of working memory are measured using the *n*-Back task remains unclear. Medium to strong correlations are reported between the *n*-Back and compound measures of complex span tasks (e.g., Shamosh et al., 2008), while other studies find stronger correlations with simple span tasks (e.g., Jaeggi et al., 2010). This study was therefore interested in investigating the working memory processes implicated in the *n*-Back task, and the extent to which these may be similar to those implicated in the Digit and Symbol Span subtests. Assuming that the *n*-Back task measures working memory capacity as processing load increases, it was expected that the *n*-Back task would be significantly correlated with the Backward and Sequencing conditions of the Digit Span subtest, as well as with the Symbol Span subtest, as measures of complex working memory. In other words, in order for the *n*-Back task to demonstrate construct validity as a measure of working memory, it would be expected to correlate with tasks that entail the manipulation and processing of information in addition to simple storage or rehearsal (Kane et al., 2007).

This study replicated weak, but significant, correlations between the *n*-Back task and working memory span (Kane et al., 2007). Specifically, 3-Back Accuracy scores correlated significantly with Digit Span Forwards and Digit Span Sequencing. This is an interesting result, since Digit Span Forwards is a simple span task, and Sequencing is considered to be a complex span task. The correlation of the 3-Back Accuracy scores with the Digit Span

Forwards was significantly greater than zero, but very weak. Since the correlation of 3-Back Accuracy with Digit Span Sequencing was slightly stronger, this may suggest that the *n*-Back task shares most variance with a complex span task. However, it is critical to note that Digit Span Sequencing requires both simple storage, in addition to processing. Therefore, the correlation between Digit Span Sequencing and the *n*-Back task may reflect shared variance due to simple STM only. Nevertheless, regardless of which component of working memory is being tapped, these findings suggest that the relationship between the *n*-Back and working memory tests used here is considerably weaker than would be expected for tasks measuring the same underlying working memory construct (Redick & Lindsey, 2013).

It should be noted, however, that a potential explanation for these smaller correlations is the lack of variability on the working memory tasks, by virtue of the high-ability sample (university students). The limited variability could certainly limit correlation magnitude (Redick & Lindsey, 2013). Complex span intra-correlations tend to vary in relation to the sample, in that correlations between complex span tasks are weaker among individuals from more selective universities, compared to samples from diverse institutions or community volunteers (Redick et al., 2012). For instance, a student sample from the Massachusetts Institute of Technology demonstrated a *n*-Back and composite complex span correlation of $r = -.09$ (Roberts & Gibson, 2002). Similarly, in two separate studies with university students, *n*-Back and average complex span correlated at $r = -.04$ (mean age of 29.09 years; Jaeggi et al., 2010) and $r = 0.1$ (mean age of 19.20 years; Unsworth, 2010). In contrast, samples consisting of a combination of both university and community volunteers (mean age of 22.21 years) obtained a *n*-Back and average complex span correlation of $r = .38$ (Burgess et al., 2011). This was replicated in a community sample which obtained a *n*-Back (omission/commission error rate) and average complex span correlation of $r = .40$ (Greenstein & Kassel, 2009). Essentially, correlations among cognitive tests tended to be smaller among individuals with higher IQs. While this may be the case for the weak correlations reported here, considering the tertiary-level student sample, it is nevertheless important to note that these assumptions about IQ are highly speculative, and beyond the scope of the current study.

It is interesting to note that 3-Back Accuracy scores only correlated significantly with Digit Span Sequencing, and not with Digit Span Backward. At first, this difference may seem unexpected since the Digit Span Backwards and Sequencing are both considered measures of complex (verbal) working memory (Wechsler, 2008a). Therefore, since one task correlated significantly with the *n*-Back task, it would be expected that the other be correlated in a similar fashion. However, the lack of significant correlation between Digit Span Backward and Sequencing suggests that these tasks may draw on separate cognitive processes (see Gathercole et al., 2019). This supports the notion that researchers should not only report which working memory tests are used, but also that different working memory measures should not be interpreted as being interchangeable (Lukasik et al., 2018; Pelegrina et al., 2015).

A possible explanation for the lack of relationship between the Digit Span Backwards and *n*-Back task is that the latter is visually presented, in contrast to the verbal presentation of the Digit Span subtests (Miller et al., 2009; St Clair-Thompson & Allen, 2013). Consequently, participants may rely on mental imagery strategies when completing the *n*-Back task and verbally-mediated ones when completing the Digit Span Backwards. However, this explanation is unlikely in the current study for two reasons. Firstly, the Digit Span Forwards and Sequencing (both verbally presented) correlated significantly with the *n*-Back task. Secondly, no significant correlations were observed between the Symbol Span and *n*-Back tasks, which would be expected if these tasks required similar strategies. It is therefore necessary to consider alternative explanations for this finding.

For one, it is useful to consider the retrieval demands of each task more closely. Digit Span Backwards requires serial *recall* of numbers, while the *n*-Back typically requires *recognition* of information, i.e., the participants need to differentiate target items from distractors (Kane et al., 2007). The updating demands of the tasks also differ. For Digit Span Backwards, the entire sequence of items must be maintained and inverted for recall, whereas for the *n*-Back task, the sequence is continually refreshed as items are simultaneously added and eliminated. In line with this, one study found that the task constructs for Digit Span Backwards and the *n*-Back task were related, but also distinct ($r =$ .66; Byrne et al., 2019, Preprint). Essentially, it appears that Digit Span Backwards and the *n*-Back task share common variance with one another, but likely tap into distinct task-specific processes, which is underscored by the lack of significant intercorrelations found in the current study.

Consistent with the lack of correlations between the *n*-Back task and Digit Span Backwards, it was also noted that the 1-Back scores did not correlate significantly with any of the Digit Span or Symbol Span tasks. This is not unexpected, since the 1-Back task is commonly used as a control condition in experimental research (Meule, 2017). Moreover, although Digit Span Forwards and Sequencing correlated significantly with accuracy scores on the *n*-Back, this was not observed with the average reaction times. This is consistent with evidence of significant correlations between *n*-Back performance and other psychometric tests in terms of accuracy, as opposed to response speed (Gajewski et al., 2018). These findings support the argument that accuracy and reaction times in *n*-Back tasks should not be interpreted interchangeably, and that studies using this task should report both of these indices (Meule, 2017).

In this same light, it is equally interesting to note that although Symbol Span correlated positively and weakly with *n*-Back accuracy scores, these were not significant. At first, this may imply verbal domain-specificity within the *n*-Back task. However, it is important to consider that the version of the *n*-Back task used in this study involved digits, and therefore can be classified as a verbal *n*-Back task (Tang et al., 2021). It is suggested that correlations between working memory tasks would be stronger when stimuli are used from the same domain (Redick & Lindsey, 2013). For instance, in a large sample (n = 6 274) of young adults (age range between 17 and 35 years), the correlation between verbal and visuospatial complex span tasks (r = .53) was found to be weaker than the correlations among verbal complex span tasks (r = .68; Redick et al., 2012). Therefore, future research should include a visuospatial version of the *n*-Back task in assessing its relationship with the Symbol Span subtest. This further supports the notion that inferences drawn regarding working memory in studies using different measures of this construct are not necessarily interchangeable.

In terms of whether the *n*-Back task shares variance with the Digit Span subtest, the strongest evidence for the relationship between these tasks comes from the multiple regression analyses, by means of its ability to model the relationship between different variables simultaneously. Noteworthy, only the Digit Span Sequencing contributed significantly to the prediction model, suggesting that these tasks tap into similar working memory processes. However, it remains unclear whether this shared variance is attributable to simple storage or processing of the central executive. Ultimately, the findings of the current study provide evidence that *n*-Back performance can only be predicted by specific tasks of verbal working memory, and that the most commonly used test of working memory (Digit Span Backwards) appears to have little relationship with the *n*-Back task. Future research, using a larger sample, is needed to statistically partial out shared variance between Digit Span Forwards and Sequencing. By evaluating the unique aspects of Digit Span Sequencing (reflecting the central executive), it would be possible to investigate the relationship between the *n*-Back task and central executive processes. Tentatively, these results are consistent with previous findings of weak associations between the *n*-Back task and other working memory measures, including Digit Span, Digit-Symbol and Stroop tasks (e.g., Gajewski et al., 2018; Jaeggi et al., 2010; Kane et al., 2007; Miller et al., 2009), and do not support the validity of the *n*-Back task as a pure measure of complex working memory.

What, then, is the *n*-Back task measuring? It has been suggested that the *n*-Back task implicates similar processes as complex span tasks under conditions of free recall. In contrast, under conditions of speeded recognition, the *n*-Back task appears to reflect different processes from complex span (Kane et al., 2007). For instance, one study found that *n*-Back accuracy and reaction times loaded together with other cognitive assessments on a common factor that was conceptualized to be speeded information processing (Miller et al., 2009). Indeed, the *n*-Back task demonstrated a stronger relationship with a measure of speeded information processing (Trail Making Test Part A) than a non-speeded working memory test (Digit Span Backwards). This suggests that *n*-Back performance may be more dependent on information processing speed than working memory (Miller et al., 2009). Furthermore, *n*-Back performance appears to share considerable variance with executive functions of inhibitory control and set shifting (e.g., cognitive flexibility). Since the *n*-Back task necessitates comparison of items no longer in the focus of attention, it has been argued that this task requires shift of attention (e.g., Verhaeghen & Basak, 2005). For example, *n*-Back performance in young adults (mean age of 29.1 years) shared variance with interference control, task switching and updating (Gajewski et al., 2018), which suggests that the *n*-Back task involves interference processing. This is consistent with the concept that both working memory and inhibitory control are required when a goal is held in mind and irrelevant (or competing) information needs to be inhibited (Diamond, 2013).

Nevertheless, the results found in this study (as well as previous research) makes it challenging to draw any clear conclusions regarding the *n*-Back task as a measure of working memory (Jaeggi et al., 2010). Ultimately, researchers should be cautious in their interpretations of results from the *n*-Back task, especially in terms of whether their findings relate to accuracy scores or average reaction times. In addition to accuracy and reaction time, researchers should report additional behavioural measures (Meule, 2017). More detailed analyses of *n*-Back task performance may provide clearer insight into its validity as a working memory measure. There is also limited understanding about the specific strategies that participants engage during task execution. A clearer understanding of the strategies involved in *n*-Back task performance would provide further insight into the processes implicated in this task.

2. Demographic Variables and Working Memory Performance

The second part of this study investigated the potential influence that demographic variables, such as number of languages spoken, proficiency in languages spoken, biological sex and SES, have on working memory performance, for each of the tests previously described. These results are elaborated in the section that follows.

2.1 Number of Languages Spoken and Proficiency Scores

Evidence suggests that individuals who grow up in a multilingual environment may develop cognitively in a different way to monolinguals (Smith et al., 2022). Importantly, in the multilingual mind, languages appear not to be separate, but form one integrated communicative system (Hayakawa & Marian, 2019). For this reason, a central feature of multilingual cognition is that multiple languages can become activated simultaneously, which subsequently necessitates inhibition of the non-target language. It is hypothesised that this perpetual practice of managing multiple languages may influence cognitive processes. In terms of working memory, regulating two or more languages may require more efficient allocation of working memory resources (Poarch & van Hell, 2012). For instance, multilinguals need to routinely assess and update their immediate social context to switch to the language relevant to the speakers they are engaged with (Antón et al., 2019). Based on this premise, speaking multiple languages could subsequently enhance working memory. However, research findings have been inconsistent (De Cat et al., 2018). To address this discrepancy, the working memory abilities of multilingual participants have been assessed through verbal and non-verbal tasks in the current study (Ratiu & Azuma, 2015). No significant correlations were found between the number of languages spoken and performance on the working memory tests. This finding is consistent with several studies that have challenged earlier findings of a bilingual advantage in executive function (e.g., Duñabeitia et al., 2013; Lukasik et al., 2018; von Bastian et al., 2016). Indeed, after controlling for publication bias, meta-analysis of 152 studies found no empirical grounds in support of a bilingual advantage in any of the six studied executive domains, including working memory (Lehtonen et al., 2018). This evidence suggests that bi- or multilingual advantages in working memory either do not exist or are limited to very specific aspects of multilingual experience (Lukasik et al., 2018; Paap et al., 2015).

