DOCTORAL (PhD) DISSERTATION

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WORKING MEMORY TRAINING: COGNITIVE AND MATHEMATICAL IMPLICATIONS IN SCHOOL-AGE CHILDREN

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Dedication

To my mom,

Hatun Boz

Thank you for always being my strength

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Chapter 1 Introduction

1.1 Background and rationale

Mathematics is an abstract symbol system that's processing is supported by working memory. The complexity of mathematics would remain elusive without a working memory framework which plays a significant role in higher order cognitive processes (Gathercole & Alloway, 2007).

Working memory (WM) is a limited capacity system which is responsible for maintaining and manipulating information over a short period of time (Baddeley, 2000). It has been studied extensively in cognitive psychology, neuroscience, and education. Its role is noteworthy in mathematical cognition and learning (Hubber et al., 2014; Bull & Scerif, 2001). Mathematical tasks involve various processes, such as understanding numerical concepts, logical reasoning, counting, and problem-solving. WM functions including storage, monitoring, and manipulation of information are strongly associated with these processes in mathematics (De Stefano & LeFevre, 2004; Raghubar et al., 2010). From an educational perspective, enhancing WM can provide a promising approach to improve mathematics education outcomes. Specifically, an interference framework of WM (Oberauer, 2001; Cowan, 2000) provides a distinctive structure to the understanding of individual differences in WM performance. WM is a limited capacity system and the interference between memory items plays a critical role in this capacity limitation as it impacts both the storage and processing of information (Oberauer & Kliegl, 2006). If the information that is no longer relevant is not suppressed, then interference with the representations of relevant items may occur while performing a task. Interference control refers to the ability to resist interference and to suppress irrelevant information during task performance. Efficient interference control can potentially lead to enhanced WM capacity. WM training programs can help reduce the likelihood of interference and perform cognitive-based tasks more efficiently (Klingberg, 2010; Jaeggi et al., 2008; Salminen et al., 2012). Therefore, WM training interventions in education may provide tools to learners to perform better in mathematical tasks.

A considerable amount of research has been conducted to interpret practical gains of WM training (Dahlin et al., 2008; von Bastian et al., 2013; Shipstead et al., 2012; Conway et al., 2011). Many of them have demonstrated significant improvement in participants' skills (Melby-Lervåg & Hulme, 2013; Lövdén et al., 2012; Brehmer et al., 2012). From this perspective, the rationale of the present research is noteworthy to investigate the impacts of targeted WM training throughout an interference framework.

1.2 Purpose and significance of the study

The purpose of the study described in the present dissertation was to discover how trained, process-specific improvements in WM performance, as defined by the interference theory (Oberauer, 2001), may contribute to cognitive-based and mathematical improvements in school-age learners. Individuals who have better ability to resist interference, as defined by interference control models, may exhibit better WM performance and potentially better mathematical skills (Kane & Engle, 2000). Therefore, another aim was to understand how the interference framework of WM characterizes individual differences in WM performance.

The findings in this study may contribute to significant domains, particularly in educational settings. First, it could advance the development of implications designed to improve WM and mathematical performance. For example, such implications would have an impact on educational practices for learners who have challenges in mathematics. All in all, connecting educational strategies with learners' cognitive abilities may result in a more comprehensive and engaging learning experience, subsequently leading to higher achievement levels in mathematics.

1.3 Outline of the dissertation

This dissertation provides different approaches to readers, beginning with an extensive literature review, followed by the description of the research design, the results of comprehensive analyses, then subsequent discussions and a conclusion. These are presented in detail across separate chapters, culminating in a total of five sections.

Chapter 1 provides a brief introduction to the topic and underscores the necessity for the current study, outlining its objectives and significance.

In Chapter 2, the literature review is presented, discussing the theoretical background of WM and the interference framework of working memory with its related components. The chapter delves into the relationship between working memory and mathematics, explores working memory training and transfer effects, and concludes with the hypotheses of the study.

Chapter 3 delineates the methodology and design of the research, employing a quantitative approach in relation to the established hypotheses. This chapter includes details on the characteristics of participants, general procedures, materials used, and the processes for data collection and analysis.

Chapter 4 presents the results of systematic analyses, supported by tables and figures, in line with the given hypotheses.

Chapter 5 discusses the findings of the current study, providing detailed interpretations connected with existing literature. This final chapter concludes with a discussion on the limitations and recommendations of the study, highlights its implications, suggests future research directions, and offers a conclusion.

Chapter 2 Literature Review

2.1 Working memory

Working memory (WM) is the system which is used for short-term storage and where information about cognitive tasks, such as reasoning, thinking, and problem solving, is manipulated (Baddeley, 1992). WM is acknowledged as a more processing-oriented construct and provides active processing and temporary storage of task-relevant information dynamically. Since WM is assumed to be a more processing-oriented and dynamic structure for temporary storage of task-relevant information, it requires a more enhanced control system for memorization strategies.

One of the most important characteristics of WM is its limited capacity, which restricts cognitive performance. To be more precise, some findings are consistent in describing capacity as the amount of items that can be hold in active processes (Miller, 1956; Woodworth, 1938), whereas other researchers, for example Oberauer and his colleagues (2007), note that capacity is not only determined by the number of items that can be maintained in WM separately, but also by the number of composite items that can be bound together simultaneously. The process of combining different pieces of information into meaningful representations is called binding. It helps to hold multiple representations as a single unit within WM. While holding and manipulating multiple bindings, interference may occur between competing representations and processes. Interference among representations or processes may enhance the challenges and constraints in overall cognitive performance (Oberauer, 2009). Oberauer’s interference framework theory, upon which this study is based, provides an explanation for the capacity limitations in WM and offers a better understanding of the role of interference control in maintaining and manipulating information in WM.

WM capacity is directly related to performance on cognitive tasks. For example, individuals with greater capacity show better performance than individuals with lesser capacity in cognitive domains, such as reasoning, reading and problem solving (Conway et al., 2007). Accordingly, understanding what constrains WM capacity is an indispensable step toward understanding the reasons of individual differences in cognitive activities (Oberauer et al., 2016). Three main theoretical frameworks have been offered to describe the basis of individual differences in WM capacity and to explain the structure and functions of WM: decay theories, resource accounts, and interference models. First, the decay and resource frameworks must be described in order to understand why the interference framework has been chosen for the present study.

The decay theory attributes limitations of the WM system primarily to time-based decay of traces held in WM (Barrouillet & Camos, 2004; Baddeley, 2003). Information is forgotten over time, unless memory traces are refreshed by rehearsal (Oberauer et al., 2016; Farrell et al., 2016). Refreshing items in memory is possible with a great deal of attention because focusing attention restores decaying memory traces (Barrouillet & Camos, 2004). With respect to the decay theory, people differ in their ability to tackle memory decay and in using strategies to avoid it, such as verbal rehearsal, while engaging in goal-directed manipulation of immediate information (Baddeley & Hitch, 1974).

Another explanation for the individual differences in capacity is provided by the resource theory which emphasizes that cognitive resources are limited and shared between storage and processing (Oberauer et al., 2016). Individual differences are attributed to differences in total capacity and processing efficiency. In this view, when resource demands of a task exceed an individual's available supply, his/her performance might be limited due to limitations in capacity (Just & Carpenter, 1992). The available resources are shared by processing and storage, thus, increasing memory load, resulting in reduced capacity for processing and vice versa. If there is a shortage in the storage function of WM, then information will be forgotten, while a shortage in the activation of the computational functions results in slower processing (Cowan, 2001).

However, decay and resource theories do not elaborate on how WM impacts individual differences in performance of complex and goal-directed tasks (Oberauer, 2009). Other factors influence WM performance, such as access to long-term memory representations, attentional control, and resistance to interference (Baddeley, 1996). Interference theory is considered a distinctive and broader perspective of WM and its functionality across various domains.

2.1.1 Interference Framework of Working Memory

Interference theory acknowledges that WM is a limited-capacity system but attributes capacity limitation primarily to interference among memory representations and processes (Oberauer, 2009). When an individual faces a flow of information, his/her limit of capacity is exceeded. This exceeding in capacity might result in limitations to hold information in memory and to update those items during the processing of new information. It eventually becomes difficult to differentiate previously learned information from the subsequently learned one. This phenomenon is called proactive interference (Jonides & Nee, 2006), where previous or current information in memory is distracting subsequent information whilst performing a task. On the other hand, when subsequently learned information interferes with the retrieval of previously learned information, retroactive interference occurs (Bower et al., 1994). New memory traces can overwrite older ones, and it becomes difficult to retrieve older information which might be suppressed or altered since the system prioritizes the recent information. Similarity between prior and subsequent items (Bäuml & Kliegl, 2013) or high cognitive load (Baddeley & Hitch, 1974; Sweller et al., 2011) can increase the likelihood of both proactive and retroactive interference in WM. Therefore, the ability to work on interference or conflict between memory traces is a key concept in learning processes. The present study focused exclusively on the phenomenon of proactive interference.

To reduce the effect of interference, active restoration is utilized for complex span tasks (Oberauer et al., 2012). In this process, active removal is required to remove maintained items that are no longer relevant. On the other hand, relevant representations must be protected from forgetting by maintenance, while providing flexibility to manipulate information in WM through updating processes which involve integrating new information into WM while replacing irrelevant information based on task-goals (Singh et al., 2018). Therefore, the cognitive control functions, namely, maintenance and updating are necessary to resolve conflict between relevant and irrelevant representations.

In recent work, it has been examined whether interference control is associated with other cognitive abilities. As an example, the cognitive processes of item-removal and inhibitory control are similar construct with interference control (Rey-Mermet et al., 2020). The item-removal process is essential to clear space for new information due to the limited capacity in WM and it also supports focusing on task-relevant information in cognitive tasks. The inhibitory process is considered different than the item-removal process, since it is assumed to suppress the possible distractors against task-relevant items. Additionally, Friedman and Miyake (2004) previously proposed that measures of interference control were related to one another and to WM performance, but not to other inhibition related factors. The different types of inhibitory processes are derived from distinct cognitive mechanisms. For instance, suppressing irrelevant response is not considered to be translated into equivalent capability in interference control, or vice versa. Here, the mechanism of automatic or prepotent response inhibition differs from interference control. According to Wilson and Kipp (1998), interference control differs from inhibition of a prepotent response in the encoding process. During inhibition of a response, actively suppressed items have been encoded in WM and active inhibition does not allow them to be retrieved by recalling (Lewis-Peacock et al., 2018). On the contrary, throughout the interference control process, irrelevant items are not encoded since resistance to interference prevents interfering items to enter WM (Hamilton et al., 2022). Therefore, these interfering items cannot be recognized or recalled easily whereas inhibited items can be recognized, but not recalled.

The terms, interference control and resistance to interference are cornerstones of this dissertation and these terms are described as the capability to resist irrelevant information and distractors in a given task (Nigg, 2000). Interference theory points out that the ability to resist interfering information is a key element in updating WM contents and is a source of individual differences in WM performance (Cowan, 1995).

Poor performance in WM is due to inadequate control of irrelevant information (Hasher & Zacks, 1988). Information must be suppressed when it becomes no longer relevant, otherwise it is inevitable to interfere with representations of relevant information and instead of target items, irrelevant information will be recalled (Palladino, 2006). Then, these relevant and irrelevant representations compete for limited access in WM during the process in which individuals resist the irrelevant representations to have access in the first place instead of relevant items or to remove them once they have obtained access (Hasher et al., 2007; Unsworth & Engle, 2007). Individuals who are able to efficiently control the processes of their memory show better performance on higher-order cognitive tasks than individuals with poor control abilities (Unsworth, 2010; Friedman & Miyake, 2004). These higher-order tasks involve the complex tasks where strong cognitive skills, such as reasoning, decision making and problem-solving are required. For instance, while performing a complex mathematical task, individuals must hold multiple steps and items in WM. Efficient interference control can help them reduce cognitive load of this task (Engle & Kane, 2004). Therefore, interference control is an essential construct of individual differences for cognitive abilities.

The interference model incorporates “a concentric structure of representations with three functionally distinct regions.” (Oberauer, 2002, p.412), which represents different levels of processing. This structure is conceptualized as activated long-term memory, region of direct access and focus of attention (Oberauer, 2009; Cowan, 1988; 1995). The working memory system decides whether the incoming information is relevant with recently encoded items or related content in long-term memory, or not. Here, recently encoded stimuli are compared to related content in long-term memory for processing after which judgements are made related to the task goal (Oberauer, 2002). WM representations as defined in this theory incorporate not only singular items, but also chunks of information and operations that can be individually accessed as task goals change (Oberauer & Hein, 2012). For instance, in an addition task, if a person sums up a three-digit number with any number, then not only do these digits need to be held in focus, but they also have to be linked to the place values (hundreds, tens and ones) of digits (Oberauer, 2002).

Oberauer's (2009) three components of WM and their roles in the WM system are summarized below. The results from an experimental paradigm, which provides evidence for the three distinct levels of this model and shows how active representations at each level may interfere with an ongoing process/task are also described. Finally, mechanisms of the declarative part of WM system that enable changes in activation level of representations and support resistance to interference among these representations as their relevance to the task goal changes are specified subsequently.

2.1.2 Activated Long-term Memory

Activated long-term memory is conceptualized as a subset of the network of representations in long-term memory that are held active during a task. Long-term memory supports the functioning of WM in two different processes: activating currently relevant items and receiving new information which can be retrieved into WM. For example, related sensory information or a specific task which needs related information to be recalled can activate the long-term memory items. This activation triggers a priming effect in which the availability of activated representations corresponds to perceptual stimuli that are primed to be recognized and processed. With this functionality of the system, new information which conforms with recently activated representations can be processed more efficiently (Oberauer, 2009). A higher level of activation enhances the speed of retrieval of these representations (Anderson & Lebiere, 1998), resulting in faster recognition and increased accuracy during task performance (Oberauer, 2009).

The degree of activation of representations in long-term memory determines the fluency in processing where new stimuli match recently activated memory items in WM (Oberauer, 2002; 2009). The increase in processing fluency depends on familiarity which is associated with novelty of items in use. In this process, a response is produced with familiarity signals to stimuli for recognition judgements. Ericsson and Kintsch (1995) demonstrated that if the tasks or knowledge are highly familiar, the access to long-term memory is effortless and immediate. Specifically, the category comparison tasks (Woltz & Was, 2006; 2007), as an example, showed that increased availability of long-term memory items occurs when memory operations are reinforced by repetition. In these experiments, the tasks represented memory set items or category items from a category not encountered before. As a result, the tasks were performed more accurately and faster when items from the same category were primed rather than unprimed.

Items are not always active in the long-term memory even though the long-term memory is not limited in capacity. Activation is affected by many factors such as recent usage of the items and relevance to the task. These items in long-term memory can be inaccessible if they are not activated, as explained by either the decay or the interference theory. Items decay in WM without rehearsal or other repetition processes. (Baddeley, 1997; Baddeley et al., 2014). Interference theory, as defined above, suggests that if WM is distracted by the encoding of new information into long-term memory or by previous memory traces when retrieving the relevant information, this may lead to interference errors and slower processing (Jonides & Nee, 2006; Oberauer et al., 2012).

2.1.3 Region of Direct Access

The region of direct access is where information is held temporarily in a directly accessible domain. A limited number of items or chunks of information are maintained in the region of direct access to be processed during a current task performance (Oberauer, 2002). In the view of this model, it is asserted that capacity limit stems from two different mechanisms of interference: one of them is competing representations of content items (Oberauer & Kliegl, 2006) and the other one is conflict between these competing items which have a similar cue or share features with each other (Oberauer & Lange, 2008). Competition between content items in the region of direct access occurs when one of the items is retrieved selectively from excluded items. On the other hand, items retained in activated long term memory do not generate competition since they are not selected with focus. Competing items which share features with each other lead to conflict among these items because they might overwrite each other's features of primary memory traces. Therefore, when those features match in later ongoing activities, interference between similar items occurs (Nairne, 1990). Several studies demonstrated this interference effect in a given task. For example, semantically similar words (e.g., cat and dog) are used to illustrate how introducing new words (e.g., tiger) which are similar to the original word list (e.g., "cat", "dog") may lead to errors in recall because of interference among items from the same category (e.g., animals). These words share similar context, therefore distinguishing them from each other during recall may be difficult (Craik & Tulving, 1975; Bower, 1981). Additionally, phonologically similar words (e.g., cat and bat) may interfere with each other more than dissimilar words as well (Baddeley, 2003).

Multiple representations may share a conceptual framework and may temporarily be bound to a common coordinate system where they are aligned in a form that creates direct access. In other words, different pieces of information that are stored in WM separately can be bound together temporarily to create meaningful connections – like the numbers 4 and 8 which belong to the category of multiples of 4 or even numbers. These connections may facilitate quick access to those items during recall. A representation can activate related information that is bound to the same coordinate system and this system is considered to establish and hold interim binding between contexts and contents (Oberauer, 2002; 2008). For example, in the word lists mentioned above, the content is the words to be remembered and the context is their position in the list. Binding relates to information about correlated features of contents, creating an integrated event or object jointly and about included part of event or object in presently relevant memory items (Oberauer & Lange, 2009). When items become accessible in the region of direct access, these items can be selected for the focus of attention regarding their content and context in that coordinate system. Items are retrieved from the region of direct access into the focus of attention either by familiarity or recollection in the process of recognition decision (Oberauer, 2009; Oberauer & Lange, 2009). On the other hand, unbinding which refers to the process of disentangling bound items helps with the updating mechanisms to adjust new information (Oberauer, 2005).

Additionally, old information in the region of direct access can be replaced by new information during updating, however, flexibility is required for the binding and unbinding of contents to their contexts in the region of direct access (Oberauer et al., 2007; Oberauer, 2009). WM mechanisms enable us to hold and maintain information, as well as update it to place new ones in a structure that serves stability and flexibility simultaneously (Kessler & Meiran, 2008). Flexibility provides a great balance between the process where representations must be maintained and the process where these representations must be replaced by new ones (Halford et al., 1998). In that case, items in an irrelevant list are removed from region of direct access or relevant and irrelevant lists are differentiated based on the binding between items and their contexts in the region of direct access. This process which will be described below is also important to maintain information and replace it with new information (Szmalec et al., 2011).

2.1.4 Focus of Attention

The highest activation level in the interference framework of WM is the focus of attention. The key role of the focus of attention is to select the target information which is held immediately in the region of direct access and used for cognitive operations. The focus of attention selects only items which are available in the region of direct access (Oberauer, 2002). The contents of the region of direct access are considered as the selection set (see Allport, 1987) for the focus of attention, where only a small set of items can be brought into the focus (Oberauer, 2009).

The function of the focus of attention is observed in simultaneous tasks where both the storage and processing of information are needed at the same time (e.g., Oberauer et al., 2001). According to Cowan's model (1995), when memory contents must be accessed during processing, an influence of the memory set on processing is noticed since either all items from this set enter into the focus of attention as a chunk or only a single element is selectively brought into the focus of attention. However, if there is no need for accessing the memory set during processing, the set can be maintained in the activated long-term memory (Cowan, 1999). For instance, a larger set of items contributes to a slowness in selection of items due to their interference with each other. In this process, temporarily irrelevant items held in the activated long-term memory can be outsourced later if they are needed (Oberauer & Hein, 2012).

Another specific function of the focus of attention is to create new chunks during processing when binding items to new formation is required in the task (Cowan et al., 2008). For example, in the running-addition task (Oberauer & Hein, 2012), when a person holds the running sum of a three-digit number from the previous arithmetic operation and then adds another number to it, the result of this operation is held in the focus of attention within its place (i.e., hundreds, tens and ones).

The focus of attention is limited to chunk capacity (Cowan, 2001; 2005; Oberauer, 2002; 2005). According to Cowan (2001), a focus of attention can hold 3-5 items, whereas Oberauer (2005) supported that a focus of attention can hold only one item. However, recent research has demonstrated that the focus of attention cannot be restricted to only one item (Oberauer & Hein, 2012). For example, arithmetic operation of two separate digits requires two items being simultaneously accessed in the focus of attention (Oberauer & Bialkova, 2009). Despite these mixed suggestions regarding the number of items that can be held in the focus of attention, researchers agree that its capacity is very limited.

There is evidence for these three activation levels of information from several empirical research studies (e.g., Oberauer & Lewandowsky, 2008), such as the activation of information with different contents of WM. The activation of information can also be defined with the phenomenon, so-called object-switch costs (Garavan, 1998; Oberauer, 2003) that the focus of attention needs to select a new information from the cluster maintained in the region of direct access. This finding suggests that the longer the relevant list (Oberauer, 2003), but not the irrelevant one (Oberauer, 2002), the greater the increase in object-switch costs occur in the operation. Object-switch costs are linked in a cognitive operation when an item from the cluster is being retrieved or updated (Oberauer, 2003).

To summarize, the WM system has been identified within the interference framework as activation states in which cognitive activities are executed to hold and manipulate information actively. For this process of information, the functions of attention and long-term memory have been incorporated into different models and the mechanisms that describe the functional structure of WM and elements for resisting interference at different stages. In this construction (see Anderson & Lebiere, 1998), a set of items can be held in the focus of attention while representations of other items are simultaneously activated in long-term memory (Oberauer, 2002). However, since these active representations are also competing with each other to enter the capacity-limited region of direct access, they may interfere with ongoing selections of representations relevant to the task goals (Oberauer, 2006).

This incorporation into the WM system is crucial for a deeper understanding of the interference control mechanisms. Moreover, comprehensive interpretation of the interference model requires consideration of additional mechanisms, such as binding and updating. These

WM functions contribute to the individual differences observed in performance on complex cognitive tasks.

2.2 Binding and Updating: Mechanisms to Resist Interference in WM

Binding is a mechanism by which new connections are built and maintained in complex activities with unified representations of a component (Oberauer & Lange, 2009). Content and context of information are integrated to create structural or relational representations in WM (Wheeler & Treisman, 2002). The system where activated representations form a new relational representation corresponds to context for binding content representations to spatial or temporal positions (e.g., words linked with list positions), or a *"schema"* for binding content items to slot (e.g., *"words bound to a syntactic schema or numbers bound to roles in an equation"*) (Oberauer & Lange, 2009, p.104).