Ultimately, this demonstrates that bilingual influences on working memory are not absolute or merely a function of how many languages one speaks. It is likely that these effects are more nuanced and may exist within the subcomponents of bilingual experience. For example, while number of languages did not correlate significantly with any of the working memory measures, several of the language proficiency scores correlated significantly with the Digit Span Sequencing task and specific *n*-Back components. Specifically, first language comprehension and reading proficiency had weak, negative predictive relationships with Digit Span Sequencing. Similarly, comprehension proficiency in the first language predicted 3-Back Accuracy scores. While the negative relationship between working memory performance and proficiency was unexpected, this could be explained within the theoretical framework of the supervisory attentional system (Norman & Shallice, 1986). This framework describes routine, ‘automatic’ actions as being based on task schemas that become activated. Essentially, well-learned routine behaviours lend themselves to a degree of automaticity, which enables one to perform a task without significant attentional demands (Stefanidis et al., 2007). When performing these well-learned behaviours, any competing schemata are regulated through inhibition mechanisms. In contrast, coordinating higher-level goals (e.g., non-routine) necessitates the implementation of a supervisory attentional system (Norman & Shallice, 1986). This system exercises top-down control through deactivating routine schemata, and activating those relevant to achieving the respective higher-order goals (Cieslik et al., 2015). This need to supress a predominant, routine response in favour of one that is context-appropriate is frequently demonstrated in cognitive tasks, including the Simon, Stroop and flanker tasks (Diamond, 2013). These tasks all require regulation of a predominant response tendency, and necessitate a context-appropriate behavioural alternative, i.e., to respond contrary to the predominant 'reflexive' response, or not respond at all.

Similarly, with the *n*-Back task, a higher frequency of non-target items induces an automatic tendency favouring a particular motor response. When presented with a target item, this predominant motor response needs to be inhibited, with non-routine, goal-oriented behaviour consequently mediated by the supervisory attentional system (Cieslik et al., 2015). It is possible that the negative correlations between comprehension/reading proficiency and the *n*-Back task reflect the inverse relationship between two processes in terms of automaticity. On the one hand, the high levels of proficiency in the first language reported by the sample (an average proficiency rating of 8.47, where 10 indicated perfect proficiency) reflect highly automized cognitive processing. Indeed, in a proficient speaker, language processes are commonly automatized, so that attention is directed in a manner that is efficient, effortless, and largely unconscious (Segalowitz & Frenkiel-Fishman, 2005). In contrast, the intense cognitive demands required during the *n*-Back task necessitate both goal-oriented attentional resources and inhibition (Adams & Shahnazari, 2014).

In addition to the negative association between first language comprehension proficiency and performance on the 3-Back task, the tests used in this study were all conducted in English. Eighty-three percent of participants had indicated a first language other than English. One of the most pronounced differences between monolinguals and multilinguals is that multilinguals regularly need to retrieve words from the target language, while simultaneously, inhibiting interference from the non-target language (Sandoval et al., 2010). This is especially relevant for the Digit Span Sequencing task, which relies heavily on verbal processing and recall. It is possible that, for the majority of the participants, unintended 'automized' activation of words from the nontarget language (their respective home language) could delay retrieval of English digits, thus impairing rehearsal processes and lowering performance (Ning, 2021). This hypothesis fits within the framework of the Multicomponent Model (Baddeley & Hitch, 1974) in considering that the phonological loop is fractionated into a passive phonological store (transiently capturing information as memory traces) and an active articulatory control process (for rehearsal of this information to prevent decay). Unintended activation of the home language (in recalling English digits) may disrupt rehearsal within the phonological store, restricting the amount of information that can be expressed before items decay from memory. Essentially, it is the interference between languages that may affect task performance, particularly during the higher cognitive processing required for the Digit Span Sequencing task. Indeed, this has similarly been reported in both the Stroop effect and reverse-Stroop effect. Participants (mean age of 25.52 years) required to identify words in their non-dominant language were observed to engage relatively more attentional resources for successful word processing, and relatively more inhibition to prevent responding to distractors (Ning, 2021). In the same way, the automaticity of word (e.g., digit) processing during the Digit Span Sequencing task may further influence processing speed, interrupt rehearsal processes and impair digit recall. This hypothesis is consistent with findings that bilinguals have lower processing speed (e.g., Schmidtke, 2016), which would subsequently influence the capacity of working memory. At this point, these interpretations are largely speculative. Moreover, first language comprehension proficiency predicted 30% of the variance in 3-Back Accuracy scores, while first language comprehension and reading proficiency together predicted 22% of the variance in performance on the Digit Span Sequencing task. This means that approximately 75% of the variance remains unexplained. This should be further investigated in future studies.

2.2 Influence of Biological Sex

Biological sex did not correlate significantly with any of the working memory variables. This finding is inconsistent with several studies reporting sex differences in working memory (Voyer et al., 2017; Zilles et al., 2016). At the same time, several studies have failed to find evidence of sex effects in working memory (e.g., Lejbak et al., 2011; Saylik et al., 2018; Schmidt et al., 2009). It is suggested that it is important to explore working memory abilities at high levels of cognitive load, in that the effects of sex may be load-dependent (e.g., Reed et al., 2017). However, in the current study, no sex effects emerged at different levels of working memory load, i.e., 1-back, 2-back or 3-back.

These findings can be interpreted in several ways. Firstly, if one were only to consider the correlation matrix, it may be that sex simply does not influence working memory. For instance, meta-analyses have reported that the differences in cognitive performance within groups of males and females are considerably larger than differences between the sexes (Hyde, 2005, 2014). In other words, individual differences in working memory are more pronounced than those exerted by biological sex. From this perspective, the data obtained from the current study suggest that males and females performed comparably on all of the working memory measures, with no differences observed, even on different components of the various tests (e.g., verbal/visuospatial modality, or simple/complex span tasks). Another possible explanation is that no sex-related effects in working memory were observed due to the participant sample, which was relatively homogenous for education and age. Level of education has a strong influence on performance in working memory tests, so that sex differences may be more evident in participants with lower education (Piccardi et al., 2016). The sample of university students may account for the absence of sex differences in the working memory tests in this study. In addition, working memory performance is at its peak during young adulthood (Greene et al., 2020; Hartshorne & Germine, 2015). High performance as a function of education and age may obscure any sex-related effects on working memory. Finally, it is possible that, even though males and females perform similarly on working memory tests, they adopt sex-specific strategies when completing these tasks (Grissom & Reyes, 2019; Lejbak et al., 2011). For instance, one study found no sex differences in performance on a spatial working memory task (Alarcón et al., 2014); even so, fMRI detected significant differences in neural activity, suggesting variation in working memory networks between males and females. It is therefore possible that while sex influences working memory, this is specific to the particular *processing strategies* that become activated during task completion, as opposed to influence on task *performance*. In other words, sex influences strategy use, and not overall scores. However, whether sex influences were present in strategy use during the working memory tasks was beyond the scope of the current study and should be investigated in future research.

2.3 Influence of Socioeconomic Status

Due to the far-reaching effects of poverty, SES is proposed to influence executive function, including working memory (Evans, 2004; Haft & Hoeft, 2017). These influences may be either negative (due to heightened stress or lack of cognitive stimulation) or positive (in terms of cognitive adaptations to unpredictable environments; Ellis et al., 2017; Johnson et al., 2016; Ursache & Noble, 2016; Young et al., 2018). However, the results of the current study did not find any significant correlations between SES and the respective working memory measures. This is consistent with research reporting no significant differences in working memory performance between low and higher income children (age range between 6.3 and 7.6 years; Engel et al., 2008). Although this finding was reported in children, if the association between SES and working memory remains stable from childhood through adolescence, as some research suggests (e.g., Hackman et al., 2014), then this may also extend to adult samples. The chronic stress hypothesis suggests that prolonged stress, due to protracted poverty exposure, may drive influences in working memory performance to emerge at a later stage (Evans & Schamberg, 2009). According to this perspective, one would expect SES, if it is influential, to affect (either negatively or positively) older individuals more strongly than younger people (Alloway & Copello, 2013). Overall, these findings support the notion that working memory may indeed be impervious to differences in SES (e.g., Cockcroft et al., 2016; Engel et al., 2008; Vandenbroucke et al., 2016). For instance, while Engel et al. (2008) found vocabulary scores to be considerably worse in low-SES children, when compared to their higher-SES counterparts, likely due to differences in knowledge-based skills facilitated by different environmental opportunities, no significant differences emerged in their working memory performance scores. This suggests that demographic background may be unrelated (specifically) to subcomponents of working memory (Engel et al., 2008). Since measures of working memory are highly sensitive to learning and language ability, they may serve as important tools for assessing cognitive functioning and learning difficulties in a way that is not biased to environmental opportunity (Engel et al., 2008). The results of the current study are therefore consistent with the notion that working memory measures may constitute fairer forms of evaluation for individuals from disparate SES environments (Cockcroft et al., 2016).

Nevertheless, it is worthwhile to consider the extent to which this lack of significant association may be accurate. A non-significant result reflects absence of *evidence* for a relationship. It is not, necessarily, evidence for a lack of relationship itself (e.g., Bialystok, 2016). The majority of participants (77%) scored between 8 and 10 on the LSM (the measure of SES), which is considered to be the bracket of individuals with most access to wealth (USDA, 2020). Moreover, considering that 6 was the minimum score achieved on the LSM in this study (with only four participants in this group), the sample was towards the higher end of SES background. Thus, the non-significant correlations may not necessarily reflect a lack of relationship between SES and working memory. For example, some research suggests that SES relates most strongly to the brain structure and cognitive functioning among the most socioeconomically disadvantaged individuals, who were absent from the sample (e.g., Noble et al., 2015). Thus, it may be that there was insufficient variance in SES among the study participants to fully explore this relationship.

3. Contributions of the Study

The findings of this study contribute to understanding how the *n*-Back task relates to the Digit and Symbol Span subtests, all commonly used working memory measures in cognitive neuroscience research and diagnosis. To the best of the researcher's knowledge, this is one of the few studies, if any, that has investigated these relationships in a sample of South African university students. Through describing the relationships (or lack thereof) between these tasks, this study contributes to a greater understanding of the *n*-Back task, and, perhaps more importantly, to what aspects remain to be explored and explained. Specifically, these results suggest that the *n*-Back task might not constitute a pure measure of working memory, but may rather be tapping into related but distinct cognitive constructs (e.g., information processing). As such, this study emphasises the need to conduct further research in this regard.

Additionally, it has been observed that within working memory research, insufficient attention is afforded to individual differences arising as a function of sample characteristics (e.g., Blasiman & Was, 2018; Jarrold & Towse, 2006). It is important to understand that performance on working memory tests is sensitive to many situational factors and variables. Therefore, a strength of the current study is the explicit inclusion of several demographic variables that were identified as potentially influencing working memory performance. In particular, this study sought to disentangle the potential effects that number of languages spoken, proficiency in these languages, biological sex and SES, have on working memory. Beyond the inclusion of demographic characteristics, the sample was significant for the particular languages spoken by participants. The focus on African languages renders this study unique from those conducted on Westernized samples in terms of linguistic characteristics and culture. As such, this study is able to address under-studied questions about the influence these specific languages could exert on working memory. While the influence of these specific languages on working memory was not directly investigated, it is possible that language-specific properties may explain the unusual pattern of results that were observed (e.g., Amici et al., 2019; Deldar et al., 2020; Emmorey et al., 2017).

4. Limitations and Recommendations for Future Research

Despite the contributions of this study, it has some limitations. Firstly, the research design was non-experimental and exploratory in nature, and as such, cannot make any assumptions about causality between variables. For this reason, conclusions drawn from this study are necessarily tentative and refer to relationships only. Secondly, in addition to the small sample size, the sample itself was relatively homogenous. Participants were approximately the same age, predominantly female, spoke between three and five languages, were all receiving tertiary education, and came mostly from economically advantaged backgrounds. It is also possible that the convenient volunteer-based sampling strategy may have biased the sample towards high-achieving student participants. It is therefore strongly recommended that the variable relationships explored be verified with a larger, more representative sample.

In terms of the measures included here, validity of the working memory tests could not be fully assessed due to the specific subtests that were used, as well as the limited timeframe in which the study was conducted, which restricted the sample size. Moreover, this study only compared the *n*-Back task to two established working memory measures: verbal and visuospatial working memory were captured using two ‘span’ tasks, i.e., Digit and Symbol Span (Wilhelm et al., 2013). It would therefore be worthwhile to include a wider range of working memory tests to more fully investigate the shared constructs tapped by the *n*-Back task, taking note also of the different modalities (e.g., verbal/visuospatial) of the *n*-Back task itself (Jaeggi et al., 2010).

5. Conclusion

In summary, this study explored the relationship between the *n*-Back, Digit Span and Symbol Span subtests in a sample of South African university students. Specifically, 3-Back Accuracy scores showed significant weak, positive correlations with Digit Span Forwards and Sequencing, and Digit Span Sequencing scores significantly predicted variance in 3-Back Accuracy scores. However, it remains unclear whether this shared variance is attributable to simple storage or processing from the central executive. Future research, using a larger sample, is needed to statistically partial out the unique aspects of Digit Span Sequencing (reflecting the central executive) and assess its relationship with the *n*-Back task. Nevertheless, the weak relationship observed tentatively supports the claim that the *n*-Back does not show construct validity as a working memory test (Jaeggi et al., 2010; Kane et al., 2007). Consequently, researchers need to be tentative when interpreting the results of complex span versus *n*-Back tasks as working memory measures (Redick & Lindsey, 2013). The data obtained from these tasks cannot necessarily be interpreted as interchangeable. It is possible that the *n*-Back task may be tapping other (related) cognitive processes, such as information processing, rather than predominantly working memory. Future studies should aim to clearly elucidate the constructs underpinning *n*-Back performance. Until research provides compelling evidence that it is an appropriate working memory measure, researchers and clinicians should continue to follow the recommendation of assessing working memory through established tests (Miller et al., 2009).

Furthermore, this study highlighted that some individual differences in terms of demographic variables may influence, and, in some cases, predict, working memory performance. This study highlights that categorising mono-, bi- or multilingual individuals by the number of languages spoken is probably too simplistic for investigating this nuanced topic. Rather, multiple aspects of the multilingual experience should be considered (Sandoval et al., 2010). For instance, although number of languages did not correlate significantly with any of the working memory measures in the current study, proficiency in these languages showed significant associations with specific components of the working memory tasks. The generally negative nature of these relationships suggests that as proficiency (in either speaking, comprehension, or reading) increased, working memory performance on the respective tasks decreased. While this was an unexpected finding, it may be explained within the framework of the supervisory attentional theory and the difference in automatization between language proficiency and a complex working memory task (Norman & Shallice, 1986). In terms of the remaining demographic variables, neither biological sex of participants nor SES background correlated significantly with any of the working memory measures. While this may suggest that neither sex nor SES influence working memory performance, it is necessary that these findings be validated in a larger, more representative sample.

In conclusion, this study contributes to understanding the complex relationships (or lack thereof) between these variables. The small sample restricts the generalisations that can be made based on these findings. Further research is therefore necessary to verify these results, in order to ensure fairer assessments of working memory in terms of the tasks used to measure this construct, as well as the individual differences that could influence performance on these tasks.

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Appendix A: Demographic Questionnaire

CODE ☐☐☐☐

Gender: ☐ M ☐ F Date of Birth: D D M M Y Y Y Y

Home Language(s): ____________________________

School Language(s): _____________________________________

Current Degree &

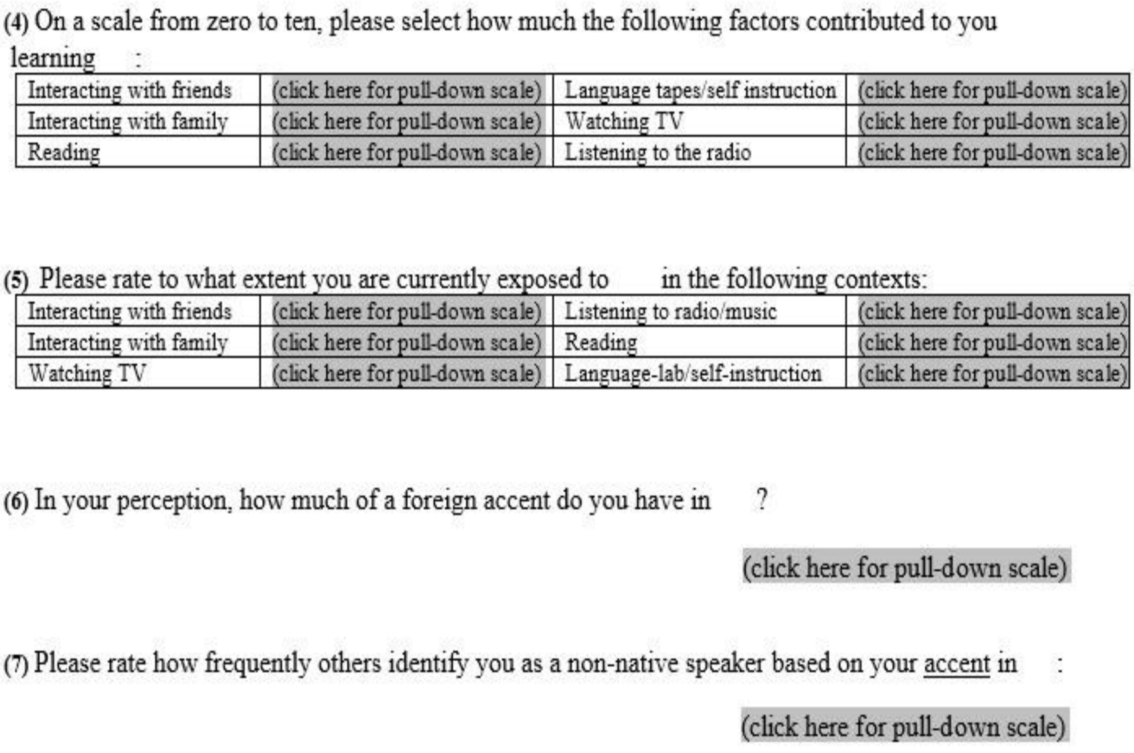
Faculty:____

Previous degrees or qualifications:

____

Current year of study (1st, 2nd, 3rd):

____



(4) On a scale from zero to ten, please select how much the following factors contributed to you learning :

Interacting with friends	(click here for pull-down scale)	Language tapes/self instruction	(click here for pull-down scale)
Interacting with family	(click here for pull-down scale)	Watching TV	(click here for pull-down scale)
Reading	(click here for pull-down scale)	Listening to the radio	(click here for pull-down scale)

(5) Please rate to what extent you are currently exposed to in the following contexts:

Interacting with friends	(click here for pull-down scale)	Listening to radio/music	(click here for pull-down scale)
Interacting with family	(click here for pull-down scale)	Reading	(click here for pull-down scale)
Watching TV	(click here for pull-down scale)	Language-lab/self-instruction	(click here for pull-down scale)

(6) In your perception, how much of a foreign accent do you have in ?

(click here for pull-down scale)

(7) Please rate how frequently others identify you as a non-native speaker based on your accent in :

(click here for pull-down scale)

How many years have you been at university?

____

Did you ever fail a grade at school? If so, which one?

____

Did you ever require an intervention from a language specialist?

____

Did you attend pre-primary school?

____

Educational and occupational status of your parents or primary caregivers:

Mother: Level of Education		**Father: Level of Education**	
No schooling		No schooling	
Less than primary school completed		Less than primary school completed	
Primary school completed		Primary school completed	
Secondary school not completed		Secondary school not completed	
Secondary school completed		Secondary school completed	
Tertiary education completed		Tertiary education completed	
Other		Other	
Current occupation:		Current occupation:	

Marital status of primary caregivers:

Married	
Living together as husband and wife	
Widow/widower	
Divorced/separated	
Other	

Number of caregivers in the household in which you spend the most time (please tick):

0	
1	
2	
>2	

Living Standards Measure:

Please answer the following questions according to your circumstances while growing up, and not in your current student accommodation if these are different.

Question	Answer	
1. I have the following in my household:		
TV set	TRUE	FALSE
VCR	TRUE	FALSE
DVD player	TRUE	FALSE
M-Net/DStv subscription	TRUE	FALSE
Hi-fi/music centre	TRUE	FALSE
Computer / Laptop	TRUE	FALSE
Vacuum cleaner/floor polisher	TRUE	FALSE
Dishwashing machine	TRUE	FALSE
Washing machine	TRUE	FALSE
Tumble dryer	TRUE	FALSE
Home telephone (excluding a cell)	TRUE	FALSE
Deep freezer	TRUE	FALSE
Fridge/freezer (combination)	TRUE	FALSE
Electric stove	TRUE	FALSE
Microwave oven	TRUE	FALSE
Built-in kitchen sink	TRUE	FALSE
Home security service	TRUE	FALSE
3 or more cell phones in household	TRUE	FALSE
2 cell phones in household	TRUE	FALSE
Home theatre system	TRUE	FALSE
2. I have the following amenities in my home:		
Tap water in house/on plot	TRUE	FALSE
Hot running water from a geyser	TRUE	FALSE
Flush toilet in/outside house	TRUE	FALSE
3. There is a motor vehicle in our household	TRUE	FALSE
4. I am a city dweller	TRUE	FALSE
5. I live in a house, cluster or town house	TRUE	FALSE
6. I live in a rural area outside Gauteng and the Western Cape	TRUE	FALSE
7. There are no radios, or only one radio (excluding car radios) in my household	TRUE	FALSE
8. There is no domestic workers or household helpers in household (both live-in & part time)	TRUE	FALSE

Appendix B: Participant Information Sheet

Psychology
School of Human & Community
Development
University of the Witwatersrand
Private Bag 3, Wits, 2050
Tel: 011 717 4503
Fax: 011 717 4559

Study title: A study of the relationship between working memory and multilingualism in young adults.

Dear student,

We are students and academics in the Department of Psychology, Wits University, and we would like to invite you to participate in our research, which examines how proficiency in many languages affects working memory. If you agree to take part in this study, the procedure can be completed individually at a time suitable for you.

Details of the Study. The first part of the study can be conducted online at your convenience. The activities will include: (1) reading though this information sheet (5-10 minutes); (2) completing the informed consent form (3 minutes), and (3) completing four questionnaire forms (5-15 minutes each). These forms and questionnaires can be completed online and submitted to us.

The second part of the study will take place in the Neuroscience Research Laboratory, Emthonjeni Centre, Wits, East Campus. This second part will be divided into two sessions, which will take place on two separate days. In the first session ('Day One of the Experiment'), participants will complete a series of brief memory assessments. In the second session ('Day Two of the Experiment'), participants will complete some tasks on a computer, while wearing an electroencephalogy (EEG) cap to measure brain function. Each session will take approximately 50-90 minutes. If you decide to participate in the first session (Day One), participation in the second session (Day Two) is not compulsory, although your participation will be greatly appreciated.

Risks. There are no foreseeable risks associated with EEG, which records electrical activity in the scalp by measuring voltage fluctuations in the brain's neurons using an electrode cap. It is a safe, non-invasive and a risk-free method, which will follow strict COVID-19 precautionary measures. To prevent minimal discomfort, the experimenter will ensure that the cap is comfortable, and the correct size is placed on the scalp. There might be some residual paste left in your hair after the electrodes are removed, but this washes out easily.

Despite COVID-19 precautionary measures, it is possible that someone will show no symptoms and spread the virus. If you are feeling unwell the day scheduled for your participation, please contact us immediately and we will reschedule your slot. If an experimenter reports COVID symptoms after interacting with you, we will contact you directly to inform you. Please also contact us immediately if you experience any COVID-related symptoms after your visit to the laboratory.

Benefits. Participation in this study requires an investment of your time, which we greatly appreciate. There are no direct benefits associated with participation. Given that participants must complete two sessions for this study in person, each participant will receive R150 per session towards travel expenses. In other words, if you choose to participate in only the first session (Day One), you will receive R150 compensation. If you choose to participate in both the first and second sessions (Days One and Two), you will receive a total of R300 compensation.