When temporary bindings in these tasks are being perpetually updated, new mechanisms are constructed and held with these newly formed bindings. It is assumed that they are built and held between contents (e.g., objects) and context (e.g., positions) by the region of direct access where old items are replaced with new items concurrently with updating (Oberauer, 2009). Therefore, dynamic binding is required for the mechanism where the new construction is set up and maintained in WM by integrating it with its representations. In this view, bindings must be quickly built and dissolved again when the representations are updated or discarded (Oberauer & Lange, 2009).

Binding is described related to its level. Low-level binding relies on components or features combining to create an object or event (Wheeler & Treisman, 2002). For example, the combination of visual features corresponding to an object, such as its color and size, requires the recall bound features that are important to remember which features are connected. Similarly, binding is necessary to prevent incorrect combination of phonemes and syllables to form a word (e.g., Treiman, 1995). On the other hand, high-level bindings represent the content determining which objects or events belong to the currently relevant context, for example recalling a list of items in a serial order (Oberauer & Lange, 2009).

Temporary bindings in the region of direct access build a structure for representations and their relations. The binding functions, such as forming and holding new structures, reflect the capacity of WM (Wilhelm et al., 2013; Oberauer et al., 2007). Since the region of direct access supplies a workspace in which those processes are maintained and manipulated during the tasks which require higher-order cognitive skills, such as decision-making, reasoning and problem-solving, its limited capacity can hinder the complexity of those processes or representations (Oberauer et al., 2007). One source of WM capacity limitations is associated with interference between temporary bindings (Wilhelm et al., 2013). When different contents of information share common features and directly get accessed in WM, the overwriting of common features of different contents in the region of direct access contributes to representational interference which causes similar items to be indistinguishable from each other (Nairne, 1990; Oberauer & Kliegl, 2006). For instance, if two sequences of numbers have the same amount of numbers and share similar elements that need to be memorized, the similarity of these elements can create interference which leads to difficulty to recall the order of numbers in each sequence. The numbers might be remembered but not the sequences they belong to, especially the position of common numbers (Barrouillet & Lépine, 2005). Additionally, retrieval competition is assumed as a source which increases interference in the region of direct access (Oberauer & Kliegl, 2001). Retrieval of a specific content item cued by its context becomes difficult with a larger number of content-context bindings competing with other contents bound to currently relevant contexts.

There are many research studies which have been done in laboratories for such tasks in line with the binding framework of WM. One of the findings asserts that differentiation of relevant representations and irrelevant ones stems from their bindings to their context, but not content (Oberauer, 2005). For instance, in order to process a sentence such as, *"The parrot beats the sheep with a cucumber."* (Oberauer, 2009, p.52) the content item *"beats"* is bound to its category of verb, which enables the WM system to establish connections among verbs, objects, agents, etc. Categorizing "beats" as a verb helps distinguish between different elements of information when the sentence has complex and/or unusual form. For instance, categorizing the numbers, as discussed previously, is a similar process to distinguishing between different sequences and remembering their positions in each sequence. Here, the context can serve as a cue to allow a content item to be retrieved for completing the task goal (Artuso & Palladino, 2011). The phenomenon of information categorization was modified from Sternberg's (1969) recognition task. In this task, subjects were presented with a set of information (e.g., letters or numbers) and asked to determine whether a given item was in that set. The task examines the mechanism of recognizing information in WM and provides understanding of how information is processed and organized in WM. Both Oberauer's and Sternberg's tasks demonstrate that categorizing or structuring information efficiently can provide quick recognition which reduces possible representational interference. Sternberg's task also provided a foundation for further study on the removal process of irrelevant representatives from WM (Oberauer, 2001). This study (Oberauer, 2001) examines the dynamic mechanism of WM to understand how relevant information is processed and maintained by expelling information which is longer needed in the current task. This process provides focus on current tasks without interference from irrelevant items. However, an item might be removed from WM, but its representation may still be available in the activated long-term memory since removed representatives are unbound, but not deleted (Oberauer, 2009). Here, unbinding prevents accessibility and relevance of the item for the immediate task. Therefore, its representation can remain activated in long-term memory for a period, even though it is no longer available in an inactive state. As an alternative, the active item-wise removal approach has been assumed as the new model of interference control in the account of maintenance and updating of WM (Ecker et al., 2014; Chang et al.,2017). This model focuses on a more selective process for identifying and removing specific items that are no longer relevant to a current cognitive task. In this process, the overload in WM is reduced and the resources in WM become available for new information.

Among the WM functions crucial for processing information, the ability of WM updating is most essential for rapid cognitive control in high-level cognitive tasks. According to Morris and Jones (1990), WM updating resides in "modifying the current status of a representation of schema in memory to accommodate new input" (p.112). However, the functions of updating vary in different tasks and situations, where current content must be replaced with new one or old content must be modified with respect to new input (Kessler & Meiran, 2008).

Some recent research shows evidence on the processes of updating to protect WM contents from interference. For instance, Kessler et al. (2023) supported that while WM is required to protect the maintained information from interference, it must also update its mechanism where context in WM is maintained but content bound to it is updated for each trial throughout a task. The balance between shielding existing information and updating serves effective WM functioning. Kessler and Meiran (2006; 2008) previously debated about the availability of two separate processes of updating. According to their theory, while one process, referred to as a local process deals with relevant items to modify them, the other, which is a global process, is engaged in replacing all or most of current information with new content. In detail, local updating process involves making focused modification or adjustment to specific pieces of information for a current task in which a complete restructuring of overall content in WM is not required but rather a targeted restructuring. Due to this fact, this process is faster and demands less effort in a cognitive task. On the other hand, in the global updating process, overall information currently held in WM is restored to adapt new contexts or tasks. This process is slower than the local updating process and contains higher cognitive demand, as more cognitive effort is required to displace the existing structure and establish a new one in this process. The capability of engaging in both processes enables individuals to switch between tasks depending on their difficulty and adapt cognitive flexibility.

Likewise, Bunting et al. (2006) supported this idea to prevent items from interference with rehearsal during updating. Each item, carrying different information, is held in WM separately and updated with the process of selective access and retrieval. Updating needs to be specific to keeping items in WM independently and make decisions about which one needs to be kept and which one needs to be removed or replaced to adapt to the new information. This process, which is also supported by Vockenberg (2006) is called a local updating process (Kessler & Meiran, 2008). For example, an individual is asked to remember a sequence of a set of numbers which are given as 2, 5, 7, 8 and then he/she is informed that the second number in the sequence is not 5, it has to be 4. He/she adjusts the sequence in WM from 2, 5, 7, 8 to 2, 4, 7, 8. The modification here is a local updating where an individual updates only one item instead of changing the rest of the sequence. After completing the task to memorize the sequence 2, 4, 7, 8, he/she is asked to remember the actual sequence 8, 3, 5, 6, which is completely different than the previous task. He/she must discard the original sequence entirely from WM and replace it with the new one which is 8, 3, 5, 6. Since the original sequence is no longer relevant, the individual displaces it to embed the new number set in his/her WM.

Furthermore, it is asserted that all items in WM are required to be updated as a whole, with respect to global updating processes, when any of these items are being modified (Kessler & Meiran, 2006). The last step of WM updating requires creating a global representation of items. In accordance, the modification of any item in WM entails instability in a unified system. Within the global updating mechanism, a unified complex representation is formed by binding each item with its context and hence, this process reflects restabilization of modified items (Kessler & Meiran, 2008). The entire mechanism requires reevaluation and adjustment even though a single item is changed. This approach ensures that all items in WM become compatible for efficient processing when they are rearranged and integrated within global updating.

Besides the WM updating functions mentioned above, another important factor in the building of bindings and updating information is to support activation and recognition of target information (Oberauer, 2009). Recognition refers to the decision process that is mobilized when we have to decide where an item or event has occurred in the past. Traditional measures of short-term memory and WM include this aspect. According to dual process models of recognition, familiarity and recollection are two dissociated processes involved in making this decision (Jacoby & Dallas, 1981). However, they operate correspondingly during item recognition even though they are separable processes.

2.3 Familiarity

Familiarity is based on the identification and activation of items in long-term memory during the recognition process. Recognition in memory derives from the assessment of familiarity and from the retrieval of a set of structural information that also involves its associated items (McElree et al., 1999). This structural information involves contexts and relationships between items helping deep and more decisive retrieval. Due to its interaction with how recently information was in use, a response to a stimulus can create a familiarity signal and then in recognition decisions, this signal becomes a source of information (Oberauer, 2009). A form of response relies on the strength of familiarity values. In research (Atkinson & Juola, 1973), for instance, items with high familiarity use are correlated with rapid old responses, while items with low familiarity measures are correlated with fast new responses. However, items including intermediate familiarity contribute to a slow searching process to recognize the current item.

On the other hand, the degree of activated items in long-term memory primarily determines the fluency of the recognition decisions. If the identification of these activated items is faster and more accurate, this activation triggers priming (earlier exposure) and thus, may result in a familiarity signal (Whittlesea et al., 1990). During this process, the accurate binding of content to a context is essential to hold current information in WM, since the retrieval of the content depends on its context. Familiarity is not sensitive to the context; therefore, it is impossible to keep the current information active only through familiarity when updating is rapid, leading to the possible retrieval of no-longer-relevant items (Kessler & Meiran, 2008).

Nonetheless, recognition is not only based on an automatic assessment of familiarity, but also on recollection that is controlled consciously, not automatically (Yonelinas & Jacoby, 1994).

2.4 Recollection

Recollection is considered as a systematic search process involving the context of an item that was previously encountered (Szmalec et al., 2011). According to Oberauer and Lange (2009), *"familiarity arises from activated representations in long-term memory, ignoring their relations; recollection retrieves bindings in the capacity-limited component of working memory."* (p.102). These bindings are accessed between list items and their list positions in the region of direct access, providing a cue indicating whether the probe item (stimulus) was involved in the relevant context before. Recollection uses this probe for retrieving the list context that is bound to the probe or uses the list context for retrieving the items that are bound to the probe. In this view, the retrieval process stands for recollected associations of a list element and its context when it is retrieved in the focus of attention and is compared with the probe. The strength of binding in the region of direct access affects the quality of recollection.

The conflict between familiarity and recollection contributes to proactive interference in WM (Oberauer, 2005). For instance, if the level of familiarity is similar or equal between items to be accepted or items to be rejected, these items are encoded simultaneously with the same strength (i.e., modified Sternberg task: Oberauer, 2001). For this reason, they are activated equivalently when the stimulus for the relevant items is presented. This process generates a conflict among representations from irrelevant information, which serves high-level familiarity. When these irrelevant representations are rejected during recollection, interference among them can be avoided (Oberauer, 2005). The *n*-back task is a typical example to demonstrate the role of binding and updating of WM representations in a conflict paradigm (Gray et al., 2003).

2.5 *n*-back Paradigm

In an *n*-back task a participant is rapidly exposed to stimuli such as letters or shapes presented one at a time. The goal is to judge whether the current item matches the one that was presented "*n*" items prior. The "*n*" can be manipulated to increase or decrease the load in the WM system. In this task, stimuli can be either target, new distractor or interference items (lures). A target item is a stimulus that matches an item presented "*n*" steps prior in the sequence, requiring a correct acceptance from the participant. On the other hand, a new distractor is a stimulus that is different from any of the preceding stimuli and does not match the *n*-back stimulus presented before.

During the task, the participant is required to make a recognition decision on each item by accepting targets and rejecting distractors in accordance with the *n*-back rule. Successful performance on this task requires the binding of each letter (content) to the appropriate temporal position (context) and the updating of these content-context bindings as they change with incoming new information (Oberauer et al., 2007). Because, in this case, information is presented rapidly and there are only "*n*" number of relevant temporal positions, incoming items are bound to the same temporal context as previous items and the WM system is required to resist interference from previously relevant but currently irrelevant information.

There are two kinds of inaccurate responses in such a task. The first, is an incorrect acceptance of a distractor item as a target. Often, this occurs because the distractor is an item that was previously bound to the relevant context and is providing a familiarity signal that results in incorrect recognition. The second inaccurate response type is the incorrect rejection of a target item. This occurs because the WM representations of the items or the content-context bindings created in the region of direct access for this item are not strong enough to promote a recollection signal. In general, performance on this task requires both strong and flexible bindings that can promote recollection and resist interference from familiarity. It is these binding and updating mechanisms that are at the heart of interference control in the WM framework described above (Oberauer, 2005). They will be the mechanisms that the proposed study intends to train using a version of the *n*-back task.

2.6 Interference Frameworks of Mathematics

In this section, the evidence suggests that interference control in WM is also a source of performance limitations in measures of mathematics learning processes. It is also important to show whether interference in WM is associated with mathematics after understanding which functions of WM are related to which activities in mathematics. Eventually, it will be proposed that interference control can provide a link between WM and information processing in mathematics.

There is a common consensus that arithmetic facts are constructed in interrelating structures in long-term memory (e.g. Campbell, 1995) and that when one encounters an arithmetic problem, pertinent incorrect answers might be activated. As a result, the cluster of related but incorrect answers creates competition with correct answers which interfere with the process of retrieving correct answers (Campbell & Tarling, 1996). This interference results in failures and slow processing of information (Noël & De Visscher, 2018).

Tasks with increased complexity typically have more steps and thereby are more susceptible to inaccurate results. This highlights the significance of monitoring the progression of a task, understanding which steps have been completed, and providing accurate calculations at each step. Therefore, monitoring skills can be an indicator of multi-step mathematical problems. However, monitoring requires a high demand on WM because information is maintained and manipulated while its quality is evaluated simultaneously (Morris & Jones, 1990). As an example, when an individual is performing arithmetic operations, holding intermediate result is required while carrying and borrowing numbers. During this process, recalling and using procedures of arithmetic could potentially be disrupted by proactive interference.

The studies on the relationship between word problems and WM have provided compelling evidence to enhance our understanding the use of WM resources while solving word problems (e.g., Swanson & Sachse-Lee, 2001; Passolunghi & Siegel, 2001; Swanson & Beebe-Frankenberger, 2004; Swanson, 2016; Ng et al., 2017). Solving word problems is a multi-step process where primarily understanding the narratives in the problem and then using relevant information while rejecting irrelevant ones before building up a mathematical sentence (e.g., equation) is indispensable to solve the problem (Peng et al., 2016). Therefore, this complex task elicits the activation of important WM resources in both mathematical and linguistic frameworks.

The presence of irrelevant information in word problems contributes to interference while attempting to solve the problem (Swanson et al., 2013; Ng et al., 2017). For instance, solving a problem such as “There are 18 bottles of milk, 6 bottles of them are sold. The bottles are glass. How many bottles are not sold?” consists of simultaneous mental activities. Both previously stored items (e.g., 18 bottles) and mathematical calculations (e.g., 18 minus 6) are accessed in memory and then the problem is solved with consideration to both relevant and irrelevant information (Peng et al., 2016). The performance here is associated with processing two activities simultaneously (i.e., dual-task mechanism), since a person is solving a problem while maintaining information in memory through rehearsal (Hitch and Baddeley, 1976;

Baddeley, 2012), which process may lead to the encoding of representations from distractors (Oberauer & Lewandowsky, 2008). These distractors create interference with encoded representations (Oberauer et al., 2012).

The influence of numerically and literally irrelevant information in a word problem-solving task may affect differently the degree of interference in WM (Ng et al., 2017). Whereas numerically irrelevant words are perceived as values that must be used in the operation or in any mathematical calculations (i.e., equation), literally irrelevant information may be detected as unnecessary information for solving the problem. Earlier research (Englert et al., 1987) has demonstrated that numerically irrelevant information in word problems reduces the possibility of correct answers more than literally irrelevant information does. On the contrary, longer sentences may have more unfavorable effects on problem solving (Marzocchi et al., 2002). Ng and colleagues have found that irrelevant numbers, but not irrelevant words, are involved in the process of problem-solving, leading to a decrease in accuracy. Therefore, the ability to suppress superfluous knowledge, such as strategies or heuristics, is the prerequisite for solving word problems (Nget al., 2017; Lee & Lee, 2019).

Regarding the context of mathematics, learning difficulties in complex topics arise from some previously learned knowledge and procedures (Lee & Lee, 2019). For example, a person with misconceptions is more prone to choosing an improper strategy to solve a mathematics problem in which well-entrenched heuristics or strategies substitute new information that seems to share a similar structure (McNeil & Alibali, 2005). Therefore, the efficiency of memory representations of arithmetic problems (especially multiplication) relies on problems which are learned previously, regarding the basis of overlap theory (Nairne, 1990). In accordance with this theory, if a problem is mostly similar to a previously learned problem, considerable interference will arise during the storage stage, and thus will reduce the possibility of retrieval (De Visscher & Noël, 2014). This notion is also supported by Oberauer and Kliegl (2006), in such that when two similar items with overlapping features need to be stored in memory, the features of representatives are more prone to interacting with each other, leading to interference. This contributes to somewhat impaired memory traces, and hence results in retrieval errors and/or slow processing.

According to Siegler's (1988) Distribution of Association model, each problem is associated with their correct and incorrect answers from previous encounters. Adversely, larger problems are more prone to be connected with incorrect answers due to increased likelihood of errors and problem size effect. For example, two-digit or complex problems are assumed to be large problems (Thevenot et al., 2010), due to their higher probability of incorrect answers. The common clarification for problem size effect is that smaller problems (e.g., simple additions, single-digit multiplication) are more frequently solved using direct retrieval strategies than larger problems (e.g., complex subtraction, multi-digit problems) (Thevenot et al., 2010; Zbrodoff & Logan, 2005). However, since a larger problem potentially represents the weight of proactive interference, individuals rely more on procedural strategies for problem-solving and they use step-by-step methods that stem from previous experiences with similar problems. These strategies can reduce the cognitive load by segregating the problem into more manageable parts, leading to decreased impact of interference in WM. However, they may also be apt to make errors based on interference if they develop strategies to solve different types of problems (Zbrodoff & Logan, 2005). Consequently, the possibility of making an error might increase when the problem size increases.

Another model, related to the basis of cooperation and competition between neighboring problems serves as the theory that answers the question whether neighboring problems compete or cooperate during retrieval of the answer to a problem (Verguts & Fias, 2005). For example, 3×8, 3×6, 2×7, 4×6 might be the neighbors of 3×7. Due to similar or same digits of a problem, neighbor answers arise and thus, this process contributes to the same response of a given problem. These answers will be consistent and provide the retrieval of the correct answer, conversely inconsistent answers will compete with the correct answer and will delay the retrieval of the correct answer. The phenomenon which also supports the principles of problem size effect is that representatives of response of large problems can be more similar to each other rather than of small problems because large problems are more prone to have inconsistent neighbors. Furthermore, the frequency of occurrence can determine the problem size effect (Ashcraft & Christy, 1995), as an example, children are engaged in smaller problems more frequently in primary schools than larger problems.

The findings demonstrate that arithmetic problems are more associated with interference in WM during information processing in mathematics (e.g. De Visscher & Noël, 2016). De Visscher and Noël (2014) proposed that similarity-based interference in arithmetic problems determines the performance on arithmetic facts. When two items have a definite amount of overlap with respect to their features, they share considerable amount of feature of their representations regarding similarity of items and these features interact with each other, resulting in interference (Oberauer & Kliegl, 2006). In other words, higher proactive interference contributes to sensitivity to item similarity (Underwood, 1983). This sensitivity to interference prevents arithmetic facts from being stored in long-term memory, so that sensitivity-to-interference could diminish individual's performance in arithmetic problems. Additionally, De Visscher and Noël (2014) examined the characteristics of the overlap theory (Nairne, 1990) in the base of arithmetic facts which lead to interference as 10 digits (0-9 digits) are incorporated in different combinations.

De Visscher and Noël (2014) counted the amount of common associated digit among the ongoing problem and previously learned problems in order to understand the strength of proactive interference in multiplication problems. The total score of proactive interference of the problem corresponds to the number of occurrences of common two-digit associations with previously learned problems. For instance, when learning 3x9=27, the combination 2–3 has been found in four previously learned problems (3x2=6, 3x7=21, 4x3=12, 3x8=24), the combination 2–7 has been found in two problems (2x7=14, 3x7=21), and similarly for the combination 2–9 (2x9=18), 3–7 (3x7=21), 3–9 (3x3=9). However, as described in the theories above, evidence that interference control is required in memory retrieval processes during mathematics learning allows consideration of the benefits of an interference-based WM training to children's performance on mathematics.

The exploration of the relationship between mathematics and interference displays a complex interplay between WM mechanisms and information processing in mathematics. Studies have highlighted how complexity and similarity in mathematics problems amplify the challenge by increasing interference in WM. The findings provide justifications and insights into WM functionality while solving mathematics problems, especially arithmetic problems, and the possible factors that create interferences in this process. were considered as a measure for their mathematics proficiency in the current study.

2.7 Working Memory Training and Transfer Effects

The evidence described thus far allows us to understand that WM is a limited capacity system which operates as a workspace of mind and an individual's capacity of WM is an important element of his/her ability to perform various cognitive tasks (Engle et al., 1999; Kane et al., 2004). Despite the limit in WM capacity, it is proposed that the efficiency of WM processes can be improved with WM training (Klingberg et al., 2005; Verhaeghen et al., 2004; Westerberg et al., 2007). The key role that WM plays in many processes and the individual differences in WM performance have inspired research questions about the potential to train the WM system and to transfer this training effect to performance on complex tasks that are known to recruit the WM system, such as language and mathematics (Sternberg, 2020).