Confidentiality and Anonymity. The data obtained from this study will not be linked to any academic results or be traceable to participants, as it will be collected with an anonymous participant number only. Anonymity is guaranteed in any resulting publications and presentations. All data will be kept confidential in anonymized, password-protected files, stored on an external hard drive, and only the researchers will have access to the questionnaires and corresponding data. The results of this research will not be used to examine individual performance; only group performance will be analysed.

Withdrawal from this Study. Participation is entirely voluntary, and you are not obliged to be involved in this study. If you do decide to participate, you have the right to withdraw from the study at any time, and this will not be held against you in any way. If you choose to withdraw, any collected data will be destroyed and will not be used in subsequent analyses.

Research Outputs. The results of this study will be disseminated through a research report, publications and conference papers. Participants may request further information about the study, although individual feedback on performance will not be available as the collected data will be anonymous. Data may be used for possible secondary analyses.

Contact Details

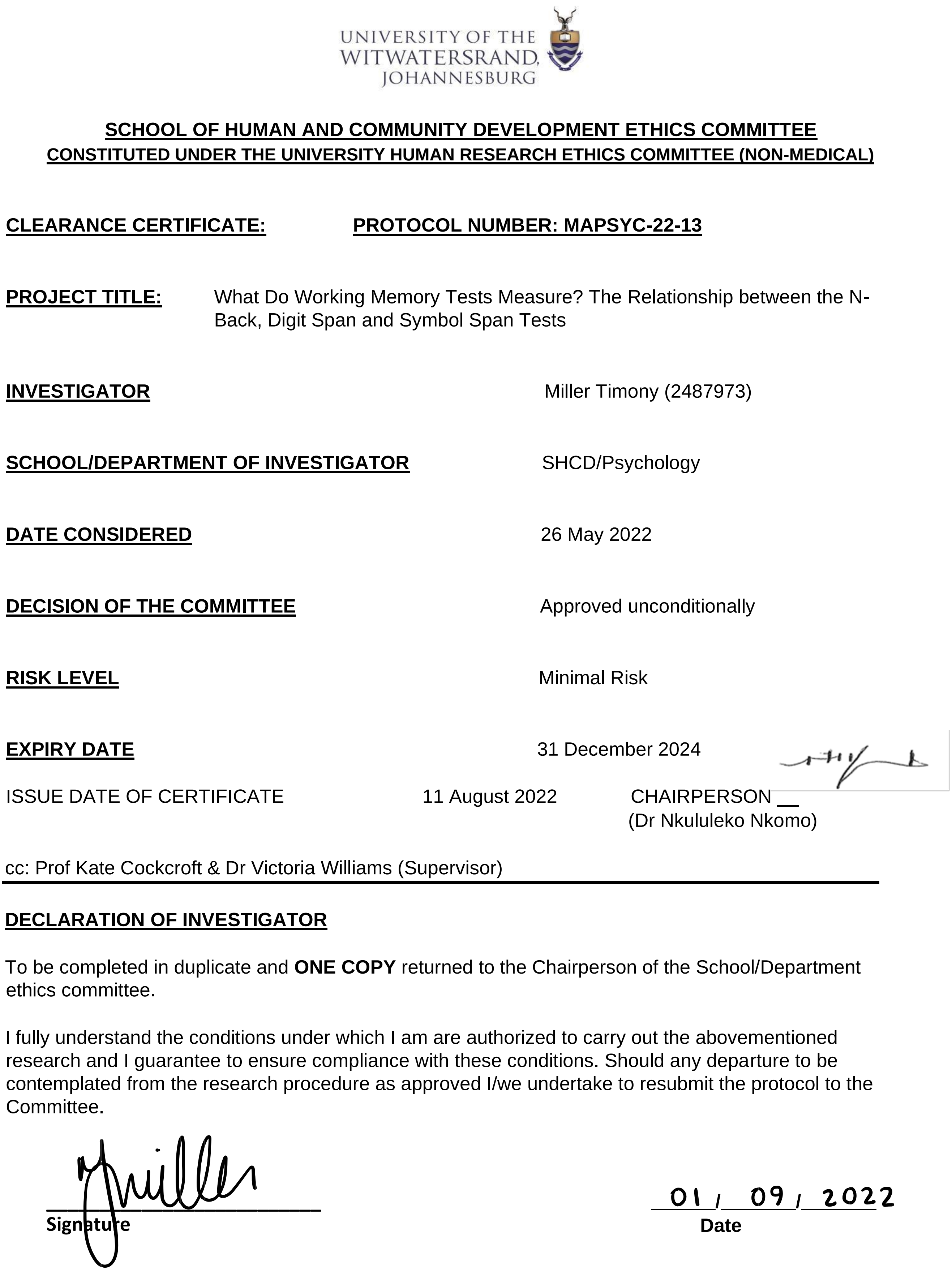
- Principal Investigator | Please contact Professor Kate Cockcroft (Kate.cockcroft@wits.ac.za / 011 717 4511) if you require further information about this study, or feedback on the progress of this research.

- HREC Administrator and Chair | Please contact Professor Clement Penny (Clement.Penny@wits.ac.za / 011 7172301) if there are any formal complaints or reservations about the ethical conduct of this research, stating the nature of your query. The Committee secretarial can also be contacted telephonically: 011 7172700/1234, or on email addresses: Zanele.Ndlovu@wits.ac.za and Rhulani/Mukansi@wits.ac.za. Any issues will be treated in confidence and investigated fully, and you will be informed of the outcome.

Thank you for taking the time to read this information sheet. If you are satisfied with the information provided, and are interested in participating in the study, please contact Timony Miller (2487973@students.wits.ac.za). You will be contributing to research that will provide insight into the cognitive benefits of linguistic diversity in our country.

Date: 05/08/2022

Appendix C: Ethical Clearance Certificate



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

SCHOOL OF HUMAN AND COMMUNITY DEVELOPMENT ETHICS COMMITTEE
CONSTITUTED UNDER THE UNIVERSITY HUMAN RESEARCH ETHICS COMMITTEE (NON-MEDICAL)

CLEARANCE CERTIFICATE: **PROTOCOL NUMBER: MAPSYC-22-13**

PROJECT TITLE: What Do Working Memory Tests Measure? The Relationship between the N-Back, Digit Span and Symbol Span Tests

INVESTIGATOR Miller Timony (2487973)

SCHOOL/DEPARTMENT OF INVESTIGATOR SHCD/Psychology

DATE CONSIDERED 26 May 2022

DECISION OF THE COMMITTEE Approved unconditionally

RISK LEVEL Minimal Risk

EXPIRY DATE 31 December 2024

ISSUE DATE OF CERTIFICATE 11 August 2022 CHAIRPERSON __
(Dr Nkululeko Nkomo)

cc: Prof Kate Cockcroft & Dr Victoria Williams (Supervisor)

DECLARATION OF INVESTIGATOR

To be completed in duplicate and **ONE COPY** returned to the Chairperson of the School/Department ethics committee.

I fully understand the conditions under which I am are authorized to carry out the abovementioned research and I guarantee to ensure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I/we undertake to resubmit the protocol to the Committee.

Miller
Signature

01/09/2022
Date

Appendix D: Participant Consent Form

Psychology
School of Human & Community Development
University of the Witwatersrand
Private Bag 3, Wits, 2050
Tel: 011 717 4503 Fax: 011 717 4559

Project: An evoked-response potential (ERP) study of the relationship between working memory and multilingualism in young adults.
Researchers: Professor Kate Cockcroft, Dr. Victoria Williams, Dr Sahba Besharati, Dr Aline Ferreira-Correia, Ms Enid Schutte; Dr Charlotte Krahe, Dr Michelle Leal, Mr Heinrich Zentgraf

I ……………………………………………………… agree to participate in this research project. The research has been explained to me and I understand what my participation will involve. I agree to the following:

(Please cross the relevant options below).

I have read the participant information letter and my questions have been answered to my satisfaction.	YES	NO
I acknowledge that participation is entirely voluntary.	YES	NO
I am aware that I can withdraw from the study at any time. I do not need to provide a reason, and this will not be held against me.	YES	NO
My data will remain anonymous (participants will be represented as a ‘code number’).	YES	NO
I give my consent to use my data for the purposes mentioned in the participant information letter.	YES	NO

……………………………………. (Signature)
……………………………………. (Name of Participant)
……………………………………. (Date)

Appendix E: Normality Outputs

Table 1

Normality Statistics for Working Memory and Demographic Variables

Variable	Skewness	Kurtosis	Shapiro–Wilk
Digit Span Forwards	−0.54	0.11	.952
Digit Span Backwards	0.57	0.39	.950*
Digit Span Sequencing	0.25	−0.52	.949*
Digit Span Subtest (Total)	−0.10	−0.23	.972
Symbol Span Subtest	−0.46	−0.26	.969
1-Back Accuracy	−0.40	−0.94	.932*
1-Back Average Reaction Time	0.66	0.47	.967
2-Back Accuracy	−0.69	−0.25	.933*
2-Back Average Reaction Time	0.92	1.05	.950*
3-Back Accuracy	0.27	−0.08	.980
3-Back Average Reaction Time	0.30	0.50	.987
Number of Languages Spoken	−0.12	−1.50	.794*
1L Speaking Proficiency	−0.90	1.01	.870*
1L Comprehension Proficiency	−1.41	2.50	.815*
1L Reading Proficiency	−1.40	2.32	.857*
2L Speaking Proficiency	−2.36	7.75	.740*
2L Comprehension Proficiency	−0.91	1.71	.829*
2L Reading Proficiency	−1.27	1.00	.821*
3L Speaking Proficiency	−0.75	−0.02	.898*
3L Comprehension Proficiency	−1.04	0.61	.892*
3L Reading Proficiency	−0.42	−0.23	.954
Socioeconomic Status	−0.35	−0.30	.905*

Notes. 1L = first language, 2L = second language, 3L = third language.

*$p < .05$.

Figure 1

Distribution Pattern of Digit Span Forwards (n = 47)

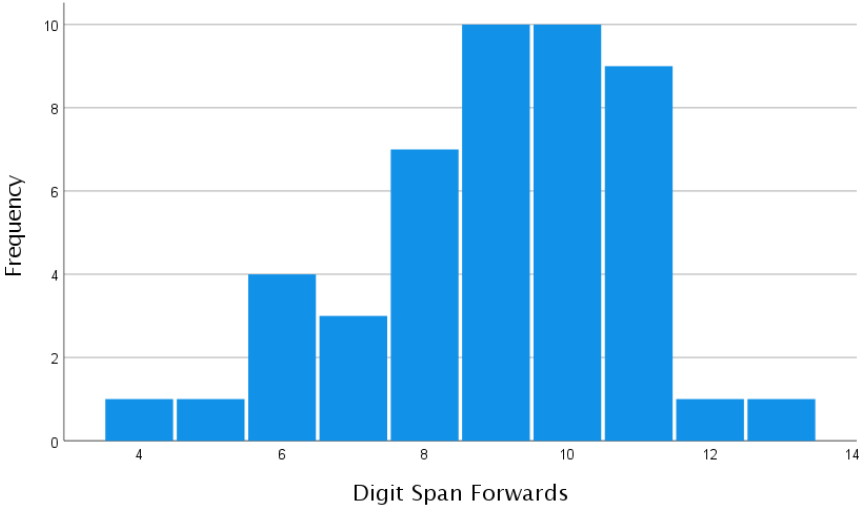


Figure 2

Distribution Pattern of Digit Span Backwards (n = 47)