The transfer effect refers to how training improvements promote other skills or performance in various cognitive tasks. It can be categorized as near or far transfer effect. As proposed by some studies (e.g., Klingberg, 2010), the improvements which can be observed behaviorally result from increasing performance on tasks similar to the trained tasks, defined as near transfer effects. Near transfer effects reflect direct acquisition from the training. In other words, near transfer effect occurs when training improves performance on tasks which are closely related to the trained task. For instance, near transfer effect can be observed after receiving *n*-back training if an individual exhibits better performance on a digit span task which refers to recalling numbers in order. On the other hand, a broader cognitive improvement is required for far transfer effect that occurs when training improves performance on specific tasks which do not share the same cognitive processes with the trained task. For example, performance improvement in language or in mathematical tasks as a result of completing an *n*-back training (Dahlin et al., 2008; Jaeggi et al., 2008).

Training-based effects possibly stem from two types of processes: “expanded WM capacity” or “enhanced WM efficiency” (von Bastian & Oberauer, 2014, pp.4). Some challenging activities contribute to cognitive demand and thus such demands can adapt to changes in brain regions, probably enhancing WM capacity by the time (Lövde´n et al., 2010). For example, complex tasks require higher cognitive demands which lead to holding more information simultaneously and help individuals use their existing WM capacity efficiently. Then, they can adapt to better processing methods or strategies to manage the complexity of a task after being exposed to such tasks more frequently.

One of the most important aims of WM training studies is to execute an exploratory implementation of a broad training that covers various cognitive resources in complex tasks to determine the range of near and far transfer effects (e.g. Titz & Karbach, 2014). In these studies, the computerized Cogmed Working Memory Training (Cogmed, 2011), which is a set of 12 visuo-spatial and verbal memory tasks in a game-based context has been used frequently.

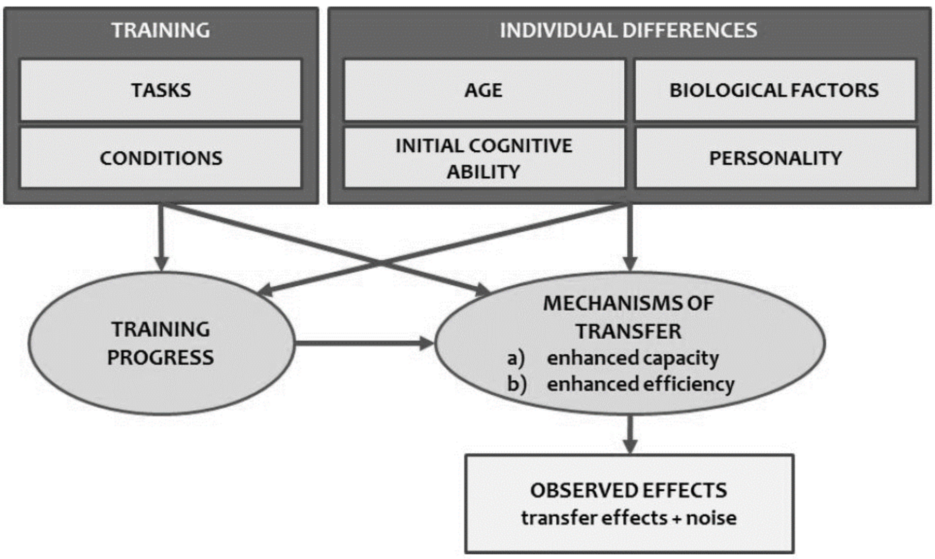
Fortunately, there are some studies that resulted in far transfer effects to reading, math, reasoning and intelligence (Wass et al., 2012), however they are often criticized for a missing theoretical explanation of results that can effectively explain what it is about WM that extends to so many different skills (Shipstead et al., 2012). A recent study (Johann & Karbach, 2019) aimed to examine the effects of training on cognitive and academic abilities with typically developing children and measured transfer effects of WM training. They reported no transfer with the following training to mathematical abilities. Participants were given six training programs, including the *n*-back training, which targets WM updating, inhibition and flexibility in game-based and standard training versions. The critical missing point in this study was that the training attempted to show improvements in academic skills but did not use a task in which participants could develop relevant mechanisms to resist interference, such as binding and updating. Enhancing binding and updating mechanisms in WM can ensure better academic performance (Obearuer & Hein, 2012). Specifically, binding skills may enable students to integrate new knowledge with their existing knowledge by forming and maintaining bound representations of information, whereas updating skills can help them monitor the latest information or instructions and be able to learn new concepts and use them correctly.

The methods of WM training generally can be classified as “core training” and “strategy training”, as revealed by Morrison and Chein (2011). This categorization is based on whether the training targets either domain-general or domain-specific aspects of WM. Core-based training paradigms are conceived to target domain-general mechanisms and precisely aimed to embrace overall functions, such as encoding, maintaining, and retrieval of information, not a specific type of information. Such training tasks are complex and necessarily include core processes and these measures, therefore, contribute to difficulty to design tasks and interpret the outcomes for specific changes gained from the training. For example, complex span tasks and *n*-back tasks which are used in wide range of research are based on core training. Since core training may target executive components of WM and enhance the domain-general aspects, increasing performance on domain-general factors may promote both near and far transfer effects of training. Therefore, high-level cognitive activities in which executive processes are necessary for ongoing task (Cowan, 2005) are connected to domain-general mechanism of WM and fortunately, it is possible to transfer the training effects to untrained tasks, as well as trained tasks by targeting certain domain-general aspects of WM.

Conversely, strategy-based training methods are designed for targeting domain-specific factors of WM. Domain-specific components of WM involve processes about maintaining and manipulating specific types of information. For example, articulatory rehearsal is associated with domain-specific aspects and here, an inner speech mechanism is used for maintaining verbally coded items (Baddeley & Hitch, 1974). Strategy-based training studies support the notion that performance on specific skills can be enhanced by practiced strategy use. Those strategies, such as grouping numbers in threes in a list to remember easier, provide effective tools for specific task situations. Nonetheless, the predominant feature of strategy-based trainings is in improving the skills only for such tasks whose materials are consistent with trained strategies and for this reason, it is hard to believe that strategy-based trainings result in higher performance on different situations (e.g., irrelevant tasks) (Morrison & Chein, 2011).

The possible outcome of the training may occur as improvements in training processes which are being strengthened during the training. In accordance with current theories about cognitive training (e.g., Jaeggi et al., 2008), these processes are likely shared by both transfer and trained tasks to acquire transfer effects of the training. Therefore, a wide range of different cognitive tasks utilizing the same process would be expected, regardless of the structure of the tasks when the cognitive skills used in the trained process overlap transfer tasks. For example, Jaeggi et al. (2010) supported this point of view with *n*-back training which demonstrated far transfer effects on fluid intelligence tasks within a greater variance with WM updating tasks.

Figure 1. Possible factors affecting outcomes of WM training (von Bastian & Oberauer, 2014, p.804)



According to a considerable number of studies (e.g., Dahlin et al., 2008; von Bastian et al., 2013; Shipstead et al., 2012; Conway & Getz, 2010), training and training acquirements are likely affected by varying factors such as individual differences (i.e., age, cognitive abilities, or motivation) and task-specific features (i.e., training tasks and training conditions), categorized in Figure 1. Age factor has been mostly investigated to interpret its correlation with training and training gains in practice. Recently, it was asserted that younger children enhance their abilities more than older ones (Melby-Lervåg & Hulme, 2013). Additionally, various number of studies have demonstrated that higher initial cognitive abilities may enable training participants to improve their skills extensively (Lövdén et al., 2012). However, although previous research (Brehmer et al., 2012) shows evidence on genetic influences leading to individual differences in training outcomes, studies about genetic factors are ambiguous. Besides all these, individuals' motivation, such as enjoyment, interest and effort, is entirely associated with cognitive performance across some measurements. For example, Duckworth et al. (2001) acquired greater performance from intelligence tests after they manipulated participants' test motivation by strengthening with material incentives. Here, their personality traits also contributed to variations in training and training effects (von Bastian & Oberauer, 2014). The findings illustrate that motivation and individual differences can influence the performance of participants during training and may also impact the training effects.

The studies on WM training are engaged in continual WM tasks which are carried out experimentally in a controlled manner and this experimental context impacts cognitive functions and reveals information about many other constructs such as intelligence and language (Jaeggi et al., 2014). These studies deal with the findings in which WM training investigates the improvements in trained behaviors, near and far transfer effects in performance (Melby-Lervag & Hulme, 2013). The efficiency of training would be predicted from its transfer effects to untrained tasks (Shipstead et al., 2012), in part, due to its contribution to a domain-general attentional capacity which is required for various tasks. Therefore, WM training is considered to provide both near and far transfer effects (Barnett & Ceci, 2002). The outcome of far transfer effect is significant to predict the efficiency of a training program, however near transfer effect might be devalued as a structure of practice effect if near transfer tests reflect similar outcomes to the training tasks (Klingberg et al., 2005). Consequently, in the perspective of far transfer effect, it is proposed that WM interacts with other cognitive skills.

Previous research has suggested that the training tasks should be constructed in reliable settings about conditions and environment where those tasks are administered since well-designed and consistent conditions provide to facilitate transfer trained skills to other contexts (Jaeggie et al., 2010). For example, the training must focus on modifications in the system of information processing, not in a singular task and, thus a training task has to reduce the development of strategies which are task-specific (Ericsson & Delaney, 1998). The notation for this is that the aim of training must be to make differences in the information processing system, not in the manner of one specific task because training tasks are required to be designed in such a way, ensuring an effective training in enhancing WM capacity in order to provide transfer effects to trainees. Furthermore, it is mentioned that it is critical to provide a continually high level of training with respect to demand and consider individual differences in performance. The appropriate method for this is the adaptive training method which progressively regulates the difficulty of ongoing training for each participant (Shipstead et al., 2012). Training programs should be built in a way to be adaptive for users in performance. In these programs, task difficulty must increase with respect to particular performance criterion that a trainee achieved. If he/she does not achieve these criteria, task difficulty must decrease. When participants meet a priori set criterion of performance accuracy (e.g., 60-70 %), then task difficulty may increase. If they do not meet even the minimum level in performance (e.g., 40-50%), task difficulty may be decreased. As a result, these adaptive programs enable trainees to complete tasks at their level without being bored or overtaxed (Lövdén et al., 2010). During training, the information processing mechanism is important in activities such as performing two tasks concurrently (Oberauer et al., 2004). The role of this mechanism is to keep information continually accessible in memory while performing a target task within the limited capacity of WM (Ericsson & Delaney, 1998). Since adaptive training gradually increases the complexity of a task, it can enhance this mechanism by allowing individuals to adapt to higher cognitive demands, thereby performing better in such tasks.

As an example, the use of *n*-back task serves adaptive WM training exercise designed to enhance WM capacity. The challenge of the task increases when trainees move to the next level (e.g., from 3-back to 4-back). They receive instantaneous feedback about their performance during the task. This enables them to figure out their progress and accordingly adapt the strategies. In this task, trainees need to update and manipulate information in WM while performing it, thereby, they can be challenged for the optimal level of the task within its adaptive nature.

Another prevailing aim of training studies is to improve performance of a specific mechanism for building the theoretical view of training process. Accordingly, WM training enables researchers to conduct the optimal methodology to describe a cause-and-effect relationship between two conceptually related constructs, that is modulated by a specific, trained process (Sala & Gobet, 2020). For instance, processing task-relevant information in any modality and context is required for individuals to remove irrelevant representations from the focus of attention. The mechanisms, content-context binding and updating are linked to resisting interference while processing information. These abilities have predicted performance on several measures of interference control (Szmalec et al., 2011).

To experimentally establish the theoretical importance of these specific processes to interference control in WM and mathematics, one study (Kuhn & Holling, 2014) implemented the updating training in children. The research focused on the improvement of elementary school children's mathematical abilities with computer-based training. Besides other computerized training programs that were implemented sequentially, *n*-back training was the one which was mainly used for spatial WM with updating tasks. Here, participants were expected to show whether a stimulus appearing on the screen was displayed in the same place as n steps before (Jaeggi et al., 2011). It was assumed that this training would improve spatial updating, which has been shown to be of high importance in mathematics (van der Ven et al., 2012). The findings showed that the training promoted significant, but small improvement to trainees' mathematics scores due to its short period of time (only 5 hours in total). However, the results were in agreement with recent research, indicating that either or both WM and number sense training reinforces mathematics abilities (A11).

In summary, a theoretically motivated training study offers the opportunity to explore relationships between two constructs by controlling implementation of a task designed to make process-specific improvements and influence performance of related skills. The evidence outlined above from both WM and mathematics fields provides support for the theoretical relationship between WM and mathematical ability. Both bodies of literature have independently identified the importance of the ability to resist task-irrelevant memory traces and stimuli, or interference control, to performance in math measures. This interference control ability can be leveraged, particularly in mathematics learners, to measure cognitive effects of an adaptive WM binding and updating training. The *n*-back training serves as a proper tool where performance on the *n*-back task requires both strong and flexible bindings that can promote recollection and support resistance to interference related to familiarity. Interference may occur when an item tends to be familiar to the previous item, but the contextual details are missing. Recollection may reduce the likelihood of interference by providing contextual details that help distinguish relevant information from irrelevant ones. Strong binding and updating of items may enhance recollection, leading to accurate retrieval in this recognition task. Therefore, binding and updating mechanisms are the cornerstone of interference control in the WM system.

Present Study

The present study was designed based on an interference framework (Oberauer, 2009). An adaptive *n*-back training was used to determine the effects of a WM training on performance in mathematics in school-age children. The overall aims for this study were as follows: Firstly, to explore the interplay between binding and updating functions that are linked to interference control in WM and understand how they interact with WM mechanisms to support cognitive adaptability and flexibility. Secondly, to find an efficient way for learners to improve their interference mechanism of WM and as a result, improve their performance on trained and untrained tasks. Thirdly, to highlight the significant role of interference control in mathematical problem-solving in school-age children.

The effects of the training were evaluated with the pre- and post-training performance measures in a set of cognitive and mathematics tasks. The differences between training and control groups were compared with pre-test performance for each task and through the analysis of changes following the training; pre- and post- test performances were compared for each task within the training groups. There were two experimental and two control groups: One experimental group received training and completed pre- and post-tests, whereas the other experimental group received training and completed only post-tests; regarding control groups, one control group completed pre-and post-tests, while the other only completed post-tests (see Figure 2). The experimental groups completed adaptive *n*-back training with lures. Within these groups, effects of individual differences and effects of experimental manipulations of interference and set size level on *n*-back performance were analyzed. Between the experimental and control groups, three sets of tests were administered before and after the training period to determine transfer effects: *n*-back, interference control and mathematics proficiency. Performances of the two control groups were compared to that of the experimental groups.

Figure 2. Design of the study

Training group 1 (T1): Pre-test → Training → Post-test

Training group 2 (T1): Training → Post-test

Control group 1 (C1): Pre-test → Post-test

Control group 2 (C2): Post-test

Hypotheses

The hypotheses of the present study highlight four main aims. First, to explore how WM training affects school-age children's WM systems within the interference framework, with a focus on binding and updating functions and limitations. Second, to show near and far transfer effects in performance. Third, to find evidence for the relationship between the mechanisms used for resisting interference in WM and mathematics performance in conditions where WM load and interference are manipulated. Fourth, to understand if individual differences in both cognitive (e.g., WM capacity, attentional control) and non-cognitive (e.g., motivation, SES) factors are related to *n*-back training performance. Overall, these aims highlight the necessity of the enhancement of WM capacity to perform better in cognitive-based tasks within an interference control framework of WM.

1) Training performance and progress (T1 & T2)
   a. It was expected that performance differences in the *n*-back tasks would stem from different task conditions and different item types of each task rather than from differences in average age, IQ or baseline memory in participants. We expected that participants in the four groups would not differ in age, nonverbal IQ, and basic memory and language tasks (i.e. digit span and semantic verbal fluency). The effect of existing factors, such as demographic and cognitive factors, are examined in research to confirm that any observed differences on task performance derive from

experimental manipulations, not from differences among participants before the experiments (Salthouse, 2010).

b. When the *n*-back level increases, participants need to hold more items in their WM and update these items while performing the task. This increased load in WM results in a high possibility of making more errors and slower performance (Jaeggi et al., 2008). Similarly, interference lures increase difficulty of holding and manipulating information, leading to a decrease in *n*-back performance (Kane & Engle, 2003). The effect of interference increases with increasing load in higher level of *n*-back tasks. Therefore, we hypothesized that *n*-back performance of participants in the experimental training groups is negatively affected by increased WM load (higher *n*-back levels) and by the presence of interference lures.

c. The Theories of Cognitive Abilities Scale was used to assess participants' motivation related to their beliefs about their capabilities in challenging tasks (Dweck, 2000). It was anticipated that individuals who more strongly believe that they can improve their abilities through training would show higher engagement in the training than individuals who believe that their abilities are given. Here, individuals' beliefs about their intelligence affect their motivation to engage in training (Dweck, 2006). Individual differences in nonverbal IQ scores predict training progress since non-verbal intelligence is of particular concern to cognitive skills (Jensen, 1998). Since tasks measuring nonverbal IQ require pattern recognition and spatial reasoning, nonverbal intelligence is significantly associated with performance in *n*-back tasks. It was hypothesized that individuals who have higher nonverbal IQ scores would improve more rapidly in the *n*-back tasks over the training program.

d. It was anticipated that individual differences in Semantic Verbal Fluency Test would predict training progress because semantic verbal fluency refers to cognitive processes which include retrieving information to related categories while inhibiting information from different categories (Lezak et al., 2012).

2) The factors such as "age", "SES", "participants' motivation", "performance change over the sessions" (the completed n-level from each session was considered.) and baseline cognitive resources – specifically assessed by reached highest level in *n*-back tasks obtained from first two sessions – can predict the progression of the training. Age-

related differences may affect the extent of the training outcomes. For example, older children can benefit from training compared to younger ones, since they have more experience in WM measures, allowing cognitive flexibility (Park & Reuter-Lorenz, 2009). However, younger children may show greater improvement over the training due to their faster learning rates (Brehmer et al., 2012). Furthermore, participants with high intrinsic motivation may engage in the training tasks more consistently, leading to better progression through increasingly challenging *n*-back levels (Deci & Ryan, 2000; Dweck & Leggett, 1988). In addition to this, high SES can contribute to participants' baseline cognitive abilities and the possibility to benefit from the training since it is correlated with better access to cognitive stimulating environment (Hackman et al., 2010; Finn et al., 2017; Mooney et al., 2021) In terms of baseline cognitive resources, individuals with higher pre-existing cognitive reserve may have a benefit in initial performance and training progression (Conway et al., 2003; Alloway & Alloway, 2010). In higher levels, participants were expected to show different performance patterns as evidence of individual differences (Kane & Engle, 2002). Noticeable variations in performance were anticipated on the *n*-back task from the initial stages of training to its completion. Those individuals who achieve higher maximum *n* scores in the first session would exhibit faster improvement compared to others in subsequent training sessions (Jaeggi et al., 2008) This suggests that the initial performance gap between participants widens over time.

3) Pre-test performance (T1&C1)
   a. No significant difference was expected between the pre-test training group and the pre-test control group in pre-test performance. We anticipated that performance differences between these groups in the testing battery would stem from different conditions and different item types in each task rather than from differences in average age, IQ or baseline memory tasks. After confirming that there was no significant group difference between the T1 and the C1 groups, the groups were combined to analyze performance in different item types and conditions for each task.
   b. *n*-back task (1-back and 2-back): We expected that participants would show better performance on new distractor items than on target items at each set size. Since processing target items requires recall and recognition of items that were displayed

n steps back, performance in the *n*-back tasks may decrease while responding to target items compared to new items which require only recognition (Cowan, 2001). In addition, their performance on target items would be better than on the interference items in the proactive interference condition (Baddeley & Hitch, 1974; Jonides & Nee, 2006). However, the effect of memory load would be the most prominent for target item accuracy. In the second set size condition, recognition of target items may be the most difficult decision to make overall. Here, the increased set size leads to increasing number of information that is prone to interference, particularly the recognition of target items (Kane & Engle, 2002).

c. Modified digit span task (MDS): This task contains four different computerized numerical tasks: t, tS, Rt and RtS tasks related to transformation, substitution, and retrieval components of updating. It was expected that participants' performance would differ in these four conditions. While arithmetic operations are performed in all conditions by acquiring new values which are either retrieved or substituted, simple arithmetic operations are carried out in the transformation component where retrieval or substitution is not required. In retrieval and substitution-based tasks, while performing arithmetical operations, results which can be used for the further operation or required to be replaced as a last product at the end of the list must be memorized for each operation to pursue the task. Therefore, performance on solving arithmetic operations was expected to be significantly better than memorizing the last items. Additionally, it was anticipated that participants would perform better in transformation-based tasks than retrieval and substitution-based tasks. The tasks involving maintaining and manipulating information require high-level cognitive control and updating skills to respond to rapidly changing task demands. Therefore, it is difficult for young children when they perform a task in which information must be retrieved from WM (Cowan, 2005; Best et al., 2011; Gathercole & Alloway, 2008).

d. Arithmetic operations: Problem size determines the conditions for four-operations. We anticipated that the pattern of performance would be different for the two conditions of multiplication and division. Participants would perform better in small-size problems than long-size problems. Larger problems are more prone to trigger proactive interference because procedural strategies which require recalling previously learned problems are used to solve larger problems (Zbrodoff & Logan, 2005). However, performance on small-size addition and subtraction problems would not be significantly different than large-size ones (Ashcraft, 2006).

e. Word problems: Neutral and biased conditions were administered in this task. While the problems in the neutral condition included relevant information, in the biased condition the problems included two types of irrelevant information: literal and numerical. The biased condition contains two types of irrelevant information in the given problems: literal and numerical. Numerically irrelevant information can be perceived as values that must be used in the operation, literally irrelevant information may be detected as unnecessary information for solving the problem (Ng et al., 2017). Participants were expected to perform significantly better on the problems which have literal irrelevant information than on the problems with numerical irrelevant information. It is due to the fact that when the numerical irrelevant information has semantic similarity with the relevant information, it may lead to incorrect solution (Cook & Rieser, 2005). The neutral condition has only relevant information. Participants were expected to perform significantly better on the neutral condition than on the biased condition.

4) Training effects, pre- to post-tests (T1)

a. Changes in performance on the 1-back and 2-back tasks may demonstrate whether the training improved performance on the trained task itself. Participants were expected to perform significantly better on both *n*-back levels after the training. It was hypothesized that performance on target items would predominantly determine changes since these items are related to WM bindings and updating and these mechanisms are required continuously to be updated during the recognition process. Since the new distractors do not match any stimuli of the previous *n*-back items, extensive binding and updating do not prevent the rejection of them (Oberauer, 2005). The rejection process of new distractors tends to be similar to the process of rejecting neutral items. Therefore, participants were expected to show no significant difference in pre- to post improvement on rejection of new distractors in both *n*-back tests because binding and updating mechanisms are less crucial to rejection of neutral items (Oberauer, 2005).

b. It was expected that changes in performance on the MDS task would show near transfer effect. We anticipated that performance on the retrieval and substitution-based tasks would improve significantly, whereas performance on the transformation-based task would not since participants would only solve simple arithmetic operation in this task. Improvement in performance on both solving arithmetic operations and recalling last items at the end of the list in which complex retrieval and substitution are involved would be significant (Raghubar et al., 2010).
c. Changes in performance on arithmetic operations task was expected to represent far transfer effect to specific processes of solving mathematics problems that are measuring similar concepts of WM, specifically, maintaining numbers, processing steps in calculations and updating intermediate results. Performance on multiplication and division was expected to improve significantly, while performance on addition and subtraction was not because the effect of training is more likely to be observed in complex tasks (Passolunghi & Pazzaglia, 2004). Overall, it was hypothesized that training would contribute to gains in a population of elementary level children with different levels of arithmetic ability (Kuhn and Holling, 2014). It is because WM training may enhance WM capacity of children who have different levels of arithmetic skills, and they show different transfer effects on mathematics tasks. For example, lower-performing children can evaluate better strategies to solve mathematics problems whereas higher-performing children may engage in more complex mathematics problems and work on them efficiently.
d. Changes in performance on word problems task would show far transfer effect to problem-solving processes which are based on interference framework of WM mechanism, such as suppression of irrelevant items. It was hypothesized that performance on problems involving literal and numerical information would significantly improve, whereas performance on problems which have only relevant information would not (Ng et al., 2017)

5) Training effect post-test performance (T2&C2)

   It was anticipated that there would be significant differences between the training group (T2) and the control group (C2) in post-test performance. The training group was expected to perform better on each task than the control group following the training period, but the extent of improvement would vary due to different task-specific factors. Since *n*-back training may provide enhancement in WM capacity, participants who have received training may exhibit better performance in various tasks, such as cognitive tasks (Jaeggi et al, 2008) and mathematics tasks (Raghubar et al., 2010).

a. *n*-back task: The training group was expected to show better performance on target items than the control group. The performance on new distractor items would not differ significantly between the groups. Specifically, *n*-back training aims to improve WM where information, such as target items, requires to be recalled and recognized for tasks (Jaeggi et al., 2008). The ability of recognition of new distractor items relies on different cognitive processes rather than recalling or manipulating information in WM (Shipstead et al., 2012).

b. MDS task: We hypothesized that the groups would not differ in transformation-based tasks while the training group would show better performance in retrieval and substitution-based tasks. Participants need to retain information and use this information in a place of additional information while performing retrieval and substitution-based tasks which directly rely on cognitive processes targeted in *n*-back training. Transformation-based tasks usually involve understanding and applying rules related to a task. Therefore, participants who receive this training may become more proficient in such tasks where manipulation of retrieved information is required (Melby-Lervåg & Hulme, 2013) Additionally, the training group was expected to perform significantly better at recalling items than the control group.

c. Arithmetic Operations: Groups were not expected to differ significantly either in small-size problems in all types of operations nor in addition and subtraction problems. However, the training group was expected to show better performance in larger problems than the control group. Since small-size arithmetic problems and addition and subtraction tasks of any size require only memorization or simple calculation strategies, WM is not exposed to high cognitive load (Bull & Lee, 2014). However, larger arithmetic problems, notably multiplication and division, create high cognitive demand in WM. Multi-step cognitive processes, such as maintaining more than one item in memory simultaneously and manipulating information to solve these problems (Alloway & Alloway, 2010; Raghubar et al., 2010; Holmes &

Gathercole, 2014). Participants whose WM capacity is enhanced by the training become more proficient in these cognitive processes.

d. Word Problems: The difference between training and control groups' performances were not expected to be significant in problems that involved only relevant information. Nonetheless, it was hypothesized that the training group would perform significantly better on problems which contain irrelevant information. One of the targets to use *n*-back training is to enhance cognitive control mechanism which involves the capacity of focusing on relevant information and resisting irrelevant information during any cognitive related tasks (Shipstead et al., 2012; Melby-Lervåg & Hulme, 2013).

6) Test-retest effect post-test performance (only C1) / (C1&C2)

a. It was hypothesized that changes in performance for the C1 group would not be significant on any task.

b. There was expected no significant difference between C1 and C2 control groups in post-test performance. C1 and C2 groups would be compared in each task to confirm that there is no testing effect in performance of participants who complete the pre-tests.

Chapter 3 Methods

3.1 Participants

Participants included 44 children in elementary level classes between the ages of 9 and 12 (Table 1). The Solomon four-group design was applied to account for testing effects in the study. Participants were randomly assigned to four groups (two training and two control groups): T1) training with pre-test and post-test; T2) training with post-test only; C1) pre-test and post-test with no training; C2) post-test with no training. This method of design for grouping participants is more advantageous than the basic two- group design because it helps to identify the occurrence of testing and training effects on experimental variables.

First, this study was approved by the Ethics Committee of Bárczi Gusztáv Faculty of Special Needs Education at Eötvös Loránd University. Then, a total of 47 students were reached by contacting teachers from various schools in Istanbul, Türkiye. The teachers assisted in selecting participants based on the first two inclusion criteria listed below. From the potential participants, one did not meet all inclusion criteria and was excluded from the study. Another student withdrew after completing tests outlined in the inclusion criteria from three to five. Additionally, one student who had begun the training did not complete all sessions and was subsequently excluded from the study. After the recruitment process was completed, IQ and cognitive abilities of the remaining participants were assessed. All participants met the following inclusion criteria: 1) absence of significant deficit or learning disability, neurological disorder or communication disorder in compliance with an interview with their parents, 2) Mathematics score between 70 and 100 out of 100, based on their average mathematics exam scores gathered by their school administration, 3) a score within the average range on the Test of Nonverbal Intelligence (TONI-4; Brown et al., 2010), 4) a Digit Span Test (DST) (Wechsler Memory Scale- III) score at least 5 points out of 14 across the lengths of item lists between 3 and 9, 5) a score on the Semantic Verbal Fluency Task (SVFT) that is at least at the mean value of the number of produced words. These two latter tests confirmed that the groups did not differ in basic short-term memory and vocabulary. The informed consent letter was signed by the children's parents to agree to their children's involvement in the training sessions and pre- and post-training testing. A questionnaire for the parents was used to collect demographic information and socio-economic status (SES) data. Parents were asked about their education level, financial status and working hours using a Google Form (see Appendix 3). These factors can determine the quality and quantity of resources available for their children to support their learning and cognitive development (Bradley & Corwyn, 2002; Brooks-Gunn & Duncan, 1997; Bianchi, 2000). All children in the study were Turkish and spoke Turkish as their first and primary language. Their parents' education level ranged from high school to college degree.

Table 1. Participant characteristics by group

Group	N	Age	TONI	SVFT	DST
T1	11	10.5 (1.0)	110.8 (12.5)	12.3 (3.1)	6.9 (1.4)
T2	11	10.4 (0.8)	114.8 (11.2)	12.5 (2.9)	7.7 (2.8)
C1	11	10.8 (1.0)	112.0 (10.8)	13.5 (3.0)	7.3 (2.0)
C2	11	10.5 (0.8)	106.9 (8.6)	13.0 (2.1)	6.5 (1.3)

Participants in training and control groups did not significantly differ in age $F(3, 40) = 0.53$, p= 0.66, scaled TONI scores $F(3, 40) = 1.00$, p= 0.40, SVFT scores $F(3, 40) = 0.41$, p= 0.75. Since DST scores were not normally distributed, Kruskal Wallis test was conducted to check the difference between groups. Participants in four groups did not significantly differ in DST scores $H(3) = 1.39$, p = 0.71.

Preliminary assessment was conducted to test skewness, kurtosis and normality of scaled TONI scores and SVF scores for all participants. According to the Shapiro-Wilk test (W), TONI score, SVFT score and achieved training level data (W ~ 1, $p > 0.05$) were normally distributed (see Table 2, below). However, only training groups were predicated on the achieved training level.

Table 2. Normality of participants' characteristics

Characteristic	*Skewness*	*Kurtosis*	*Normality (W)*	*Normality (p)*
TONI score	0.332	2.373	0.971	0.330
SVFT score	0.707	3.185	0.953	0.073
Achieved training level	0.653	3.187	0.918	0.070

3.2 General procedures

The study implemented a training paradigm and interpreted its effects on groups of elementary level children in mathematics and cognitive skills. Children who participated in this study were recruited with the agreement between their parents and the researcher. All recruitment, testing, and training procedures were carried out by the researcher. The training groups completed sixteen 20-minute sessions of adaptive *n*-back task over four weeks. Participants performed pre- and post-tasks or only post-tasks depending on their group assignment, before and after the training period (see Table 3, below). The experimental groups completed the adaptive *n*-back training with lures. Within these groups, the effects of individual differences were tested with the Theories of Cognitive Abilities Scale (Dweck et al, 2000) to understand whether participants' intrinsic motivation influenced the results of the study. Between the experimental and the control groups, three categories of pre-/post-tests were administered to determine transfer effects: *n*-back tasks (1-back and 2-back), modified digit span (MDS) task, and mathematics proficiency tasks.

All tasks and training sessions were administered online using E-Prime Go which was obtained from E-Prime 3.0 software (Psychology Software Tools, 2020) to present stimuli and record responses remotely.

Table 3. Testing and training procedure for each group

Group	Testing Session 1	Training Week 1	Training Week 2	Training Week 3	Training Week 4	Testing Session 2
T1	Testing battery	20-minute training sessions (×4 days)	20-minute training sessions (×4 days)	20-minute training sessions (×4 days)	20-minute training sessions (×4 days)	Testing battery
T2	NA	20-minute training sessions (×4 days)	20-minute training sessions (×4 days)	20-minute training sessions (×4 days)	20-minute training sessions (×4 days)	Testing battery
C1	Testing battery	NA	NA	NA	NA	Testing battery
C2	NA	NA	NA	NA	NA	Testing battery

3.3 Stimuli/Materials

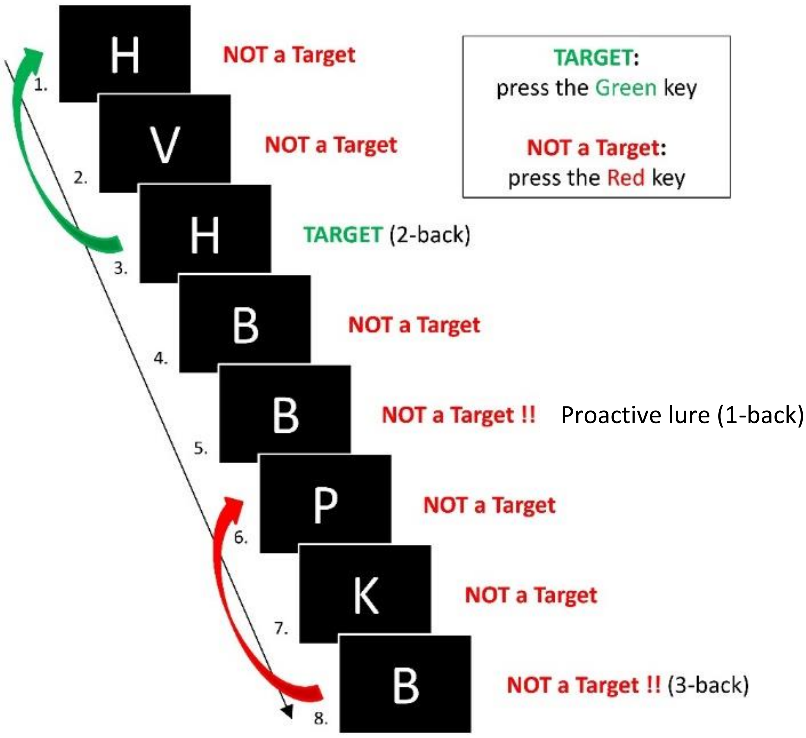
Training

Participants from experimental groups were engaged in the adaptive *n*-back training, that was an adaptation of the letter *n*-back in which one letter at a time was displayed on their screen and the task goal was to recognize the current letter whether it matched the letter that had been displayed "*n*" items prior. The number displayed by "*n*" constituted the rule for performing the task. The experimental training paradigm included ten set size conditions: 1-back to 10-back with new (neutral) and proactive distractors in each set size. New distractors do not directly connect to target stimuli, but they are identified as distractors which significantly interfere with target items; however, proactive distractors are designed to simulate target stimuli and contribute to the challenge for determining actual target information, leading to proactive interference. This data corresponded to 16 total levels of training.

Stimuli were presented one by one as white letters in the center of a black screen for 600 ms of duration and an interval between each stimulus was 2400 ms. Throughout the *n*-back task, participants were responsible to press a green button for the target and a red button for any distractor item (see Figure 3, below). They were asked to place the stickers for the response buttons on their own keyboard before starting a task: A green sticker on "M" key and a red one on "X" key.

Every *n*-back task included 1 practice block and 3 experimental blocks. Each block contained 24+*n* trials of *n*-back level. In the training sessions, participants were responsible to complete two different conditions for each *n*-back level, which are neutral condition and proactive interference condition for the levels ranging from 1-back to 10-back. For the neutral condition, there were 2 different item types: target (an item that matches the letter that appeared "*n*" prior) and neutral distractor (letter that is not the target). For the proactive interference condition, there were 3 different item types: target, neutral distractor, and proactive lure (i.e. target letter appeared at *n*-1 position). For the 1-back task, the condition is not real proactive interference, and this condition is called as "possible proactive interference condition" where participants are prone to make possible errors. In the proactive interference condition, proactive lure is a distractor which was presented previously and resembles a target information. It creates interference to recognize the current information (target) (See Figure 2). In this condition, each block consisted of 25% targets, 50% neutral distractors, 25% proactive interference lures.

Figure 3. Example of 2-back task with lures (provided by Cognition and Language laboratory at The Graduate Center, CUNY)



After participants completed one block of practice trial in the beginning of each level, the accuracy was checked, whether it was greater than 60%. They could pursue experimental blocks of a current level if they received this accuracy rate from the practice trial. Further, their performance adaptation was adjusted to a suitable *n*-back level based on accuracy of the previous level. When a participant reached less than 60% accuracy in the experimental blocks, they repeated the trials at the previous level. When they achieved the accuracy rate between 60%-85%, they trained at the current level. When they received above 85% accuracy, they were presented with the next length of training in the next block. In the training, the independent variables were the n-level, item (stimulus) type, and condition while the dependent variables were accuracy and reaction time.

All participants in the training groups completed a Theories of Cognitive Abilities Scale (Dweck et al., 1999) before starting the first training session to gather data regarding their motivation and beliefs about the benefits of cognitive training. The questionnaire (see Appendix

A) consisted of three statements, such as *your intelligence is something about you, that you can't change very much*, which were rated from one (Strongly agree) to six (Strongly disagree).

Pre and Post Tests

All participants completed a battery of tests (Table 4) depending on their group assignment to understand the effect of the training within-groups and to compare their performance between groups. Accuracy and reaction time data for each task were collected from E-Prime Go result sheets. All groups completed the same battery in the same order, other than arithmetic operations and word problems, in the week before and the week after the training period. The difficulty of the arithmetic operations and word problems was adjusted to children's grade level and Turkish mathematics curriculum was considered to decide the digit size of the numbers for each mathematics test.

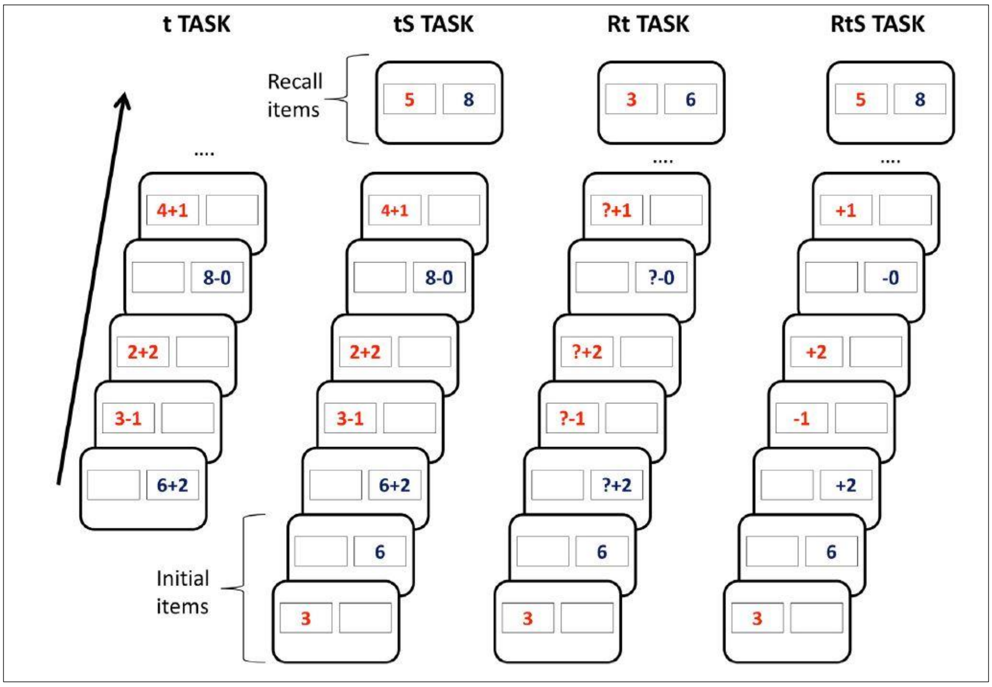
Table 4. Detailed information on pre and post-tests

Tasks	Conditions	Item Types
1-back	Neutral	New Distractor Target
	Possible Interference	New Distractor Target Target (Possible error)
2-back	Neutral	New Distractor Target
	Interference	New Distractor Target Proactive interference
Modified Digit Span	Transformation	New Distractor Target
	Substitution	
	Retrieval	
	Retrieval and Substitution	
Arithmetic Operations	Baseline	Target
	Interference-based	
Word Problems	Baseline	Target
	Literal irrelevant information	
	Numerical irrelevant information	

n-back: 1-back and 2-back tasks were administered to examine participants' WM updating skills. Each condition of these two tasks included one practice block and three experimental blocks which were considered to gather data. Participants completed the neutral condition of the *n*-back tasks before the possible proactive interference condition for the 1-back task and the proactive interference condition for the 2-back task in the order in which they received the 1-back and the 2-back tasks respectively. Even though there is no proactive interference condition for the 1-back task, proactive interference error can possibly occur if a participant responds "Yes" incorrectly to an item which was presented two steps back and is no longer relevant. In this task, the independent variables were the n-level, item (stimulus) type, and condition while the dependent variables were accuracy and reaction time.

Modified Digit Span (MDS): Four tasks were included as different components of WM system. Arithmetical operations were presented sequentially in two boxes for each task on participants' computer screens. In some tasks, participants were responsible to retrieve the information in the box where they used it as an operand to apply the operation and then substitute the result in the relevant box (see Figure 4). In the t task, only transformation was required, and participants simply did the calculations and typed the results in the corresponding boxes without retrieving or substituting any information. Due to no presence of any information to memorize, this condition did not include initial and recall items. In the tS task, participants had to remember the first presented initial items and apply the operations in each box. Since this task involved substitution, they were required to hold the result of each operation in mind to memorize recall items at the end of each list. In the Rt task, which included retrieval, two initial numbers presented in the beginning of each list were required to be memorized, associating with the box. Then, each number was retrieved to use it in incomplete operations (e.g., ? + 2) depending on its box. After participants performed the operations and entered the results, they typed these initial numbers in their associated boxes at the end of the list. In the RtS task, which included retrieval and substitution, participants were responsible to remember the first presented initial item for each box and use it to perform the first incomplete operation (e.g., + 3) of the associated box. The result of each box had to be remembered to use it as an operand for the following operations. At the end of the list, the last result of each corresponding box had to be entered. The tasks consisted of 40 lists in total (10 for each task) and the length of a list varied between 4 and 10. It should be noted that participants did not anticipate the end of each list which was randomized in order. Initial items and first operands comprised of numbers between 2 and 9, and arithmetical operations involved only ±1, ±2 or ±3. In this task, the independent variables included task type (condition) and item type, while the dependent variables included accuracy and reaction time.

Figure 4. Example list of each MDS task



Arithmetic Operations: Baseline and interference condition of arithmetical operations were administered to measure far transfer effect of the training to performance to resist interference while solving arithmetical operations within large size. Participants were presented questions on their computer screen consecutively without limiting time until they answered them. This task was separated into four tasks: Addition, Subtraction, Multiplication and Division and each task included 10 questions within the two different conditions. Throughout the tasks, participants had to press a correct answer on their keyboard among A, B, C and D, which were associated with answer options. The baseline condition contained simple operations with small size (e.g. 3-digit numbers) of operands for each operation, whereas the interference-based condition involved large-size operands. For addition, subtraction, multiplication and division, the baseline condition contained seven, five, five and four questions respectively, the rest of out of 10 questions belonged to interference-based condition. In this task, the independent variables were condition and operation type while the dependent variables were accuracy and reaction time.