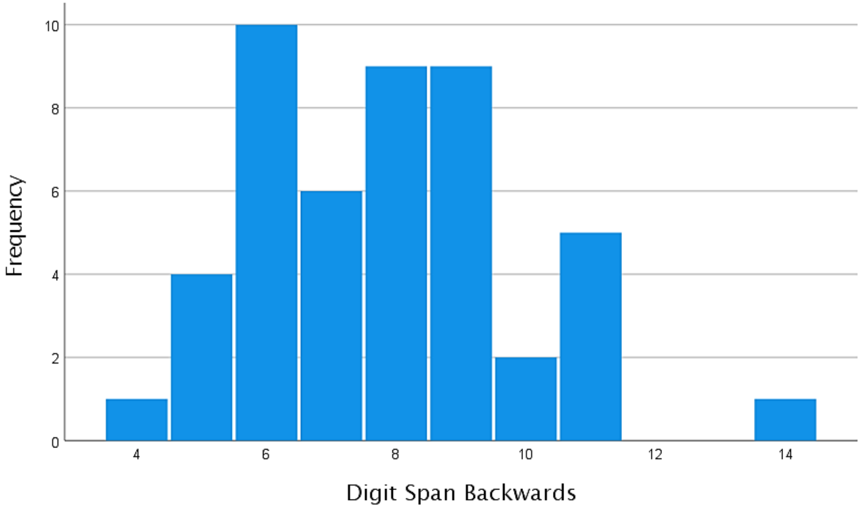


Figure 3

Distribution Pattern of Digit Span Sequencing (n = 47)

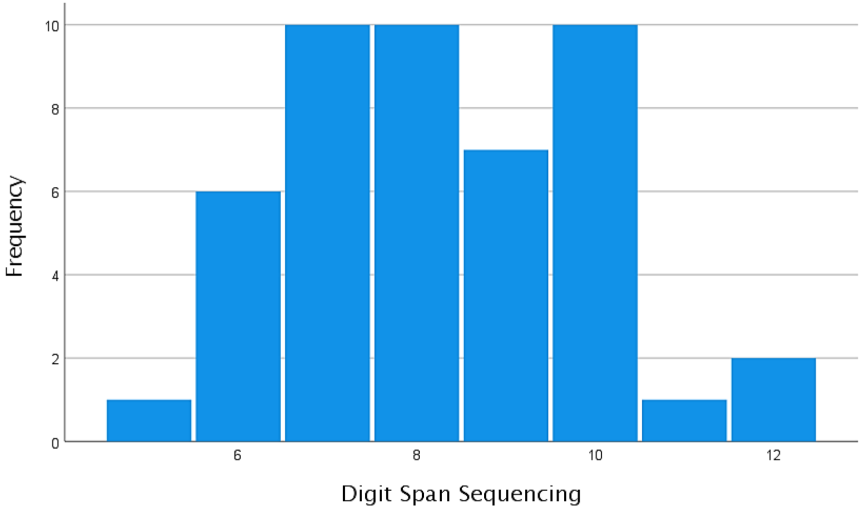


Figure 4

Distribution Pattern of Digit Span Subtest (n = 47)

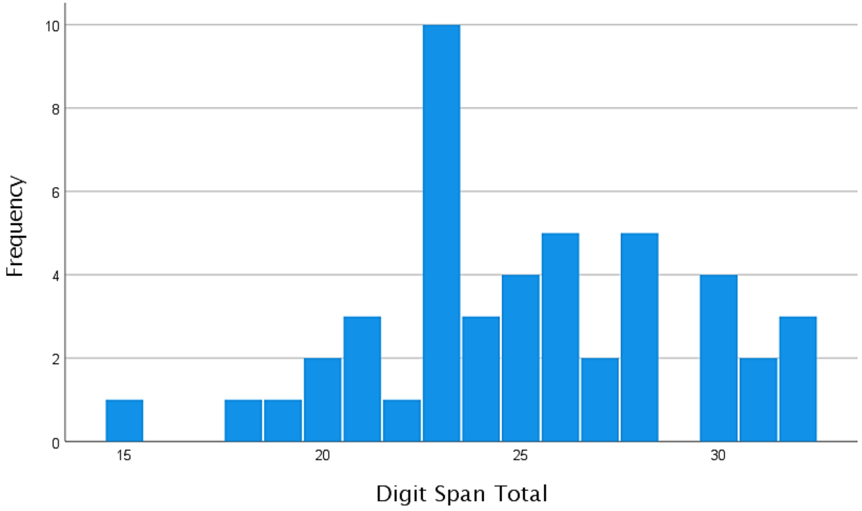


Figure 5

Distribution Pattern of Symbol Span Subtest (n = 47)

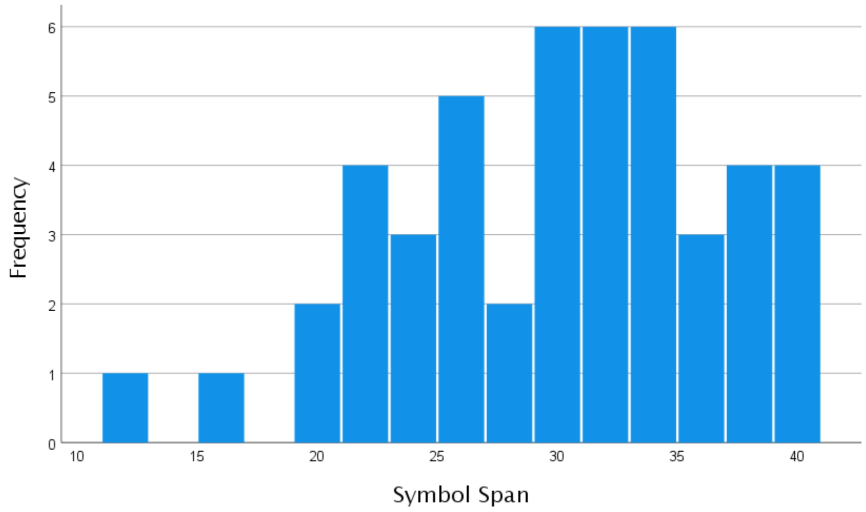


Figure 6

Distribution Pattern of 1-Back Accuracy (n = 47)

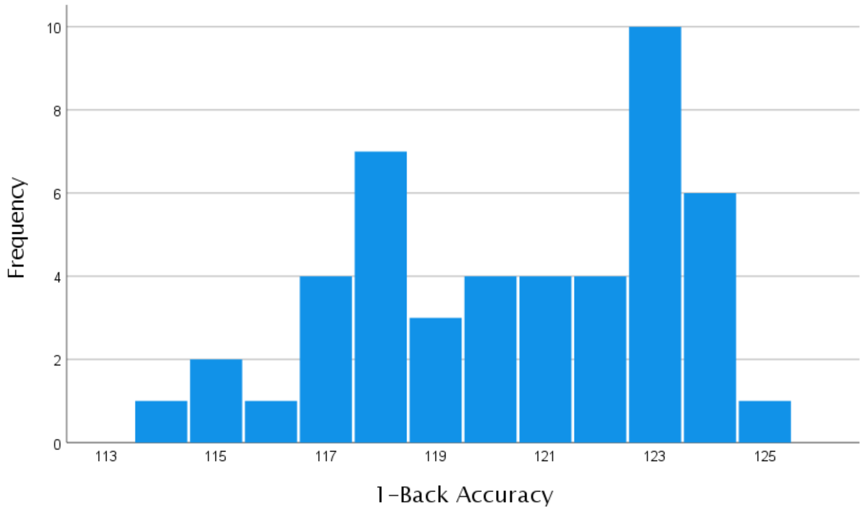


Figure 7

Distribution Pattern of 1-Back Average Reaction Time (n = 47)

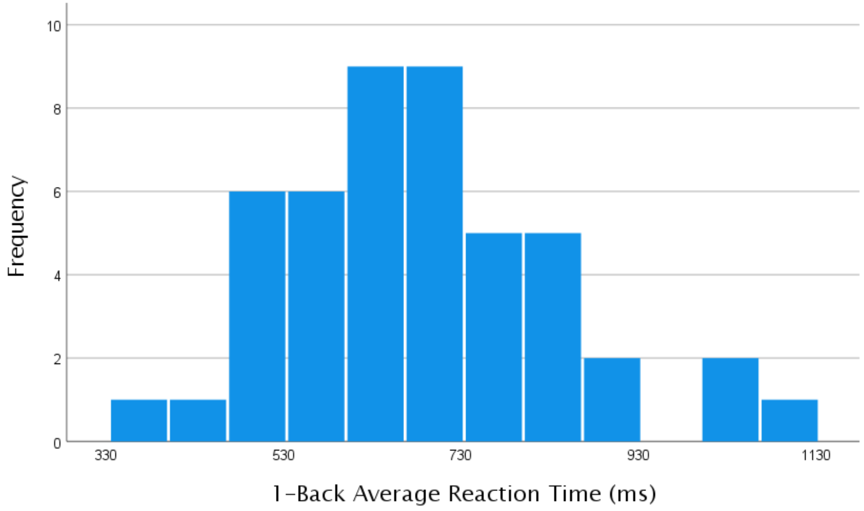


Figure 8

Distribution Pattern of 2-Back Accuracy (n = 47)

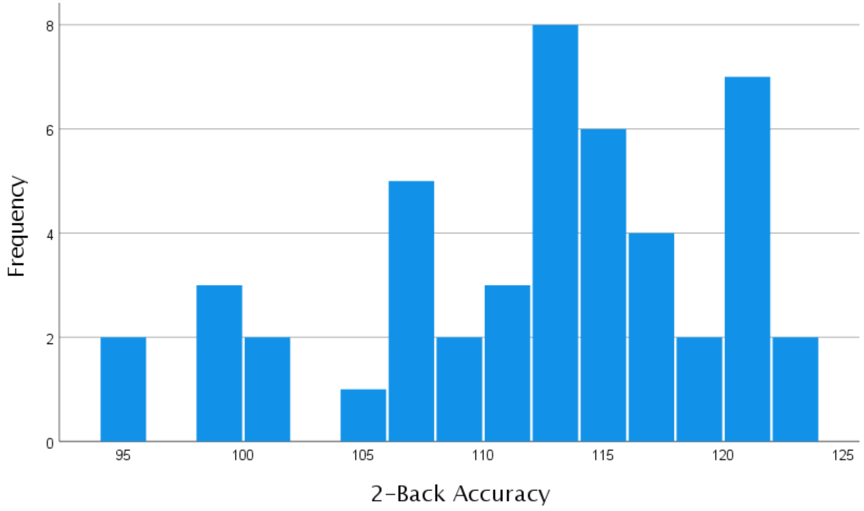


Figure 9

Distribution Pattern of 2-Back Average Reaction Time (n = 47)

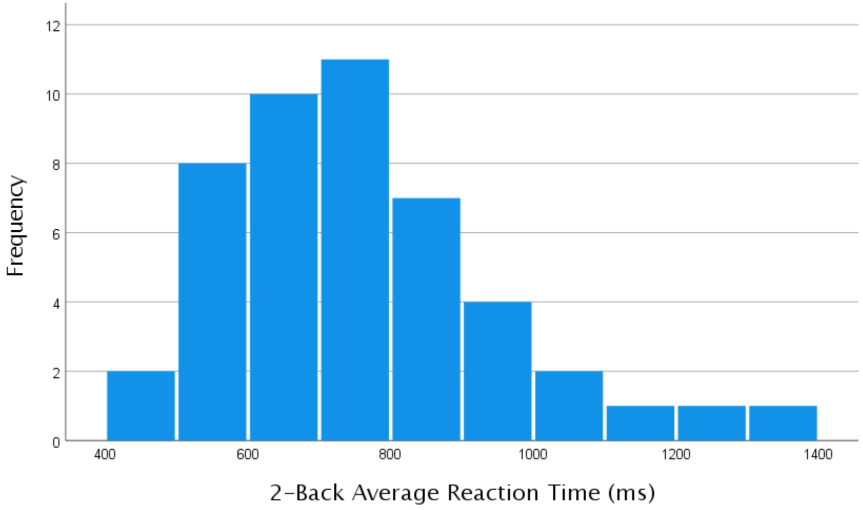


Figure 10

Distribution Pattern of 3-Back Accuracy (n = 47)