Figure 5. Example of the baseline condition

2) 432
x 2

A) 964 **B)** 876 **C)** 654 **D)** 864

Figure 6. Example of the interference condition

6) 23
x 34

A) 161 **B)** 682 **C)** 6 992 **D)** 782

Word Problems: A total of six-word problems (Ng et al., 2017) were administered to measure far transfer effect of the training to performance on mathematics problems which included literal and numerical irrelevant information. First, the problems were translated into Turkish from the English version. The task consisted of two conditions: The baseline condition had two problems which did not include any irrelevant information, and the biased condition contained four problems with irrelevant information either literally or numerically. Simple addition and subtraction were required to solve the problems in two steps. The questions appeared on their computer screen consecutively and each question contained 4 answer options with associated letters (e.g., A. 3456). Participants were responsible to press one letter on their keyboard among A, B, C and D after they solved each question. In this task, the independent variables were condition and information type while the dependent variables were accuracy and reaction time.

Example for baseline condition, the problem without irrelevant information:

"John baked 3124 cupcakes on Monday. On Tuesday, John baked another 2353 cupcakes. The next day, he baked 5468 cupcakes. How many cupcakes did John bake all together?" (Ng et al., 2017, p.8).

Example for the biased condition, the problem with a literal irrelevant information:

"On an island, there are 3196 trees. A big fire destroyed 34 trees in summer and a smaller fire destroyed 59 in spring. A few of the trees destroyed were banana trees. How many trees are left on the island?" (Ng et al., 2017, p.8).

Example for the biased condition, the problem with a numerical irrelevant information:

"Jurong East library has 4619 books. The library can keep 7646 books. This year, the library lost 42 books and another 12 books were thrown away. How many books are left in the library?" (Ng et al., 2017, p.8).

Data Processing

Data on the progress of each participant in the training groups were collected to monitor their completion level of the adaptive *n*-back task in each session. The achieved highest *n*-level was determined based on completed sixteen sessions to measure the progress of each participant. Accuracy and reaction time data were collected from both the pre- and post-tests. R studio (2022) was used for both data processing and analysis. The outliers were detected by calculating standard deviations and z-scores of reaction time data gathered from each trial within each condition of all tasks in each session. Any data that were below or above three standard deviations from the aggregated mean of the participant were removed from the dataset. The percentages of removed data for each pre- and post-test were less than 2%. Accuracy and reaction time data were used separately as dependent variables to compare between group performance at pre-test or post-test regarding group type. To compare within group performance, change in performance from pre- to post-test in terms of accuracy and reaction time was used as dependent variables. Changes in outcomes were calculated for each participant by determining mean accuracy or reaction time aggregated only at probe type level and then subtracting the mean of pre-test from the mean of post-test to obtain the difference.

3.4 Data Analysis

The analysis confirming that participants in all groups did not significantly differ in factors such as age, nonverbal IQ, and WM capacity, as measured by digit span and semantic verbal fluency tasks, was conducted. To understand the extent to which individual differences in these factors predict the maximum level achieved in the *n*-back task throughout the training duration, a correlation analysis was performed. The progression of participants in both training groups was studied through a multilevel regression analysis to identify which specific factors, including age, socioeconomic status (SES), motivation, session, and baseline cognitive resources, could predict the attained *n*-level in each session.

Subsequent analyses were carried out to determine if there was a significant difference in terms of accuracy and reaction time performance patterns across all tasks and conditions between the pre-test training and control groups. All participants from these two groups were then combined to evaluate performance patterns across different tasks, conditions, and item types in the pre-test battery.

To test the training effect, two different analyses were performed. The first set of analyses aimed to determine whether there was a significant change in accuracy and reaction time performance in the pre-test training group after the training period. Secondly, the post-test performance of the post-test training group and the post-test only control group were compared for each task, with only group differences considered.

To analyze the test-retest effect, two different analyses were conducted. The first analysis checked for changes in performance in the pre-test control group (C1) to understand whether their performance significantly differed from pre- to post-tests. Secondly, the post-test performance of the pre-test control group (C1) and the post-test only control group (C2) was evaluated to determine if there was a significant performance difference between these groups.

Four analysis goals were addressed using a mixed-effects regression analysis to investigate both within- and between-subject effects in hierarchical data. The responses and level-1 variables for each task were nested within each participant. To do this, the dependent variable was identified, its distributions were checked, and the model was initially run without any predictors. Level-1 predictors were incrementally added in subsequent analyses. The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) statistics were compared to evaluate whether the model was the best fit. The model chosen for this study had the lowest AIC/BIC values. In the regression analyses, significance level (p = 0.05) was considered.

Chapter 4 Results

4.1 Training progress

Descriptive analyses were conducted to identify all five parts of hypothesis 1 within the progress of training and identify participants' characteristics in this progress. The level of *n*-back task they completed differed across the participants. The minimum level achieved by only one participant was 2-back level with proactive interference lures, and the maximum level achieved by only one participant was 8-back level with proactive interference lures (see Figure 7 below). The participants did not differ in self-reports of motivation which was measured by the Theories of Cognitive Abilities questionnaire (Dweck, 2000). The Likert scale data was gathered from the three questions which were rated on a scale from one to six. All participants, except one, received total scores between 13-18 out of 18, the one participant scoring six out of 18. Therefore, it was assumed that the Theories of Cognitive Abilities questionnaire was not a sufficient predictor of individual differences in this training progress. According to normality test (see Table 2, above), TONI and SVFT scores which measured verbal memory were normally distributed, so these results were used to examine the relationship between each variable and training progress in Pearson correlation.

Figure 7. *n*-back level achieved by participants in training groups

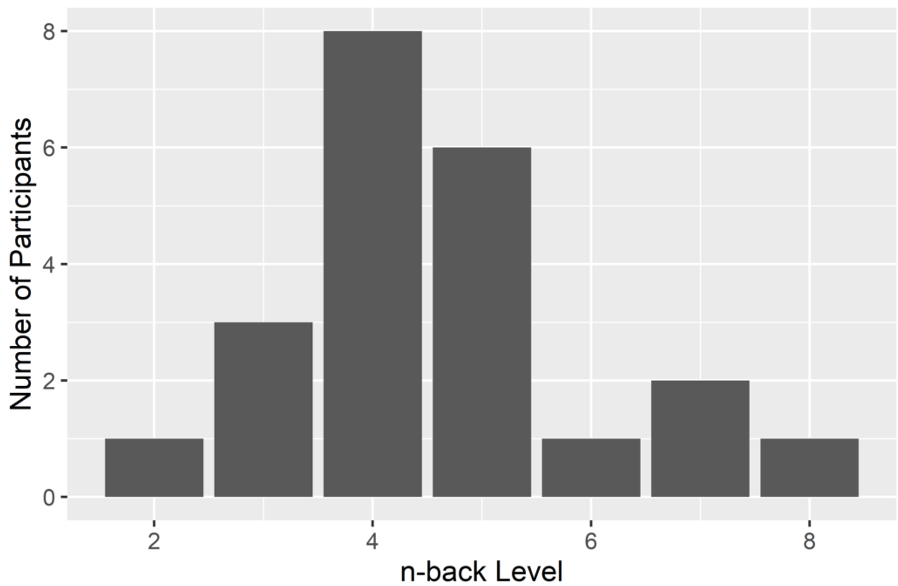


Table 5. Correlation of participants' characteristics and their training progress

Variable	*t*	df	p	r
Nonverbal IQ	1.494	20	0.151	0.317
SVFT scores	0.667	20	0.513	0.147

According to correlation analysis (Table 5), nonverbal IQ and SVFT were not correlated with the achieved training level. As a result, participants' cognitive abilities were not significantly correlated with the maximal training level they completed.

Figure 8. Plot of nonverbal IQ score by level of training progress

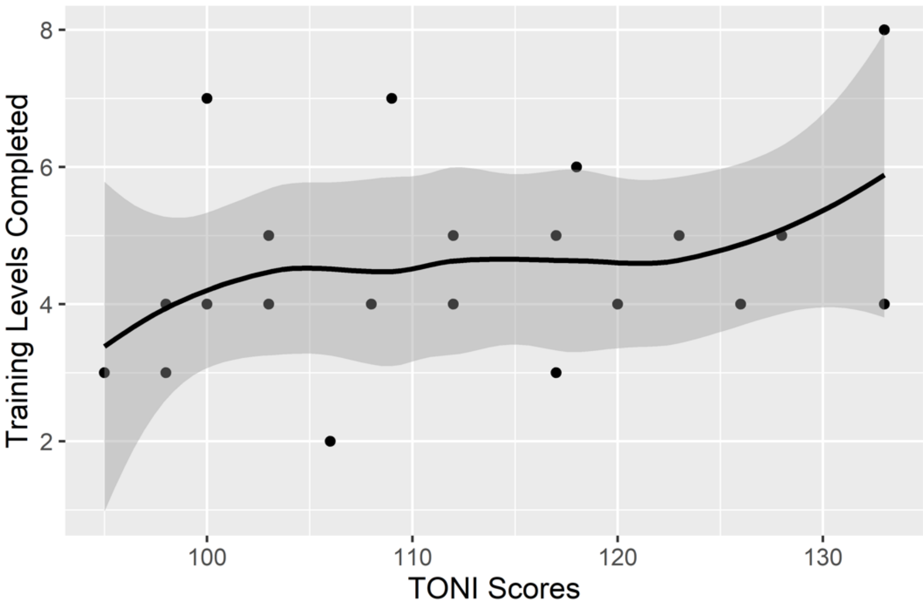
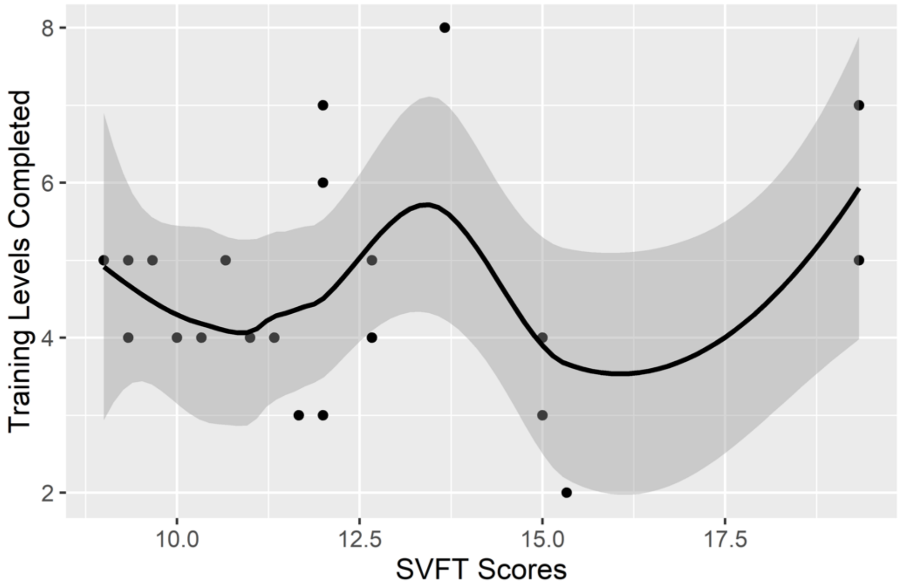


Figure 9. Plot of SVFT score by level of training progress



Hypothesis 1b indicated that participants would show improvement throughout the training period. The distribution of maximum n-level achieved in each session was analyzed to observe the progression of each participant's training from the beginning to the end in the scatter plots (see Figure 10 and Figure 11 below).

Hypothesis 1e posited that baseline cognitive resources would predict participants' training progress more than other factors, such as age, SES, motivation, and session. To test this hypothesis, multilevel regression analyses were used separately for each factor. The last completed n-level was gathered as a score for baseline cognitive resources. The maximum *n*-level from each session was chosen as a reference for each predictor. The results showed that the main effect of session and baseline cognitive ability on *n*-level was significant. However, there was no significant main effect of age, SES or motivation on the maximal completed n-level (Table 6).

Figure 10. T1 group training progress

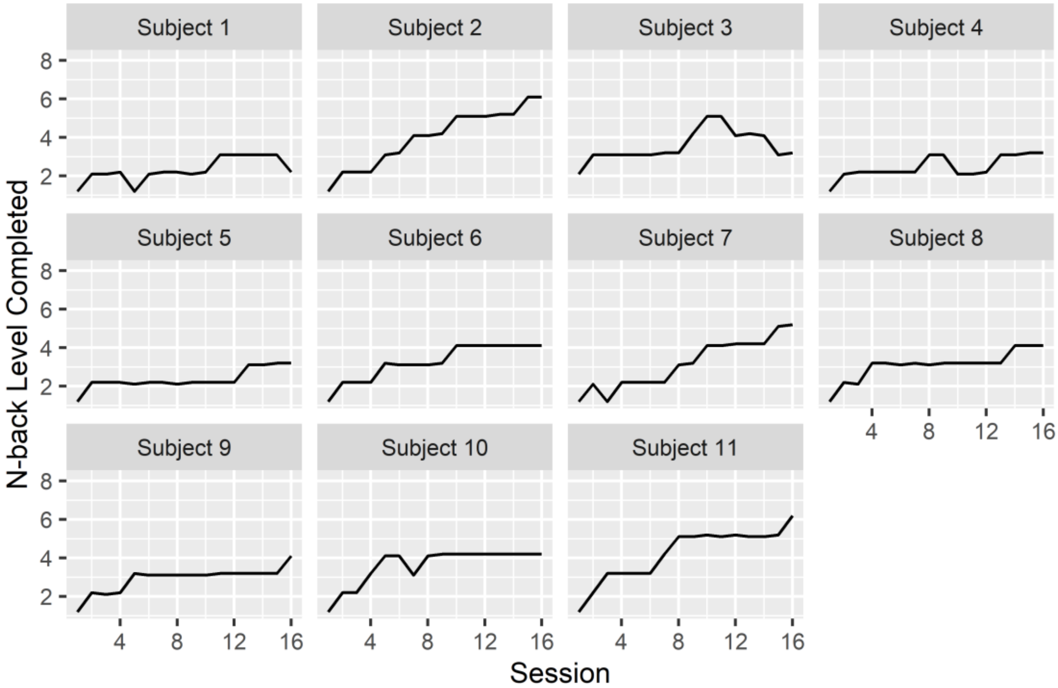


Figure 11. T2 group training progress

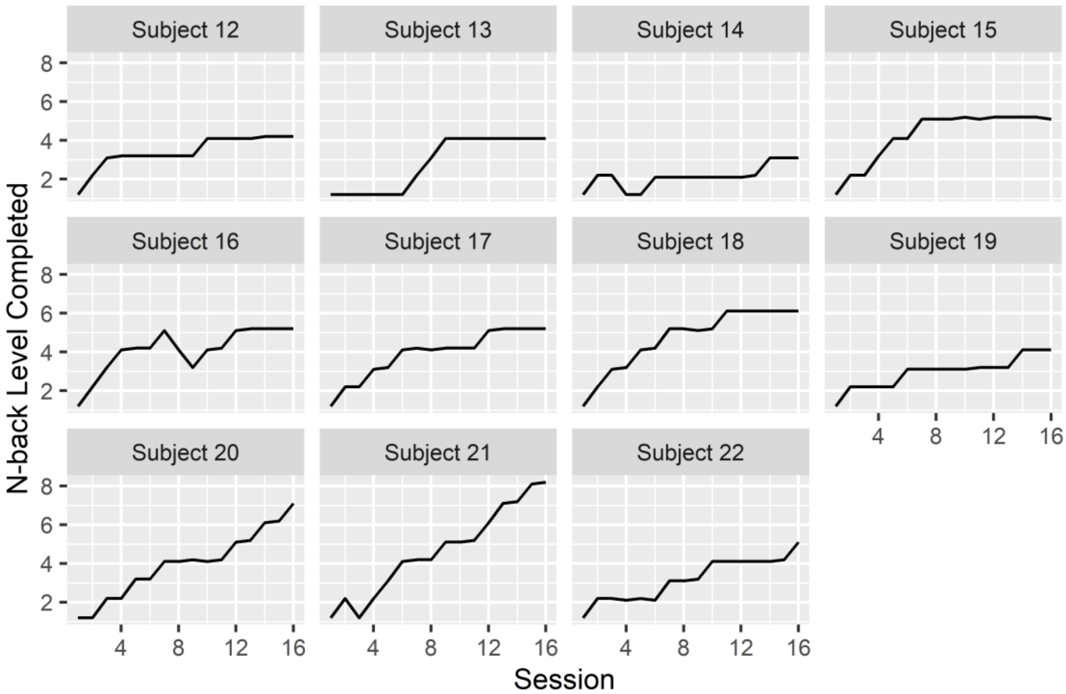


Table 6. Multilevel analysis of training data

Change in time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	1.507 (0.174)	8.664	**< .001**
Session	0.207 (0.008)	26.077	**< .001**
Random effects	Variance	*sd*	
Intercept	0.536	0.732	
Residual	0.470	0.686	
Age as a predictor			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	0.914 (1.765)	0.518	0.610
Age	0.228 (0.170)	1.337	0.196
Random effects	Variance	*sd*	
Intercept	0.455	0.675	
Residual	1.438	1.199	
Socioeconomic Status as a predictor			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	2.109 (0.929)	2.271	**< .05**
SES	0.072 (0.057)	1.261	0.222
Random effects	Variance	*sd*	
Intercept	0.460	0.678	
Residual	1.438	1.199	
Motivation as a predictor			
Variable	Estimate (SE)	*t*	*P*
Fixed effects			
Intercept	2.543 0.916	2.778	**< .05**
Motivation	0.048 0.059	0.800	0.433
Random effects	Variance	*sd*	
Intercept	0.485	0.697	
Residual	1.438	1.199	
Baseline as a predictor			
Variable	Estimate (SE)	*t*	*P*
Fixed effects			
Intercept	1.776 (0.524)	3.388	**< .01**
Baseline	0.655 (0.223)	2.942	**< .01**
Random effects	Variance	*sd*	
Intercept	0.325	0.570	
Residual	1.438	1.199	

Note: Group presented is the T1 group and T2 group (total n = 22). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Further analyses were conducted to examine participants' performance in each task and to test training and practice effects on the tasks. The distribution of groups varied across the different sets of tasks (see Table 7).

Table 7. Summary of testing batteries across groups and tests

Tests / Performance	Interpreting each task	Training effect	Practice effect
Pre-tests	T1 & C1		
Post-tests		T2 & C2	C1 & C2
Change in pre to post tests		T1	C1

4.2 Pre-test performance

A set of analyses was conducted to address hypothesis 2 with its five parts, which were built to interpret participants' performance on pre-test tasks. Pre-test data was not aggregated for any tasks before the analysis. Correct and incorrect answers in accuracy data were gathered as binary data and a mixed-effects logistic regression model was conducted in condition of family binomial and link logit. Unaggregated reaction time data which was normally distributed was transformed by removing outliers for each participant. A mixed-effects linear regression model was conducted with maximum likelihood estimation.

Hypothesis 2a postulated that T1 (training group that completed pre- and post-tests) and C1 (control group that completed pre- and post-tests) groups would not differ significantly in any task of the testing battery. This part of hypothesis 2 was initially tested for each task by selecting group and condition as predictors. The other parts of hypothesis 2 claimed to interpret participants' performance on task manipulations of each task and were tested by including condition and item type as predictors. The model of random effects with random slope and random intercepts was used for each part of the hypotheses since it is the strongest model for confirmatory hypothesis testing (Barr et al., 2013).

n-back Task

Group, condition, and item type were involved in both the accuracy and reaction time datasets as predictors. C1 group was chosen as a reference for the group variable; 1-back was the reference for *n*-back variable; neutral condition was the reference for the condition variable. The results of the analysis showed that the main effect of group on accuracy and reaction time performance was not significant and while there was no main effect of *n*-level on accuracy performance, on reaction time performance, the main effect was significant (Table 8). The model was created to test *n*-back performance within different conditions by combining the two groups after analysis of group difference. The main effect of condition on accuracy and reaction time performance was significant for both 1-back and 2-back tasks (Table 9-10).

Table 8. Accuracy and reaction time predicted by group and *n*-back level

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	1.652 (1.169)	1.412	0.158
Group	0.535 (0.749)	0.714	0.475
2-back	-0.050 (0.212)	-0.237	0.813
Random effects	Variance	*sd*	
Intercept	2.711	1.646	
Reaction time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	805.86 (125.15)	6.439	**< .001**
Group	-80.676 (78.459)	-1.028	0.317
2-back	0.058 (0.027)	2.160	**< .05**
Random effects	Variance	*sd*	
Intercept	32412	180.0	
Residual	69096	262.9	

Note: Group presented is the T1 group (n = 11), reference group is the C1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

In the 1-back condition, participants performed with significantly lower accuracy in the possible proactive interference (PI; including possible interference errors) condition than in the neutral condition (no interference items) and there were higher reaction times in the PI than in the neutral condition (Table 9).

Table 9**.** Pre-test 1-back accuracy and reaction time predicted by condition

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	0.840 (0.310)	2.713	**< .05**
Proactive	1.653 (0.175)	9.465	**< .001**
Random effects	Variance	*sd*	
Intercept	1.492	1.221	
Reaction time			
Variable	Estimate (SE)	*t*	*p*

Fixed effects			
Intercept	485.65 (34.040)	14.267	< **.001**
Proactive	0.218 (0.022)	9.982	< **.001**
Random effects	Variance	*sd*	
Intercept	19399	139.3	
Residual	96797	311.1	

Note: Sample n = 22. The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Figure 12. 1-back pre-test accuracy mean by condition

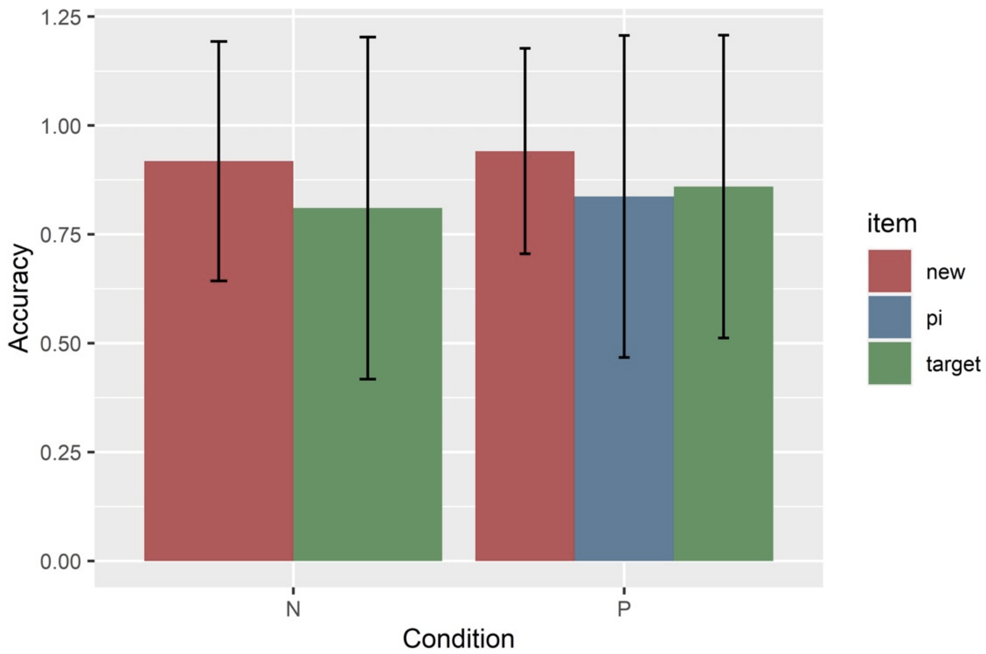
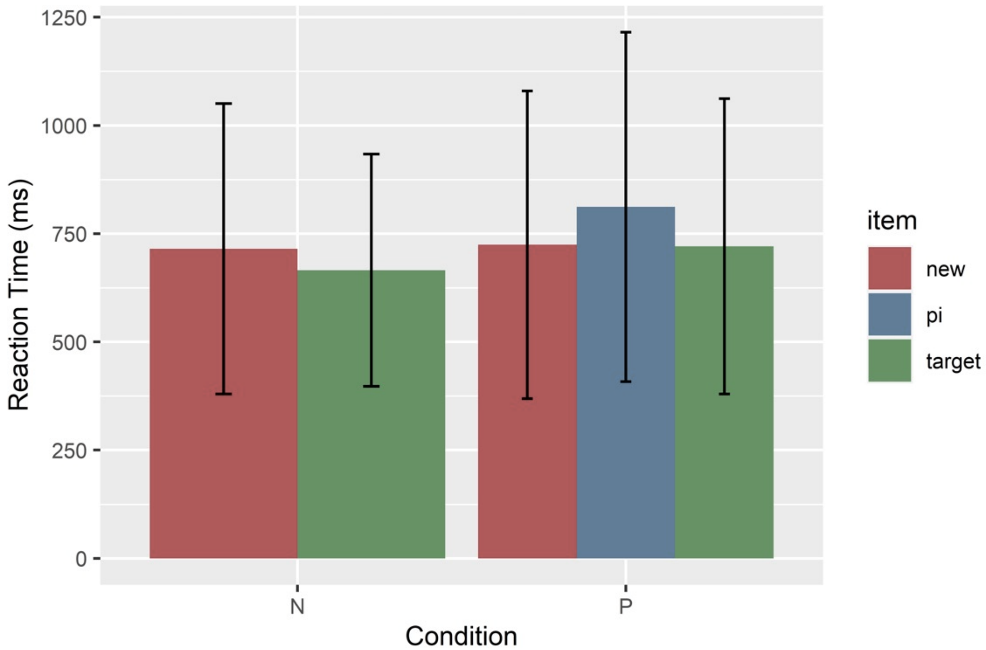


Figure 13. 1-back pre-test reaction time mean by condition



In the 2-back, participants performed with significantly higher accuracy in the PI condition than in the neutral condition and produced higher reaction times in the PI condition than in the neutral condition (Table 10).

Table 10. 2-back pre-test accuracy and reaction time predicted by condition

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	1.228 (0.262)	4.683	< **.001**
Proactive	0.311 (0.144)	2.155	< **.05**
Random effects	Variance	*sd*	
Intercept	1.143	1.069	
Reaction time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	671.7 (53.98)	12.442	< **.001**
Proactive	0.072 (0.021)	3.357	< **.001**
Random effects	Variance	*sd*	
Intercept	55691	236.0	
Residual	86351	293.9	

Note: Sample n = 22. The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Figure 14. Pre-test 2-Back accuracy means by condition

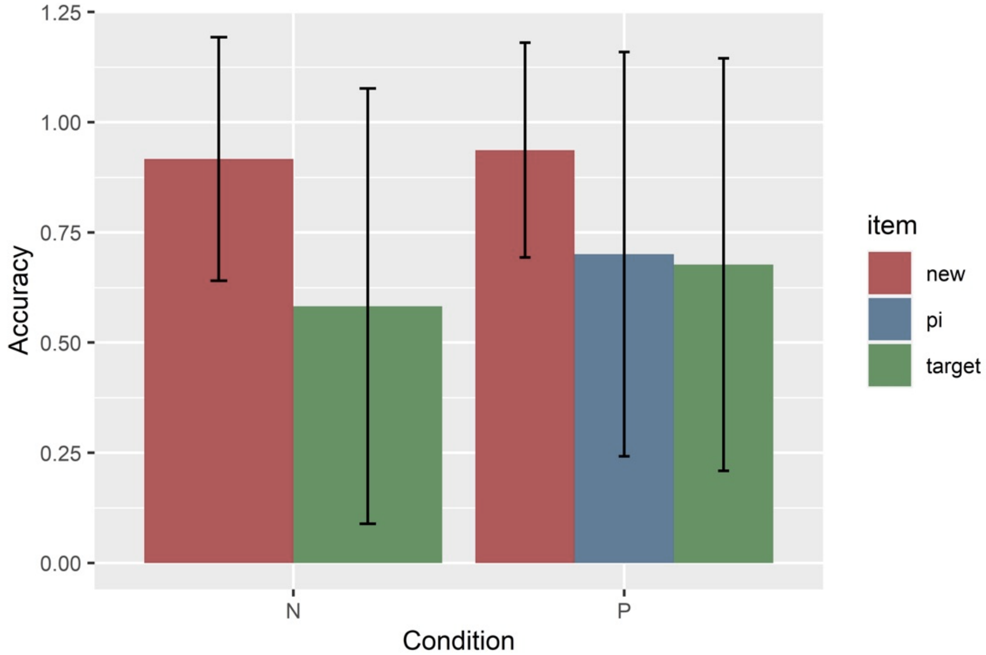
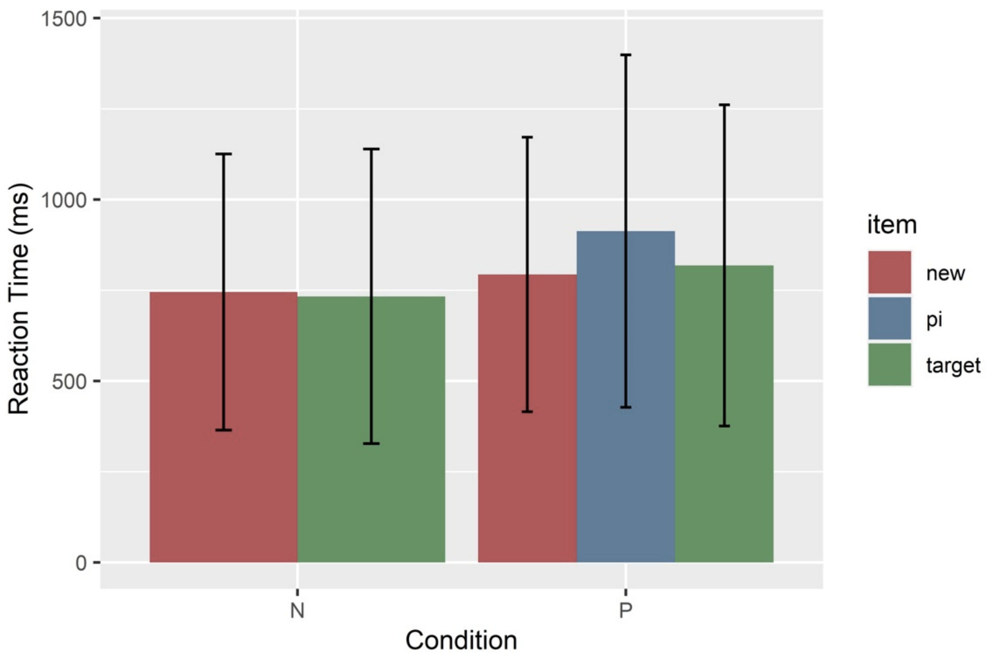


Figure 15. Pre-test 2-Back reaction time means by condition



MDS Task

Group and condition were initially entered as the predictors for accuracy and reaction time performance. The performance on the modified digit span task was analyzed by baseline and interference conditions separately. Interference condition included different conditions itself: tS, Rt and RtS conditions. The item type consisted of operation and recall item type. The data gathered from different conditions and item types was categorized into two blocks: short-listed and long-listed. The reference for group was C1, whereas the tS and short-listed blocks served as reference for condition. The main effect of group was not significant on accuracy and reaction time performance (Table 11). There was also no main effect of item type on accuracy or reaction time performance for the baseline condition (Table 12). The main effect of condition on accuracy performance was significant for the RtS condition with short and long-listed blocks (Table 13). The main effect of condition on reaction time performance was significant for both the tS condition with long listed blocks and the RtS condition with long-listed blocks (Table 13). After testing group difference and performance on the baseline and interference condition, performance on tS, Rt and RtS conditions were analyzed by each item type.

Table 11. Pre-test MDS task accuracy and reaction time predicted by group

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	4.067 (0.727)	5.598	**< .001**
Group	-0.253 (0.448)	-0.564	0.573
Random effects	Variance	*Sd*	
Intercept	0.522	0.722	
Reaction time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	2444.9 (747.3)	3.272	**< .01**
Group	-388.4 (472.6)	-0.822	0.421
Random effects	Variance	*sd*	
Intercept	1217278	1103.3	
Residual	774191	879.9	

Note: Group presented is the T1 group (n = 11), reference group is the C1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Table 12. Pre-test MDS task accuracy and reaction time predicted by item type of baseline condition

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	2.485 (1.041)	2.387	**< .05**
Operation (long)	0.841 (1.072)	0.784	0.433
Random effects	Variance	*sd*	

Intercept	1.676e-13	4.094e-07	
Reaction time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	1909.5 (244.6)	7.806	**< .001**
Operation (long)	88.09 (75.02)	1.174	0.241
Random effects	Variance	*sd*	
Intercept	1277350	1130	
Residual	811749	901	

Note: Sample n = 22. The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Table 13. Pre-test MDS task accuracy and reaction time predicted by condition of interference condition

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	3.147 (1.169)	2.692	**< .01**
tS (long list)	-1.426 (1.094)	-1.303	0.193
Rt (short)	-0.015 (0.423)	-0.036	0.972
Rt (long)	0.454 (0.408)	1.112	0.266
RtS (short)	1.783 (0.437)	4.077	**< .001**
RtS (long)	-0.981 (0.438)	-2.239	**< .05**
Random effects	Variance	*sd*	
Intercept	0.535	0.732	
Reaction time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	1987.5 (165.4)	12.01	**< .001**
tS (long list)	229.1 (67.29)	3.406	**< .001**
Rt (short)	-53.82 (59.20)	-0.909	0.364
Rt (long)	152.0 (100.8)	1.508	0.132
RtS (short)	89.41 (67.95)	1.316	0.189
RtS (long)	173.1 (68.72)	2.519	**< .05**
Random effects	Variance	*sd*	
Intercept	526589	725.7	
Residual	1514693	1230.7	

Note: Sample n = 22. The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

There was no significant effect for item type on accuracy performance for the tS condition (Table 14) and Rt condition (Table 15), except with the RtS condition (Table 16), while the main effect for item type on reaction time performance was significant for each condition. In the RtS condition, participants performed with significantly lower accuracy in long listed operation item type than in short and long listed recall item type (Table 16).

Specifically, participants performed with higher reaction time in long listed operation type than other item types for the tS condition. In Rt condition, participants showed higher reaction time performance in long listed operation and short-listed recall item types. In the RtS condition, the performance in reaction time across item types was similar.

Table 14. Pre-test MDS task accuracy and reaction time predicted by item type of tS condition

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	10.892 (104.529)	0.104	0.917
Operation (long list)	-7.225 (104.543)	-0.069	0.945
Recall (short list)	0.390 (0.985)	0.396	0.692
Recall (long list)	0.134 (1.005)	0.133	0.894
Random effects	Variance	*sd*	
Intercept	0.858	0.926	
Reaction time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	2128.88 (129.58)	16.429	**< .001**
Operation (long list)	870.14 (134.07)	6.490	**< .001**
Recall (short list)	41.05 (114.58)	0.358	0.721
Recall (long list)	115.01 (99.57)	1.155	0.250
Random effects	Variance	*sd*	
Intercept	172047	414.8	
Residual	1518750	1232.4	

Note: Sample n = 22. The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Table 15. Pre-test MDS task accuracy and reaction time predicted by item type of Rt condition

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	0.244 (1.169)	0.209	0.8348
Operation (long-list)	1.202 (0.625)	1.924	0.054
Recall (short-list)	-0.235 (0.627)	-0.375	0.707
Recall (long-list)	1.089 (0.723)	1.506	0.132
Random effects	Variance	*sd*	
Intercept	7.286	2.699	
Reaction time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	2779.31 (224.19)	12.397	**< .001**
Operation (long-list)	534.53 (212.29)	2.518	**< .05**
Recall (short-list)	360.61 (156.41)	2.306	**< .05**
Recall (long-list)	158.45 (158.70)	0.998	0.320
Random effects	Variance	*sd*	
Intercept	712887	844.3	
Residual	3132345	1769.8	

Note: Sample n = 22. The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Table 16. Pre-test MDS task accuracy and reaction time predicted by item type of RtS condition

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	-0.353 (0.700)	-0.504	0.614
Operation (long-list)	2.156 (0.697)	3.095	**< .01**
Recall (short-list)	1.062 (0.617)	1.720	0.085
Recall (long-list)	0.419 (0.557)	0.752	0.452

Random effects	Variance	*sd*	
Intercept	2.687	1.639	
Reaction time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	2291.66 (351.91)	6.512	**< .001**
Operation (long-list)	101.99 (149.97)	0.680	0.497
Recall (short-list)	-51.93 (127.80)	-0.406	0.685
Recall (long-list)	-233.32 (124.29)	-1.877	0.062
Random effects	Variance	*sd*	
Intercept	2444910	1564	
Residual	2040096	1428	

Note: Sample n = 22. The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Figure 16. Pre-test MDS task accuracy means by condition and item type

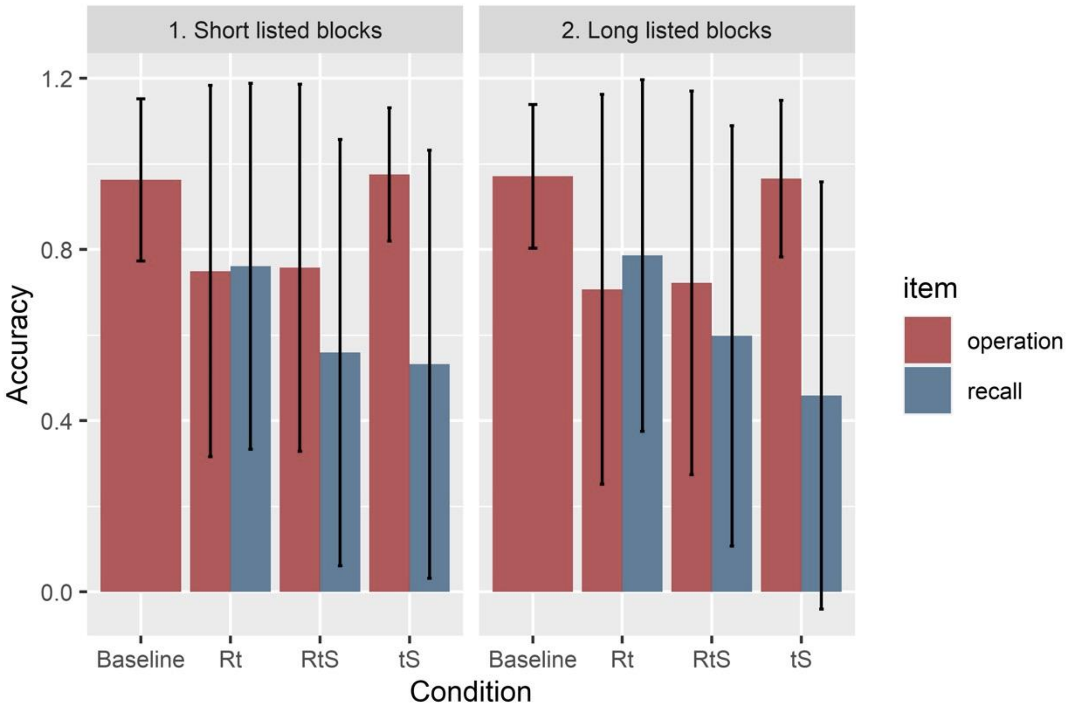
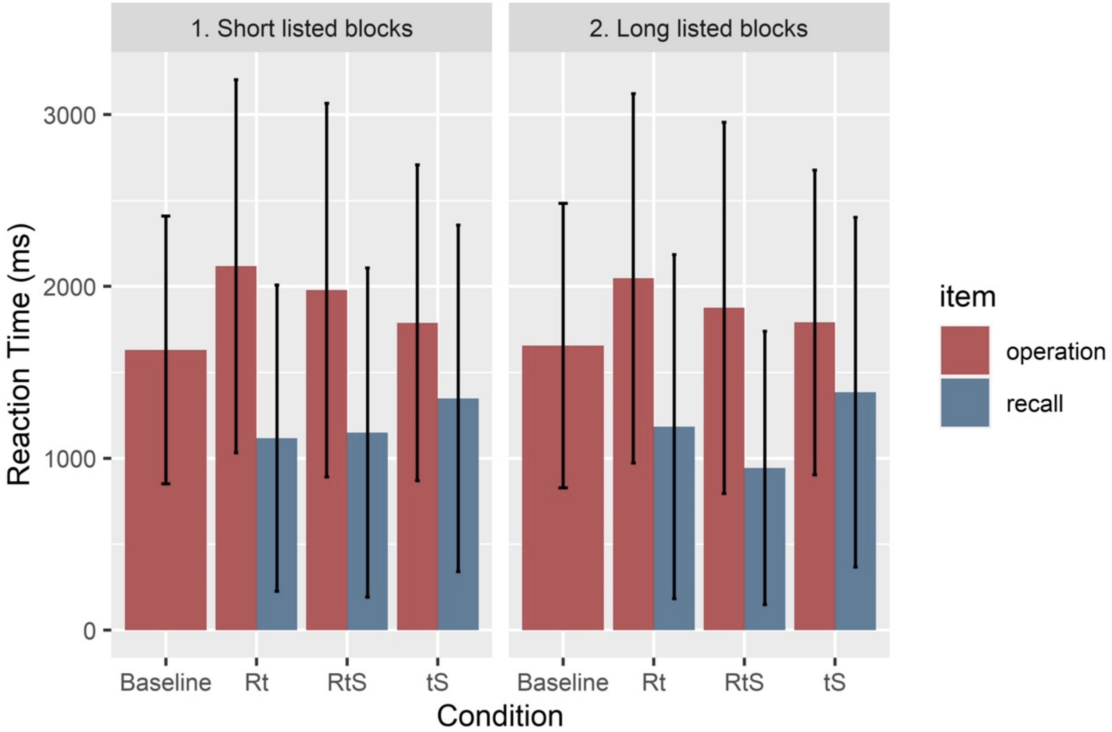


Figure 17. Pre-test MDS task reaction time means by condition and item type



Arithmetic Operations

Group was chosen as a predictor alone for primary analysis. For group variable, C1 group was chosen as a reference; for the condition, baseline condition was chosen as reference; for item variable, all operation types were chosen as a reference. There was no main effect of group on accuracy or reaction time performance.

Table 17. Pre-test arithmetic operations accuracy and reaction time predicted by group

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	4.355 (1.215)	3.586	< **.001**
Group	-0.608 (0.711)	-0.855	0.392
Random effects	Variance	*sd*	
Intercept	1.270	1.127	
Reaction time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	25418.3 (6179.3)	4.113	< **.001**
Group	-880.4 (3908.1)	-0.225	0.824
Random effects	Variance	*sd*	
Intercept	69708220	8349	
Residual	300225536	17327	

Note: Group presented is the T1 group (n = 11), reference group is the C1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

The main effect of condition was not significant for accuracy performance, but it was significant for reaction time. Specifically, participants showed lower accuracy performance in interference condition than in baseline condition and higher reaction time performance in interference condition. In baseline condition, their accuracy performance was similar across operation type, however, they had a higher reaction time on subtraction and multiplication than on addition and division. In the interference condition, participants performed with similar accuracy across operation types, while their reaction time performance was higher in multiplication and division than in addition and subtraction.