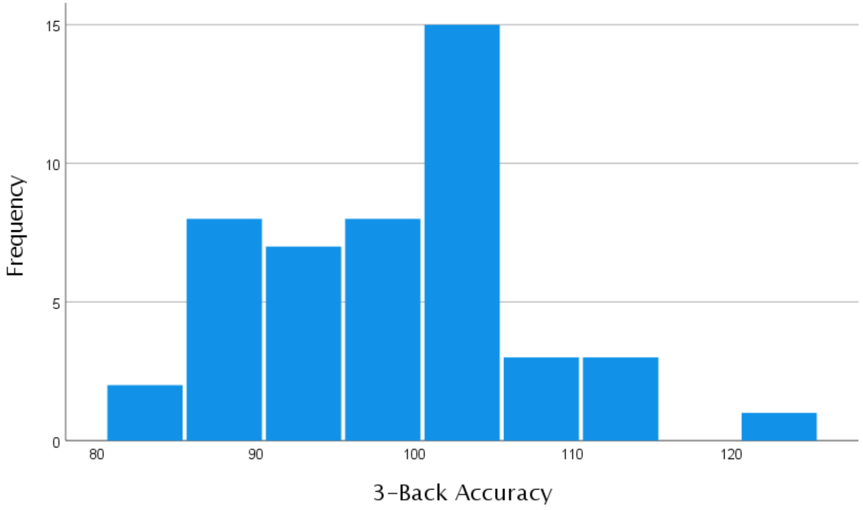


Figure 11

Distribution Pattern of 3-Back Average Reaction Time (n = 47)

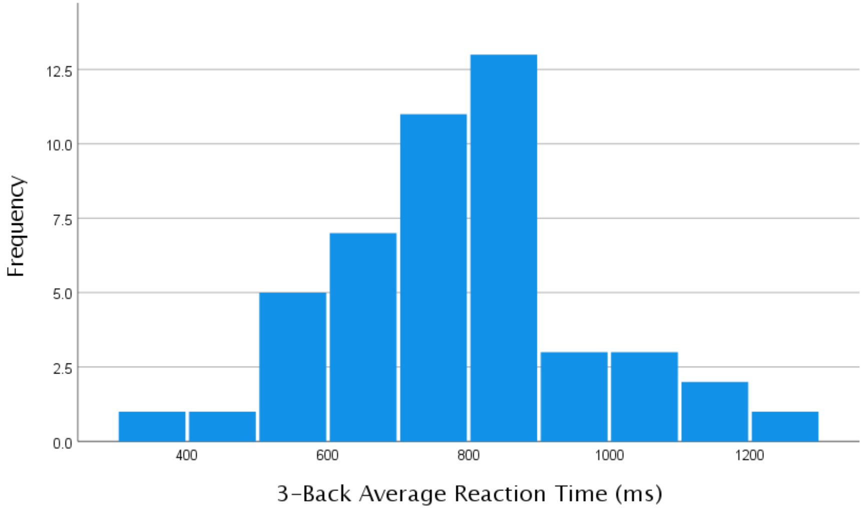


Figure 12

Distribution Pattern of Number of Languages Spoken (n = 47)

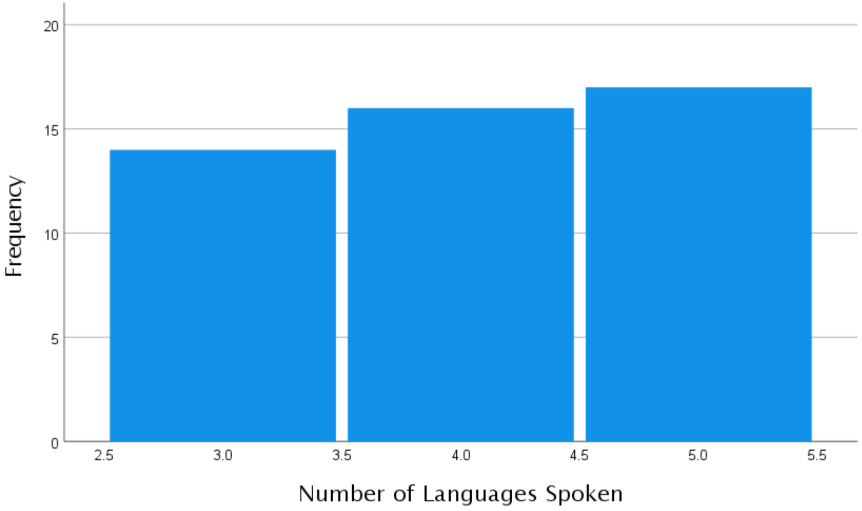


Figure 13

Distribution Pattern of 1L Speaking Proficiency (n = 46)

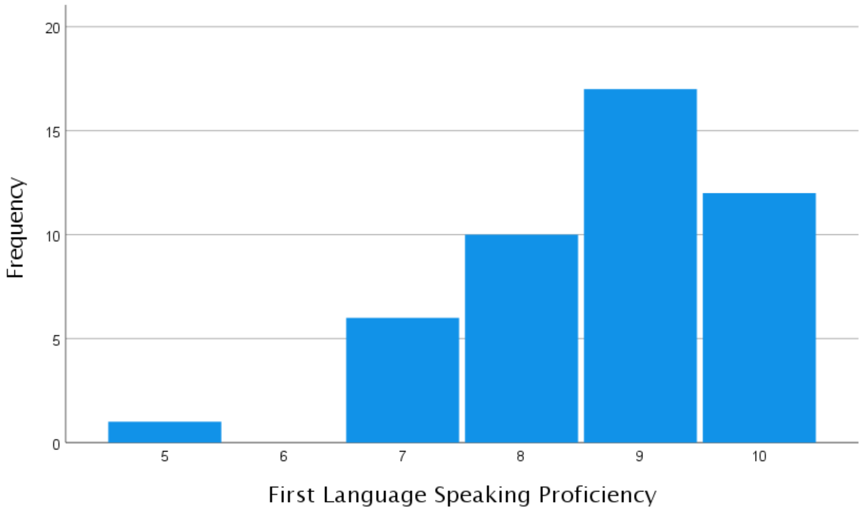


Figure 14

Distribution Pattern of 1L Comprehension Proficiency (n = 47)

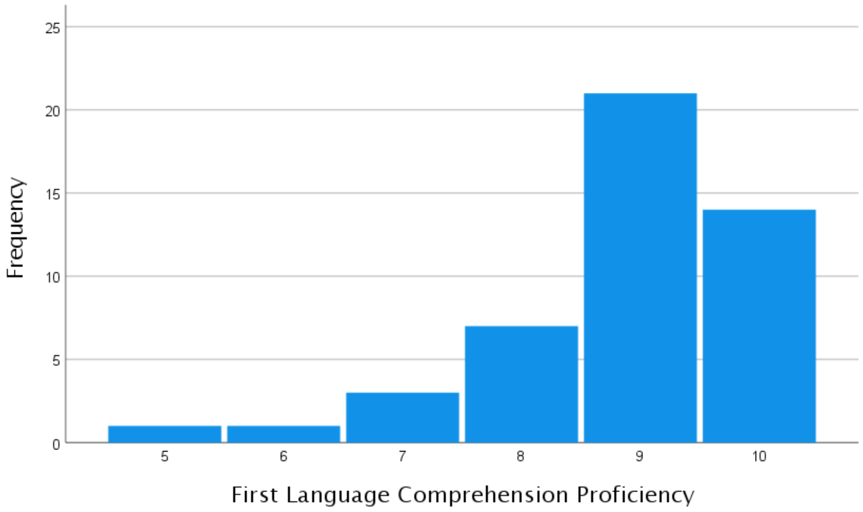


Figure 15

Distribution Pattern of 1L Reading Proficiency (n = 47)

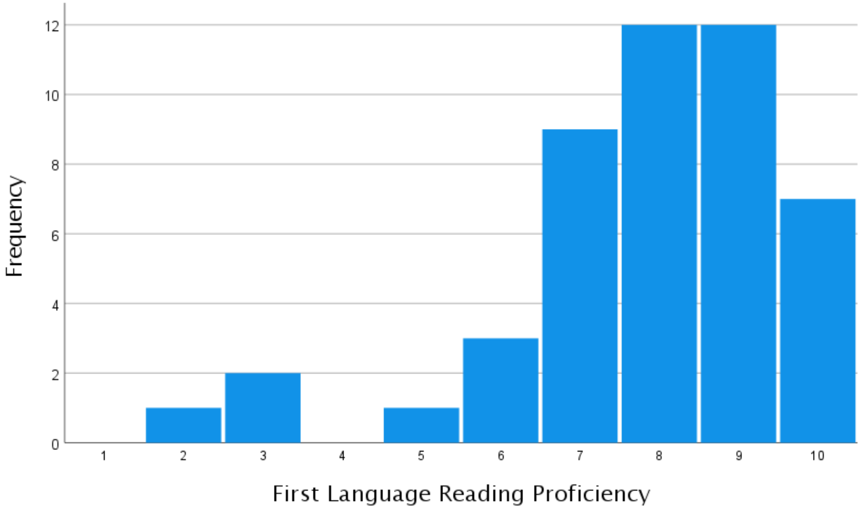


Figure 16

Distribution Pattern of 2L Speaking Proficiency (n = 47)

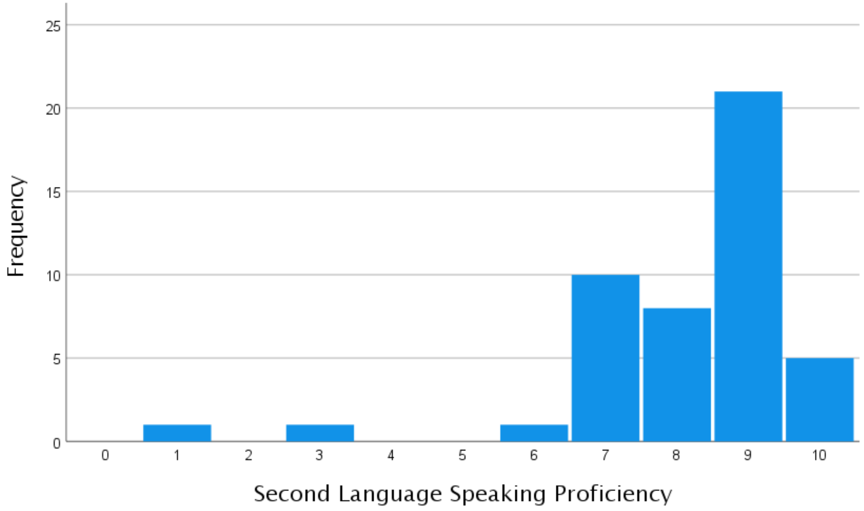


Figure 17

Distribution Pattern of 2L Comprehension Proficiency (n = 45)

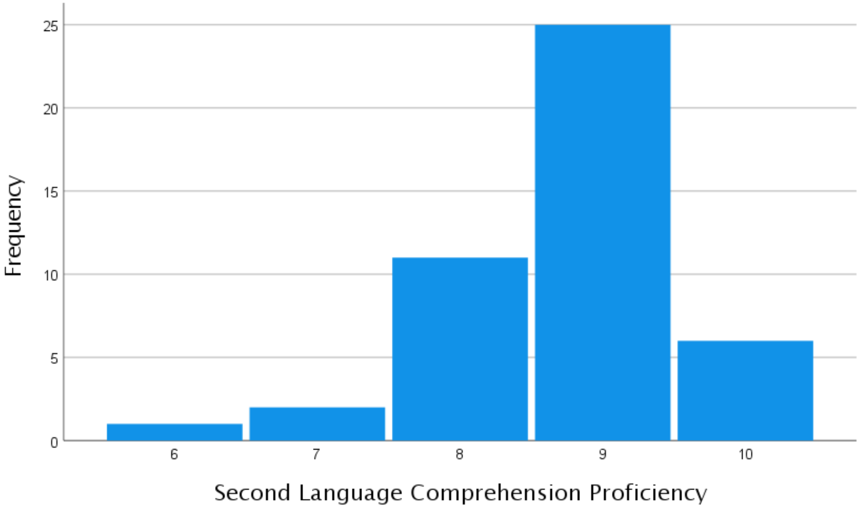


Figure 18

Distribution Pattern of 2L Reading Proficiency (n = 47)