Table 18. Pre-test arithmetic operations accuracy and reaction time predicted by condition

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	2.836 (0.638)	4.447	**< .001**
Interference	0.675 (0.551)	1.226	0.22
Random effects	Variance	*sd*	
Intercept	1.122	1.059	
Reaction time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	23271.78 (1641.87)	14.174	**< .001**
Interference	3680.38 (901.14)	4.084	**< .001**
Random effects	Variance	*sd*	
Intercept	45212281	6724	
Residual	267784655	16364	

Note: Sample n = 22. The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Table 19. Analysis summary: Pre-test arithmetic operations accuracy and reaction time predicted by condition of baseline condition

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	47.27 (759.3)	0.062	0.950
Subtraction	-17.00 (605.9)	-0.028	0.978
Multiplication	-13.16 (587.9)	-0.022	0.982
Division	-14.18 (580.7)	-0.024	0.981
Random effects	Variance	*sd*	
Intercept	0	0	

Reaction time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	18635.9 (1259.0)	14.80	**< .001**
Subtraction	2127.5 (745.5)	2.854	**< .01**
Multiplication	1564.9 (684.1)	2.288	**< .05**
Division	-691.9 (890.0)	-0.777	0.439
Random effects	Variance	*sd*	
Intercept	28590852	5347	
Residual	24323676	4932	

Note: Sample n = 22. The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Table 20. Pre-test arithmetic operations accuracy and reaction time predicted by operation type of interference condition

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	-1.068 (1.408)	-0.758	0.448
Subtraction	0.824 (0.861)	0.956	0.339
Multiplication	1.512 (1.181)	1.280	0.200
Division	0.911 (1.144)	0.796	0.426
Random effects	Variance	*sd*	
Intercept	0	0	
Reaction time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	35547.1 (2512.2)	14.15	**< .001**
Subtraction	4140.4 (2485.3)	1.666	0.103
Multiplication	5881.8 (2863.1)	2.054	**< .05**
Division	7720.4 (1623.7)	4.755	**< .001**
Random effects	Variance	*sd*	
Intercept	77714019	8816	
Residual	99851109	9993	

Note: Sample n = 22. The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Figure 18. Pre-test arithmetic operations accuracy means by condition and item type

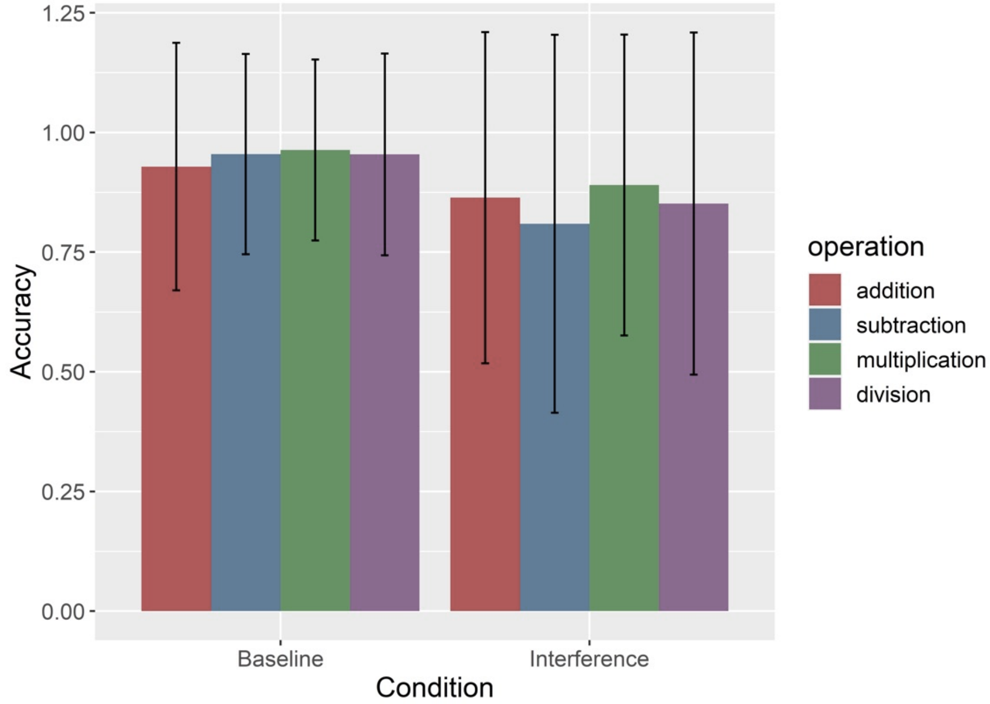
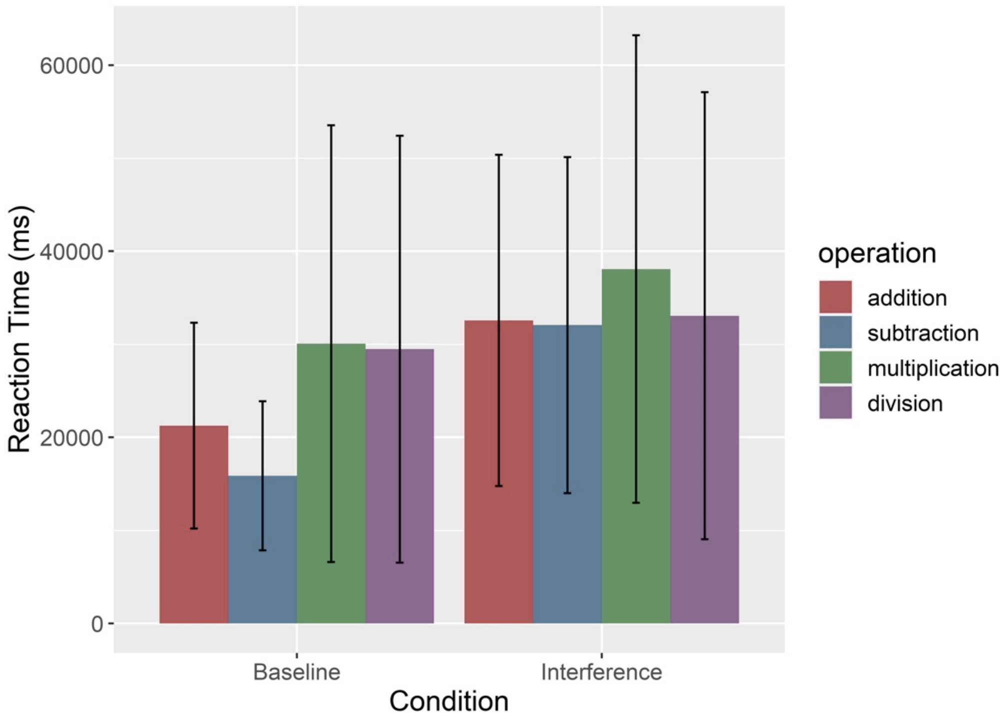


Figure 19. Pre-test arithmetic operations reaction time means by condition and item type



Word problems

The initial analysis was conducted to analyze the group difference and group was entered as a single predictor. The reference for group was C1 group; the reference for condition was the neutral condition, and the reference for information type was relevant information included in word problems. There was no significant main effect of group on accuracy and reaction time performance for word problems.

Table 21. Pre-test word problems accuracy and reaction time predicted by group

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	3.787 (2.177)	1.739	0.082
Group	-0.742 (1.264)	-0.587	0.557
Random effects	Variance	*sd*	
Intercept	1.099e-09	3.315e-05	
Reaction time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	85838 (28616)	3.000	**< .01**
Group	-13359 (18098)	-0.738	0.469
Random effects	Variance	*sd*	
Intercept	8.595e+08	29318	
Residual	1.884e+09	43405	

Note: Group presented is the T1 group (n = 11), reference group is the C1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

There was also no significant main effect of condition and item type on accuracy or reaction time performance. Additionally, while the main effect of information type was not significant on accuracy, the main effect on reaction time was moderately significant. Specifically, participants had lower accuracy on problems which included numerical irrelevant information than those with literal irrelevant and relevant information and higher reaction time on problems which included numerical irrelevant information than those with literal irrelevant and relevant information.

Table 22. Pre-test word problems accuracy and reaction time predicted by condition

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	32.59 (97.99)	0.333	0.739
Interference	-22.78 (97.99)	-0.233	0.816
Random effects	Variance	*sd*	
Intercept	257.6	16.05	
Reaction time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			

Intercept	65987.44 (9897.69)	6.667	**< .001**
Interference	556.76 (12070.72)	0.046	0.963
Random effects	Variance	*sd*	
Intercept	8.180e+08	28601	
Residual	1.944e+09	44088	

Note: Sample n = 22. The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Table 23. Pre-test word problems biased condition accuracy and reaction time predicted by information type

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	70.77 (31.39)	2.255	**< .05**
Literal distractor	-33.42 (31.39)	-1.065	0.287
Numerical distractor	-24.04 (31.39)	-0.766	0.444
Random effects	Variance	*sd*	
Intercept	2908	53.93	
Reaction time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	89490 (18048)	4.958	**< .001**
Literal distractor	-31426 (15190)	-2.069	0.052
Numerical distractor	66702 (32986)	2.022	0.058
Random effects	Variance	*sd*	
Intercept	2.084e+09	45649	
Residual	2.115e+09	45994	

Note: Sample n = 22. The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Figure 20. Pre-test word problems accuracy means by condition and information type

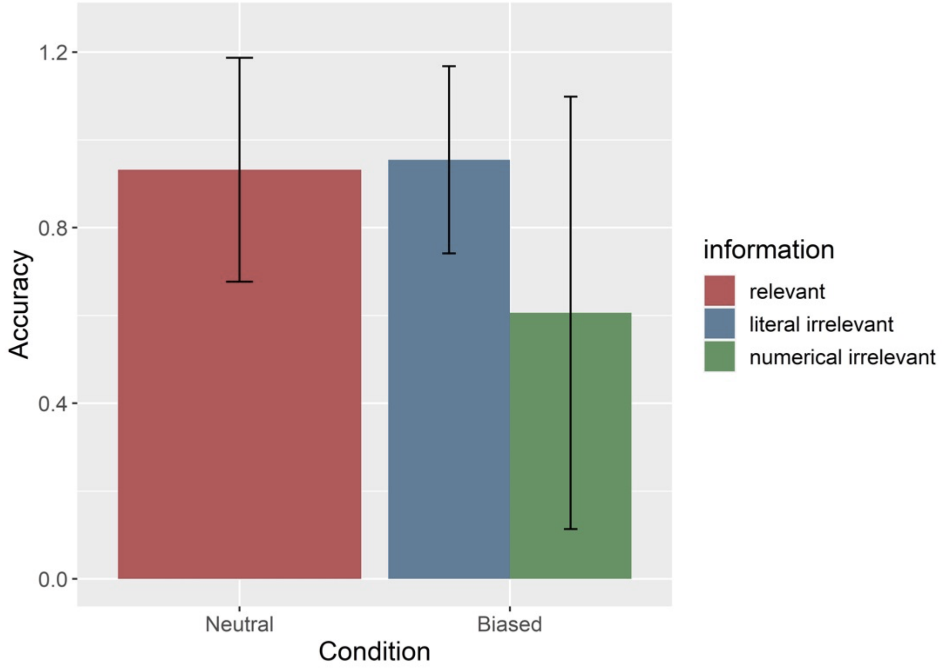
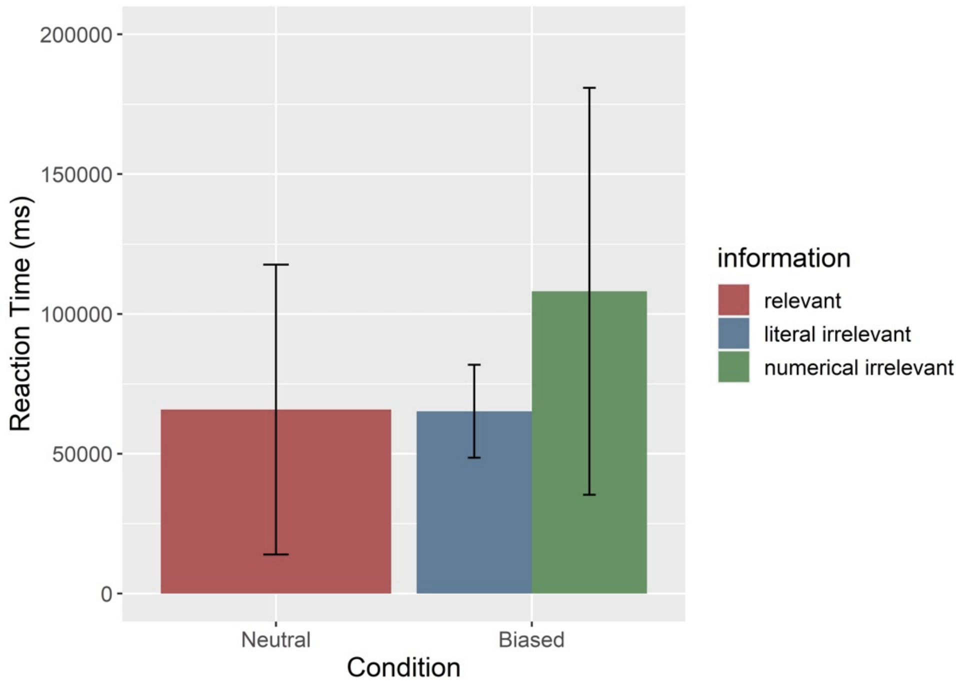


Figure 21**.** Pre-test word problems reaction time means by condition and information type



4.3 Training effect

The subsequent examinations focused on evaluating the effectiveness of training by assessing its influence on cognitive and mathematical assessments. A sequence of analyses was carried out to address hypotheses 3 and 4, which were formulated to determine whether the training groups exhibited enhanced performance on each task after the training.

4.3.1 Pre- to post-test change

The analyses conducted aimed to investigate the effects of manipulation on the performance changes of the training group across different tasks in the test battery, based on the four parts of hypothesis 3. The data sets were cleaned and transformed as differences between pre- to post-tests, and this data was aggregated at the final step. Since the calculated change in performance (both accuracy and reaction time) was a continuous dependent variable, mixed effects linear regression models with maximum likelihood estimation were used to analyze the results.

Different models were compared for each task, including the null model (no predictors), a model with random intercept, a model with random intercept and random slope, and a model with random intercept, random slope, and interactions. The null model was particularly important in determining whether the change score for each task significantly differed from zero. After the initial assessment, predictors of change were added to each model to determine the best fit. Ultimately, the final chosen model beyond the null model included a random intercept without interactions. The results are presented for the null model, the model with the condition predictor, and the model with item type predictors within each condition.

n-back

The intercepts for null accuracy and reaction time change were not significant. Therefore, the changes on condition and item type of 1-back or 2-back tasks were not analyzed.

Table 24. *n*-back accuracy and reaction time change null model

Accuracy Change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	0.037 (0.026)	1.419	0.186
Random effects	Variance	*sd*	
Intercept	0.002	0.045	
Residual	0.011	0.103	
Reaction Time Change			

Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-105.16 (67.12)	-1.567	0.148
Random effects	Variance	*sd*	
Intercept	38582	196.4	
Residual	21937	148.1	

Note: Group presented is the T1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

The analysis revealed that there was a ceiling effect in accuracy for new distractors in 1-back task, indicating that the participants reached a maximum correct response beyond which further improvements could not be observed (see Figure 22). However, the accuracy of target items slightly increased from pre to post-test. The reaction time for both item types decreased from pre to post-test (Figure 23).

Figure 22. 1-back training group accuracy change

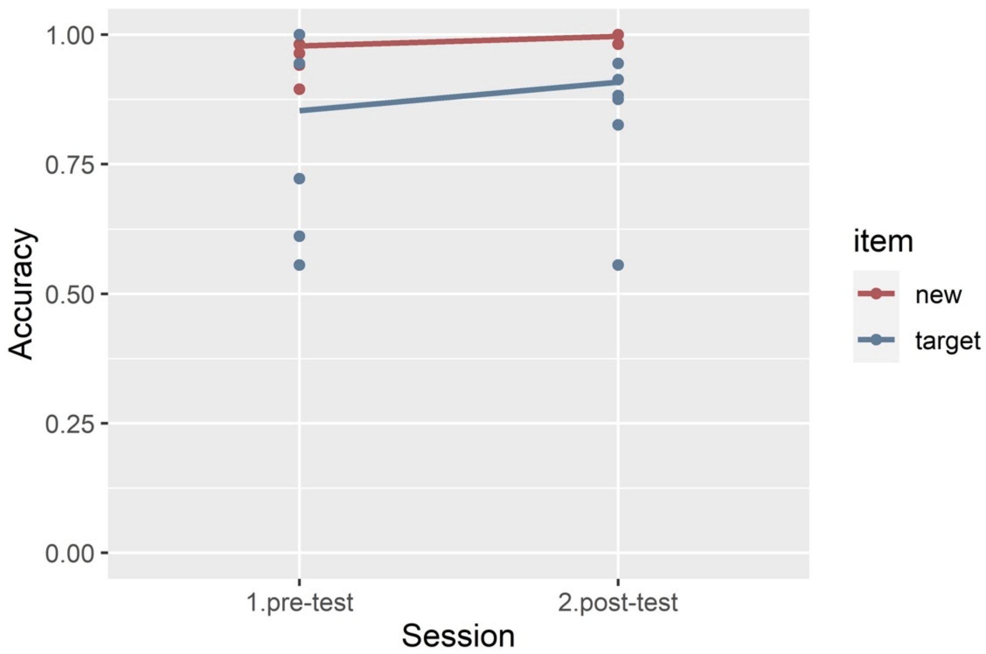
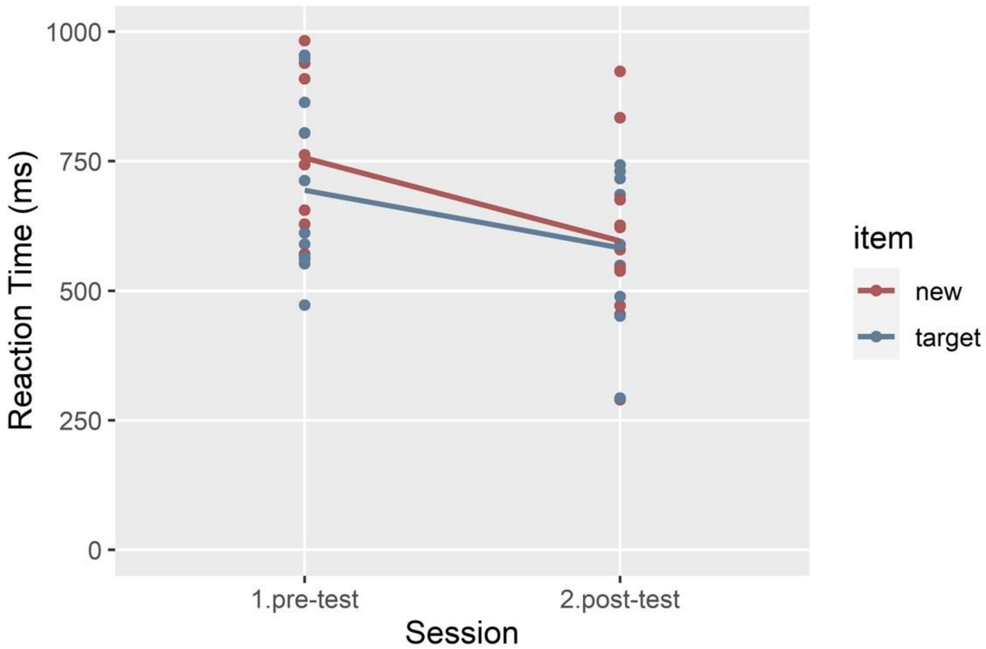


Figure 23. 1-back training group reaction time change



In the 2-back task, the accuracy mean for new distractors was slightly higher in the post-test than in the pre-test, and the accuracy mean for target items was also significantly higher in the post-test than in the pre-test (Figure 24). Concurrently, the reaction time mean slightly decreased in the post-test (Figure 25).

Figure 24. 2-back training group accuracy change

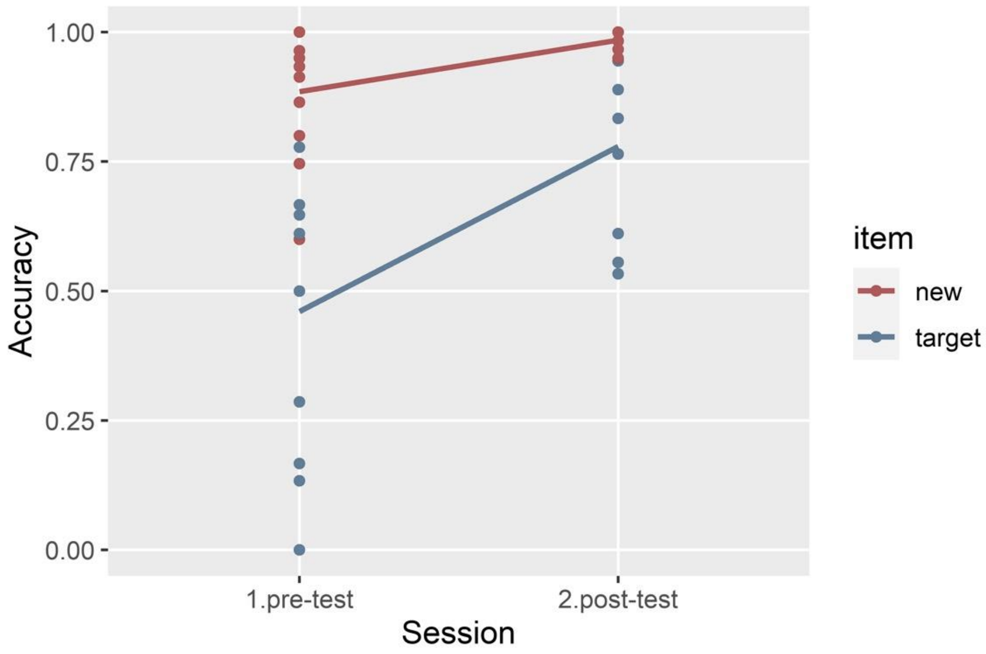
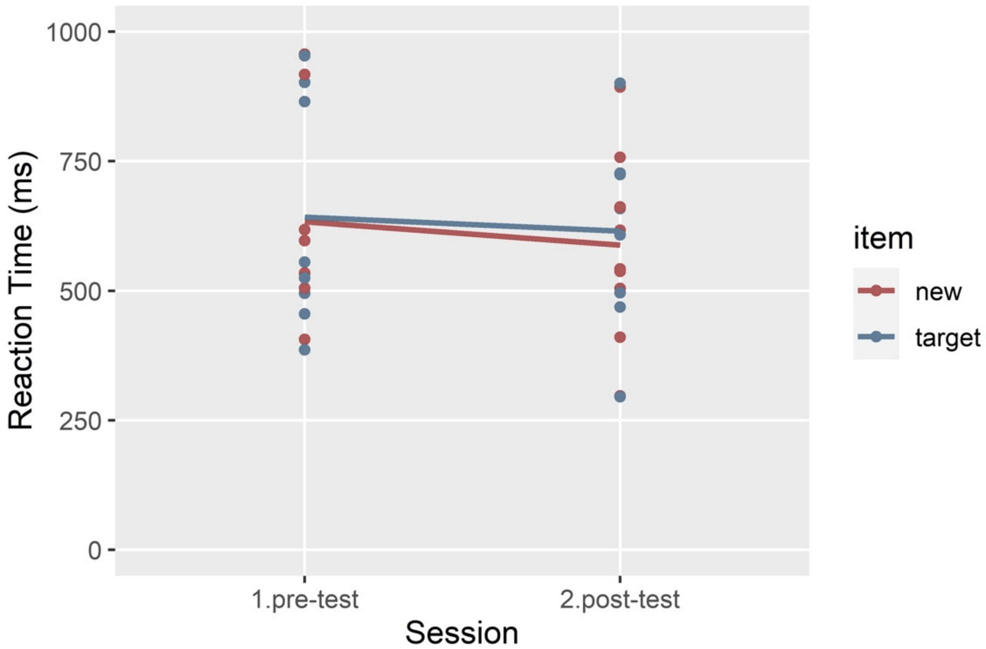


Figure 25. 2-back training group reaction time change



MDS Task

There was significant intercept in the null model for both accuracy change and reaction time change. Because of that, accuracy and reaction time measurement of this task was planned to analyze for condition and item type specific changes. The condition of this task was added as a first predictor. Only long listed the tS condition was significantly different than other interference conditions in both accuracy and reaction time.