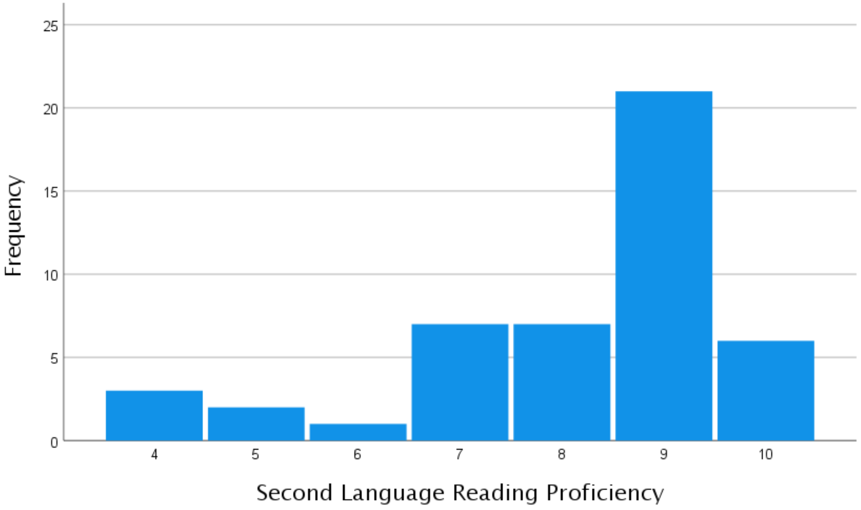


Figure 19

Distribution Pattern of 3L Speaking Proficiency (n = 47)

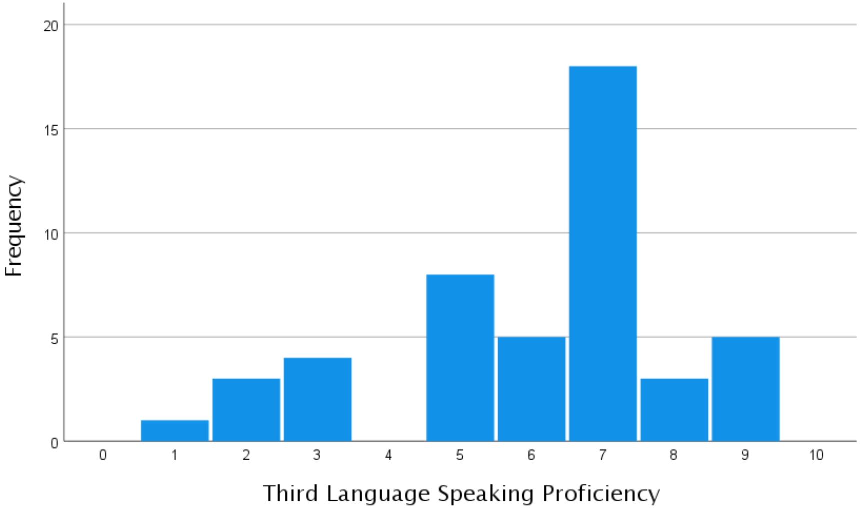


Figure 20

Distribution Pattern of 3L Comprehension Procifiency (n = 47)

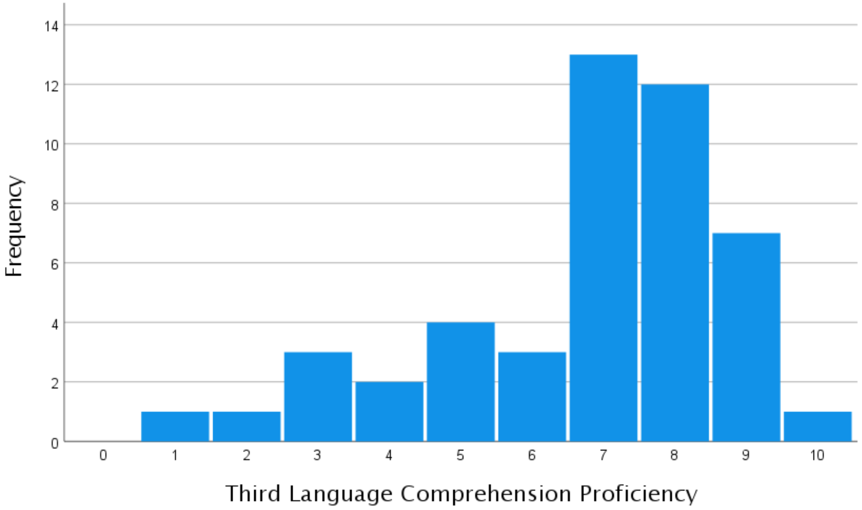


Figure 21

Distribution Pattern of 3L Reading Proficiency (n = 47)

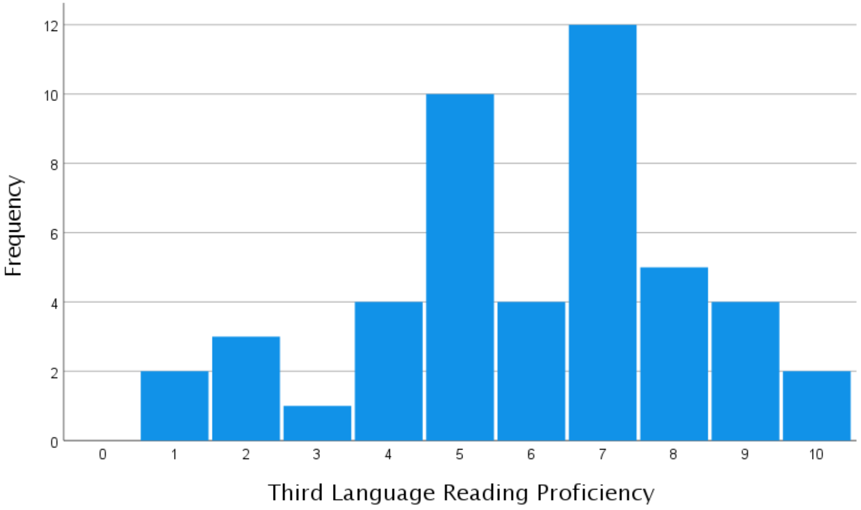
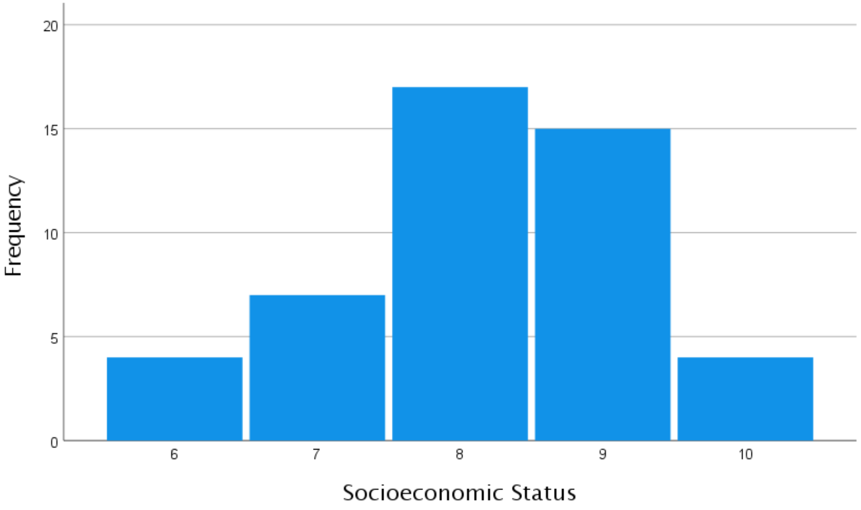


Figure 22

Distribution Pattern of Socioeconomic Status (n = 47)



Appendix F: Regression Assumptions

Figure 1

Homoscedasticity Scatterplot for DSF and DSS predicting 3-Back Accuracy

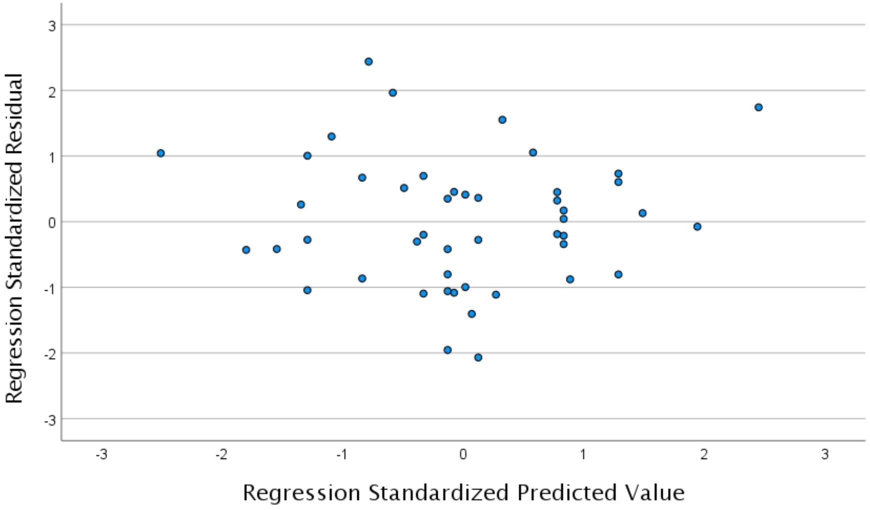


Figure 2

Residual Distribution for DSF and DSS predicting 3-Back Accuracy

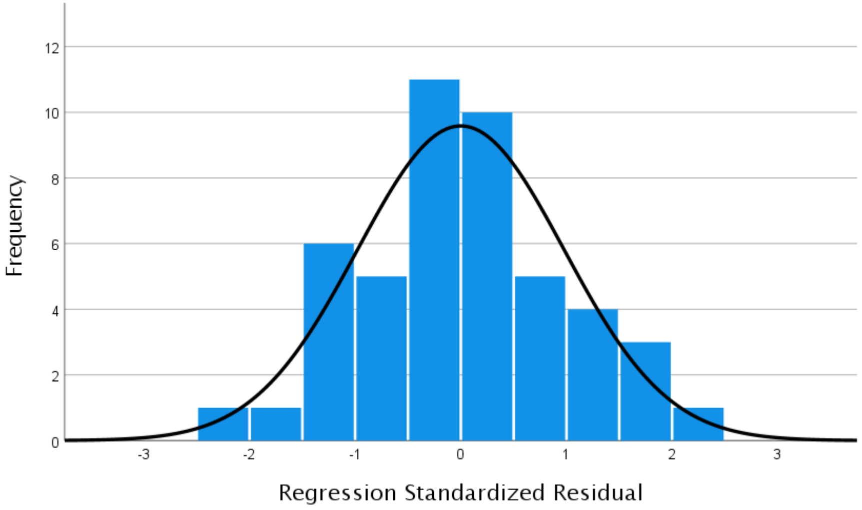


Figure 3

Homoscedasticity Scatterplot for 1LC and 1LR predicting DSS

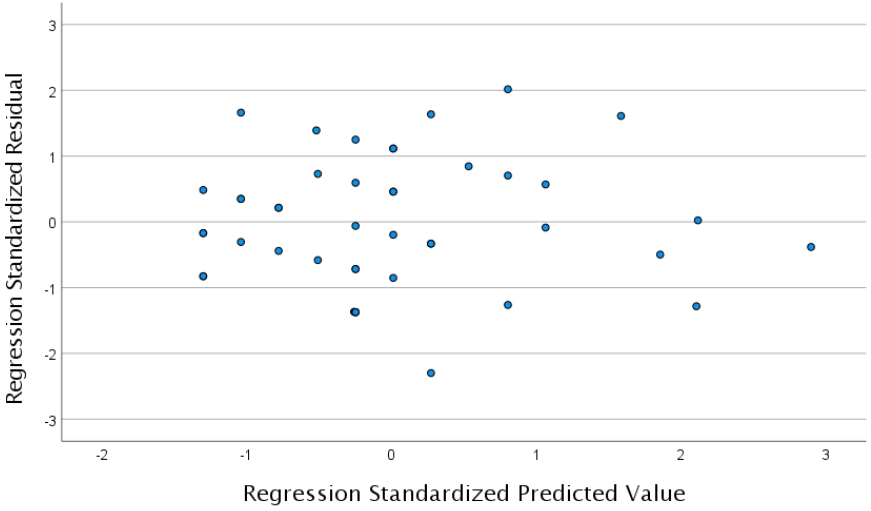


Figure 4

Residual Distribution for 1LC and 1LR predicting DSS

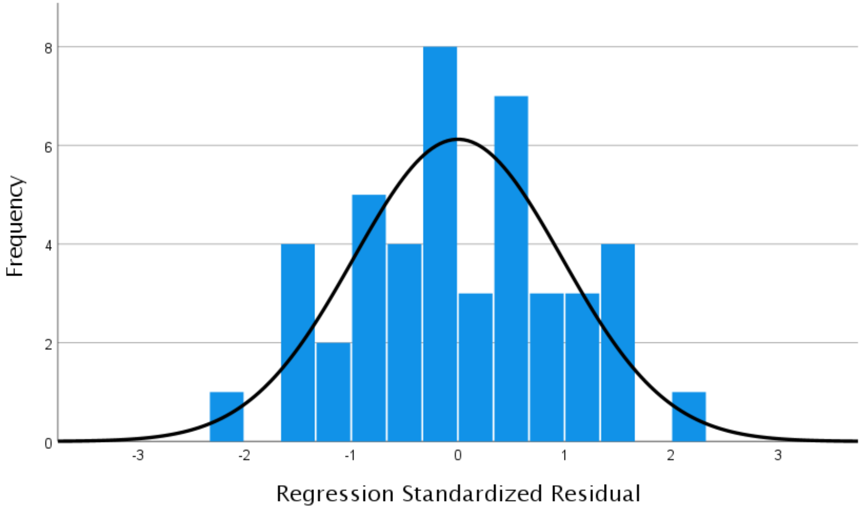


Figure 5

Homoscedasticity Scatterplot for 1LC predicting DSS

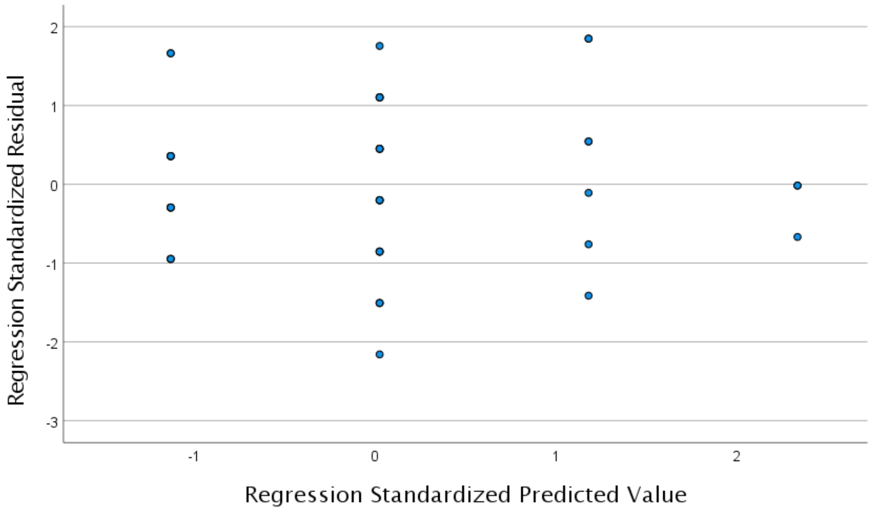


Figure 6

Residual Distribution for 1LC predicting DSS

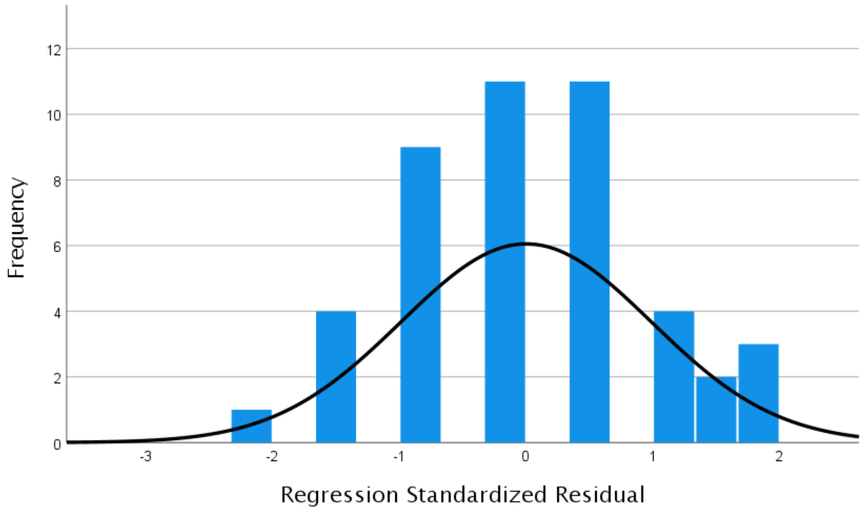


Figure 7

Homoscedasticity Scatterplot for 1LR predicting DSS

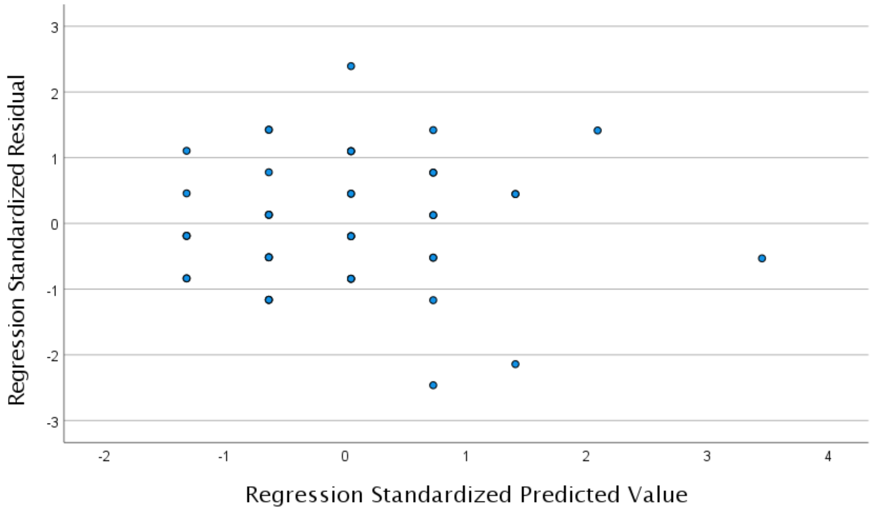


Figure 8

Residual Distribution for 1LR predicting DSS

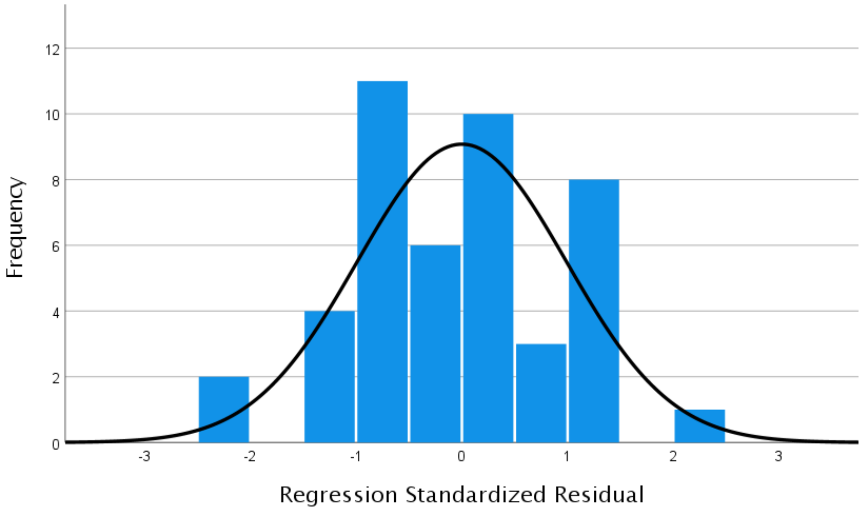


Figure 9

Homoscedasticity Scatterplot for 1LC predicting 3-Back Accuracy

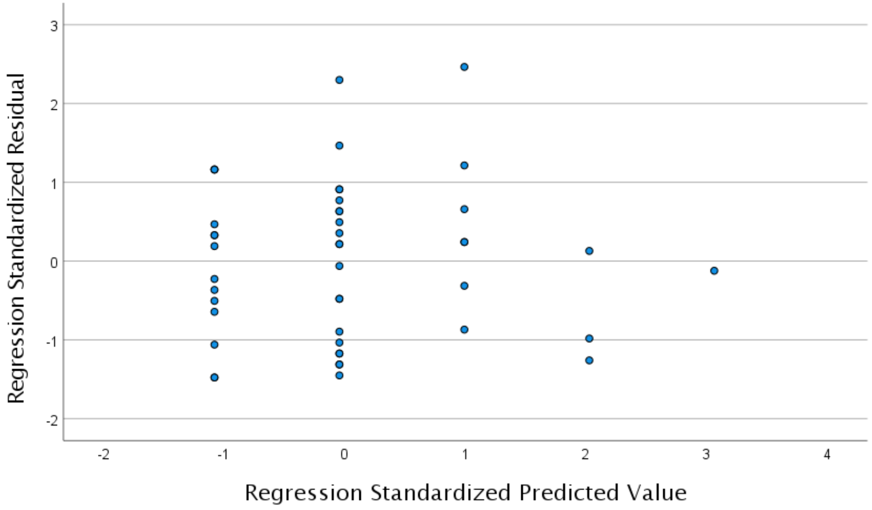


Figure 10

Residual Distribution for 1LC predicting 3-Back Accuracy

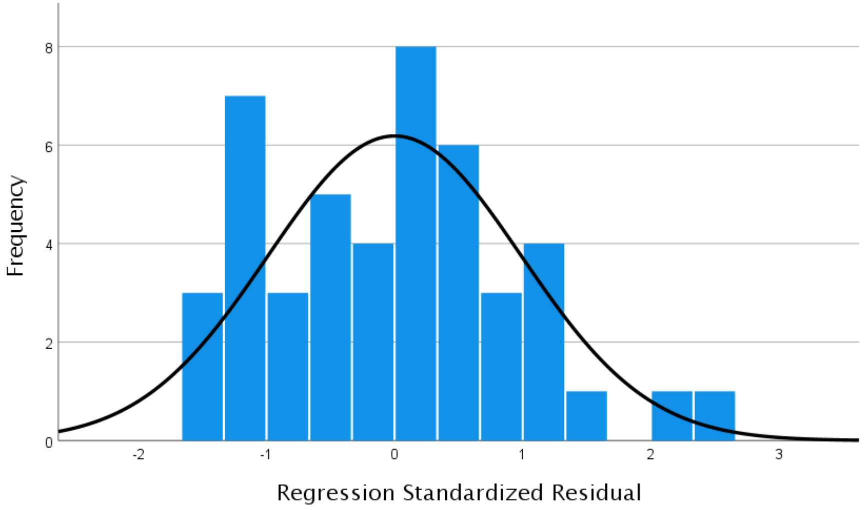


Figure 11

Homoscedasticity Scatterplot for 3LS predicting 1-Back Accuracy

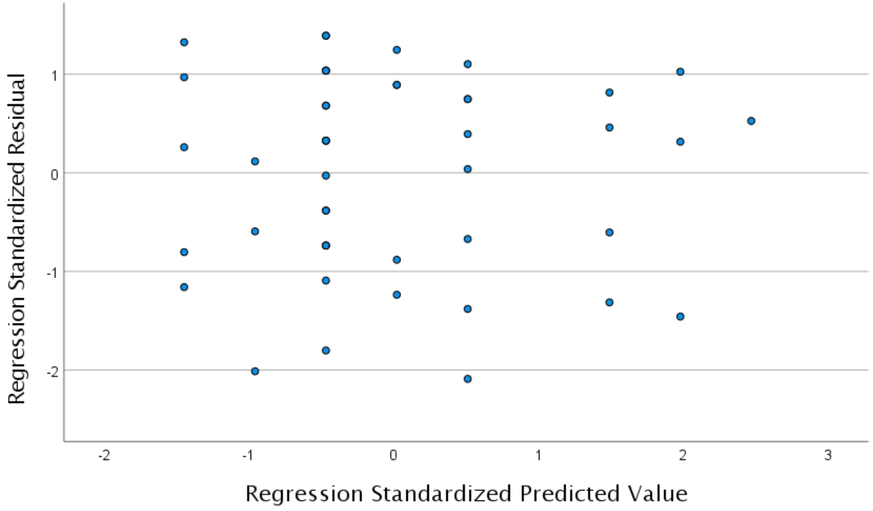


Figure 12

Residual Distribution for 3LS predicting 1-Back Accuracy