Table 25. MDS task accuracy and reaction time change null model

Accuracy Change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	0.230 (0.080)	2.882	< **.01**
Random effects	Variance	*sd*	
Intercept	0.000	0.000	
Residual	0.140	0.374	
Reaction Time Change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-362.8 (168.3)	-2.156	< **.05**
Random effects	Variance	*sd*	
Intercept	237467	487.3	
Residual	148247	385.0	

Note: Group presented is the T1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Table 26. MDS task accuracy and reaction time change predicted by condition

Accuracy Change			
Variable	Estimate (SE)	t	*p*
Fixed effects			
Intercept	0.088 (0.100)	0.880	0.392
tS (long)	0.682 (0.263)	2.590	**< .05**
Rt (short)	0.087 (0.437)	0.199	0.845
Rt (long)	-0.239 (0.450)	-0.532	0.602
RtS (short)	0.013 (0.381)	0.035	0.973
RtS (long)	-0.011 (0.377)	-0.030	0.977
Random effects	Variance	*sd*	
Intercept	0.000	0.000	
Residual	0.104	0.322	
Reaction Time Change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-76.88 (102.9)	-0.747	0.469
tS (long)	0.706 (0.113)	6.222	**< .001**
Rt (short)	-0.417 (0.228)	-1.828	0.088
Rt (long)	0.289 (0.151)	1.915	0.079
RtS (short)	0.097 (0.195)	0.497	0.626
RtS (long)	0.182 (0.108)	1.686	0.115
Random effects	Variance	*sd*	
Intercept	48229	219.6	
Residual	36912	192.1	

Note: Group presented is the T1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Each condition of this task was analyzed separately indicating the effect of item type on accuracy and reaction time change. Only reaction time change was significantly greater for recall items in the tS condition than operation items. For the RtS condition, both accuracy and reaction time change were significantly higher in recall items than operation items.

Table 27. MDS task tS condition accuracy and reaction time change predicted by item type

Accuracy Change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	0.020 (0.019)	1.073	0.296
Recall	-0.033 (0.031)	-1.045	0.308
Random effects	Variance	*sd*	
Intercept	0.000	0.000	
Residual	0.003	0.055	
Reaction Time Change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			

Intercept	382.5 (179.2)	2.135	0.053
Recall	1.050 (0.257)	4.090	**< .001**
Random effects	Variance	*sd*	
Intercept	131907	363.2	
Residual	81211	285.0	

Note: Group presented is the T1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Table 28. MDS task Rt condition accuracy and reaction time change predicted by item type

Accuracy Change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	0.068 (0.106)	0.638	0.540
Recall	0.063 (0.175)	0.360	0.723
Random effects	Variance	*sd*	
Intercept	0.116	0.340	
Residual	0.015	0.123	
Reaction Time Change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-191.4 (119.6)	-1.600	0.135
Recall	0.008 (0.175)	0.047	0.963
Random effects	Variance	*sd*	
Intercept	86790	294.6	
Residual	66934	258.7	

Note: Group presented is the T1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Table 29. MDS task RtS condition accuracy and reaction time change predicted by item type

Accuracy Change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	0.040 (0.066)	0.598	0.564
Recall	0.551 (0.136)	4.049	**< .01**
Random effects	Variance	*sd*	
Intercept	0.026	0.162	
Residual	0.036	0.189	
Reaction Time Change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	76.83 (162.1)	0.474	0.645
Recall	0.906 (0.292)	3.097	**< .01**
Random effects	Variance	*sd*	
Intercept	20563	143.4	
Residual	319720	565.4	

Note: Group presented is the T1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

The analysis revealed that there was a ceiling effect in accuracy for both baseline and tS conditions in this task, indicating that the participants reached a maximum correct response beyond which further improvements could not be observed (see Figure 26).

Figure 26. MDS task training group accuracy change

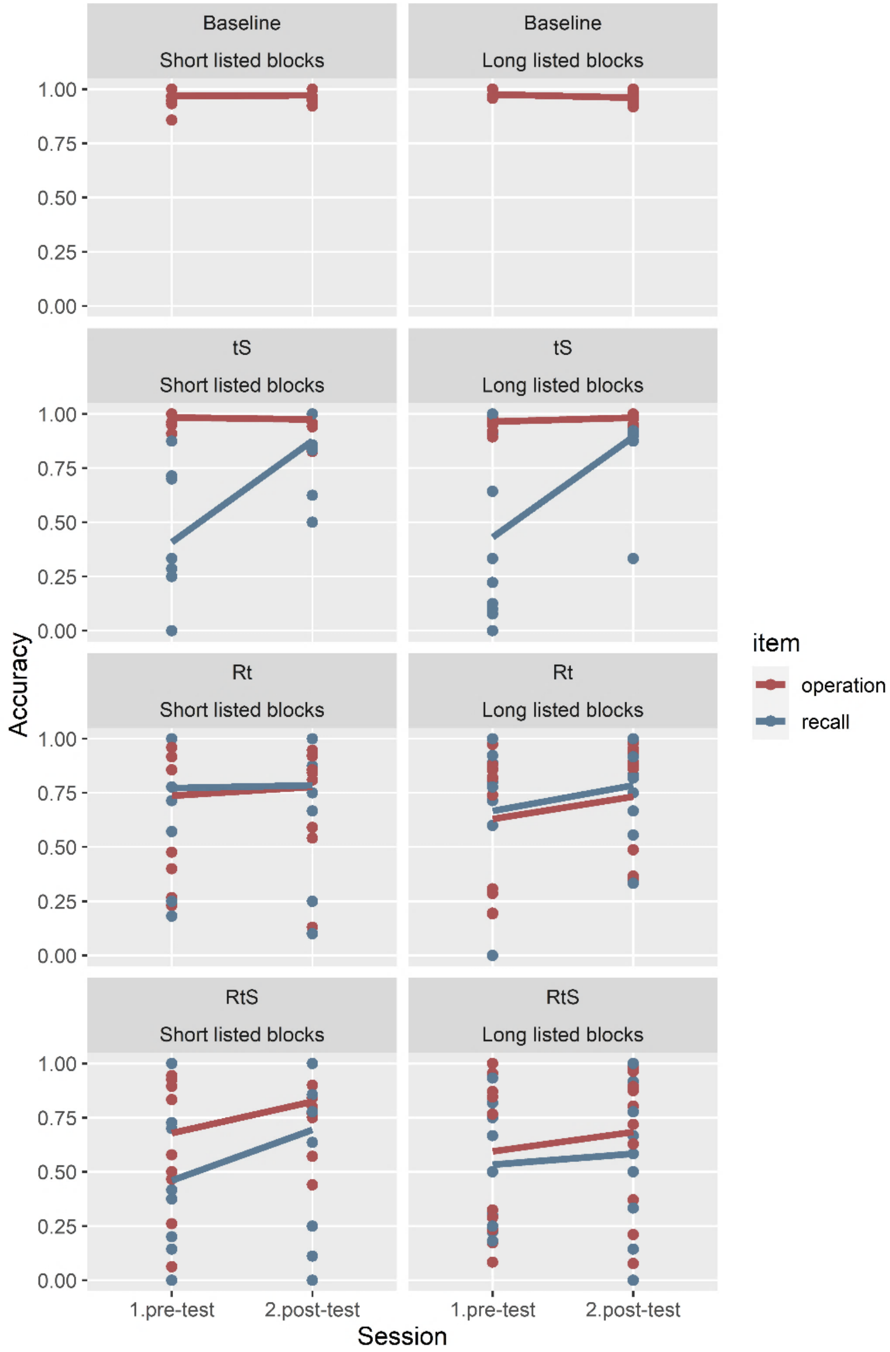
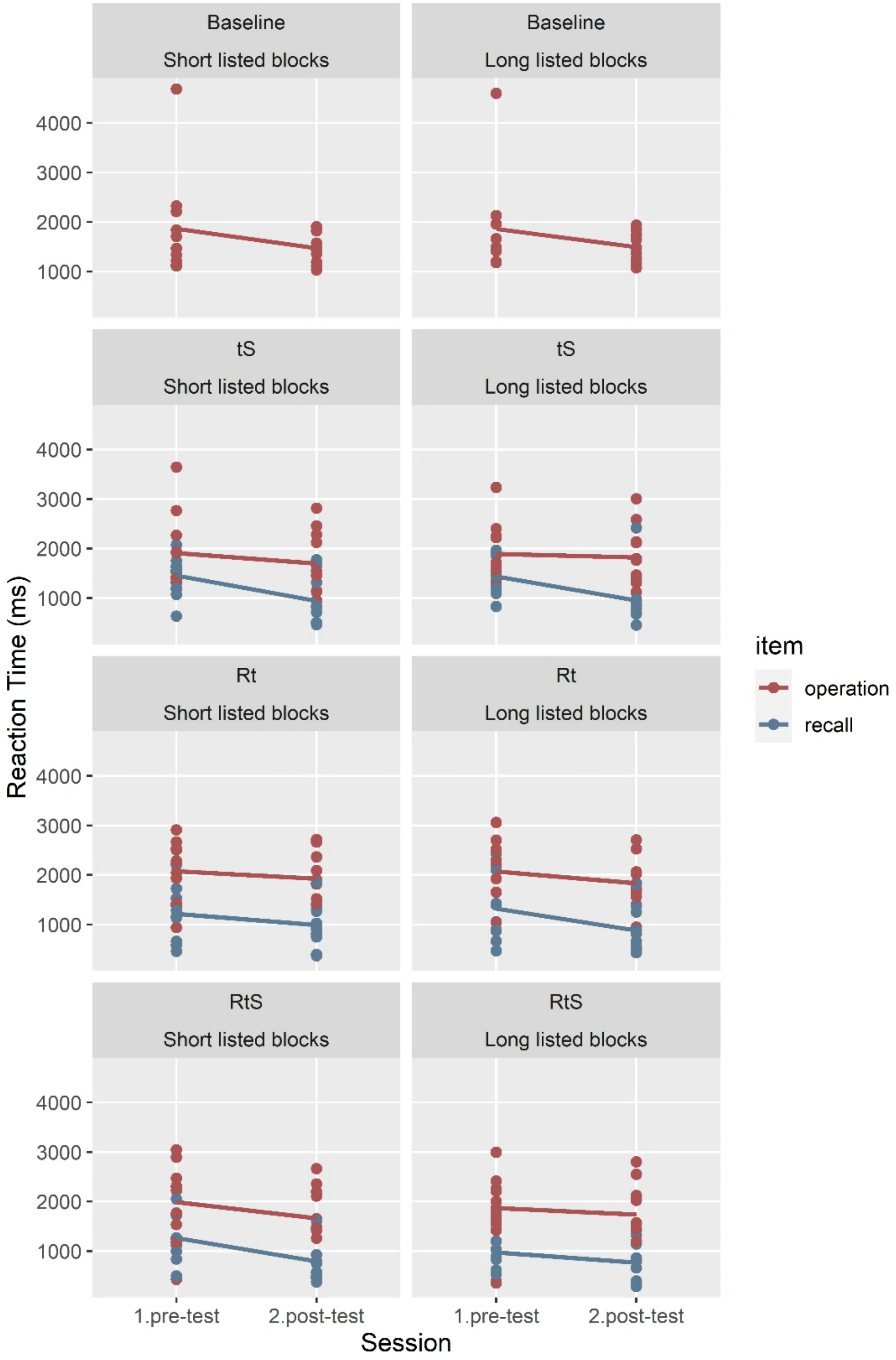


Figure 27. MDS task training group reaction time change



Arithmetic Operations

The model without predictors for accuracy change did not have significant intercept for this task, but for reaction time change, the intercept was significant. The condition was added as a first predictor. The reaction time change of the interference condition was significantly different than that of the baseline condition.

Table 30. Arithmetic operations accuracy and reaction time change null model

Accuracy Change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	0.009 (0.030)	0.289	0.779
Random effects	Variance	*sd*	
Intercept	0.006	0.080	
Residual	0.072	0.269	
Reaction time change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-6684 (2153)	-3.104	< **.05**
Random effects	Variance	*sd*	
Intercept	35680343	5973	
Residual	321523675	17931	

Note: Group presented is the T1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Table 31. Arithmetic operations reaction time change by condition

Reaction time change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-5399.5 (1581.7)	-3.414	< **.01**
Interference	701.3 (887.4)	1.917	< **.05**
Random effects	Variance	*sd*	
Intercept	19227592	4385	
Residual	148425085	12183	

Note: Group presented is the T1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

The baseline and interference conditions of this task were separated to analyze the effect of item type as a predictor for accuracy and reaction time changes. In the baseline condition, reaction time change was significantly greater only in subtraction and not in the other operation items. However, reaction time change was significantly higher only in division compared to the other operation items in the interference condition.

Table 32. Arithmetic operations baseline condition reaction time change by operation type

Reaction time change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-4310.4 (1287.9)	-3.347	< **.05**

Subtraction	2737.6 (1041.9)	2.627	**< .05**
Multiplication	884.5 (1362.0)	0.649	0.520
Division	1778.9 (1193.6)	1.490	0.149
Random effects	Variance	*sd*	
Intercept	6721045	2592	
Residual	45658097	6757	

Note: Group presented is the T1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Table 33. Arithmetic operations interference condition reaction time change by operation type

Reaction time change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-11951.8 (4488.7)	-2.663	**< .05**
Subtraction	-1138.9 (3520.4)	-0.324	0.749
Multiplication	-1837.5 (3233.9)	-0.568	0.576
Division	8254.7 (2502.1)	3.299	**< .01**
Random effects	Variance	*sd*	
Intercept	140549787	11855	
Residual	135986663	11661	

Note: Group presented is the T1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Figure 28. Arithmetic operations training group accuracy change by condition and operation type

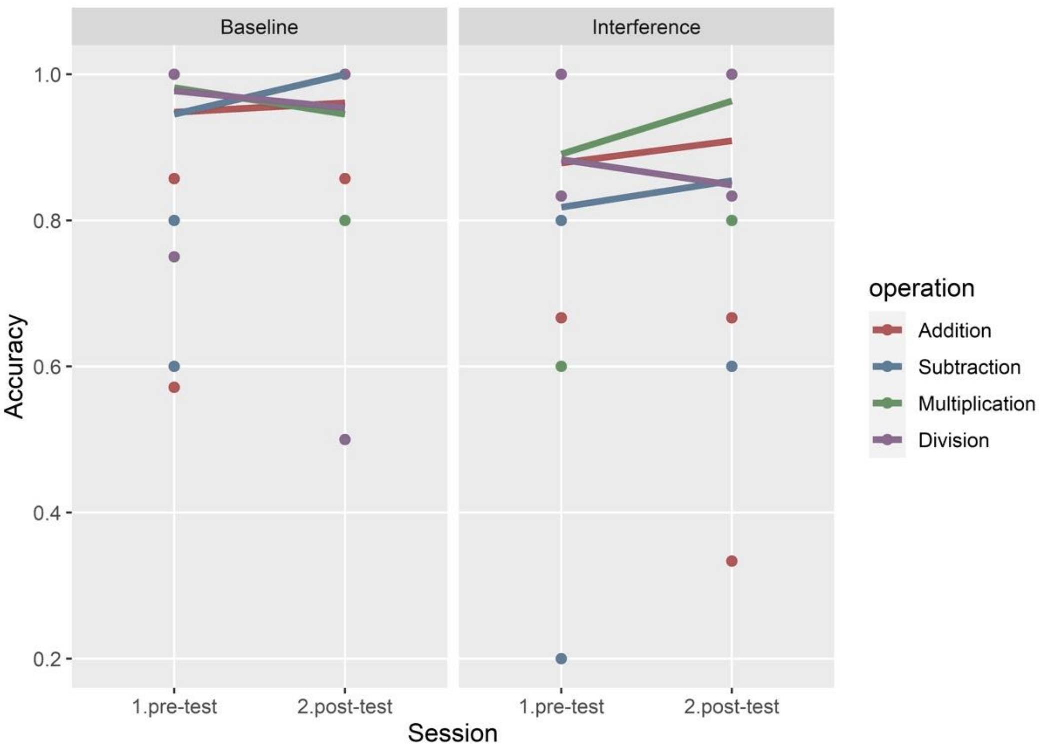
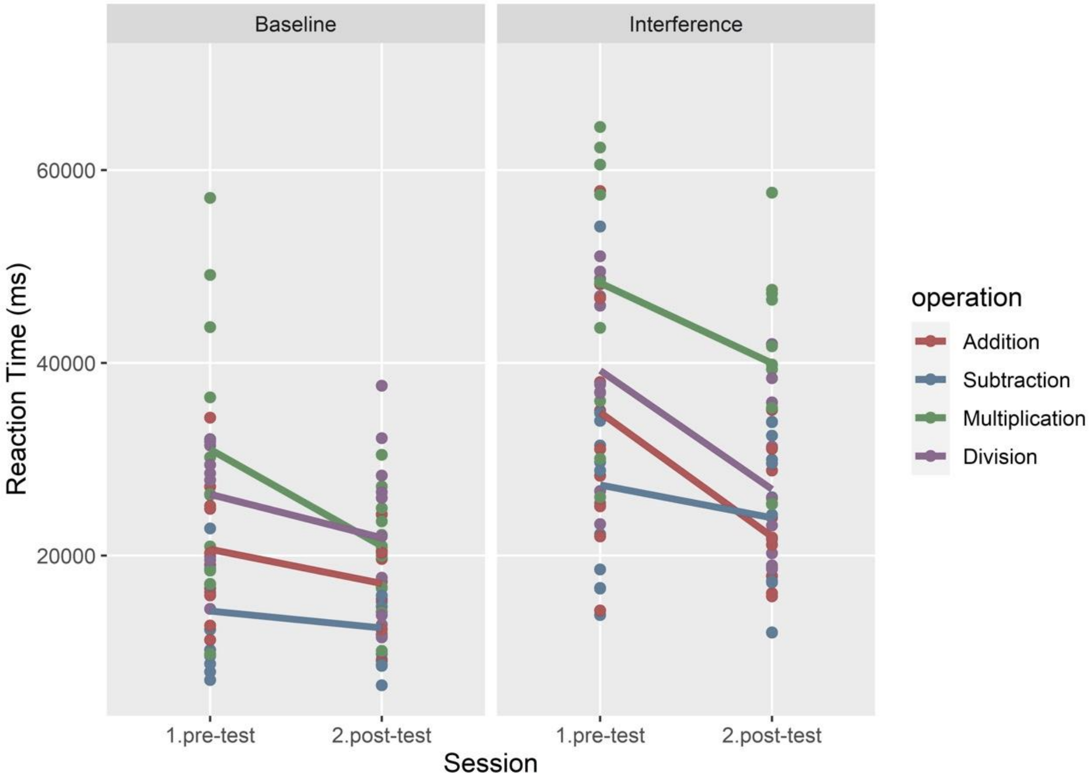


Figure 29. Arithmetic operations training group reaction time change by condition and operation type



Word Problems

The model without any predictors for accuracy change did not have significant intercept for this task, but for reaction time change, the intercept was significant. The condition was added as a first predictor. Biased condition was not significantly different from the baseline condition in reaction time change.

Table 34. Word problems accuracy and reaction time change null model

Accuracy Change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	0.048 0.048	1.00	0.329
Random effects	Variance	*sd*	
Intercept	0.000	0.000	
Residual	0.048	0.218	
Reaction time change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-15864 (5260)	-3.016	**< .01**
Random effects	Variance	*sd*	

Intercept	0.000	0.000
Residual	581104335	24106

Note: Group presented is the T1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Table 35. Word problems reaction time change by condition

Reaction time change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-26620.1 (18841.9)	-1.413	0.197
Biased	-17614.8 (10887.3)	-1.618	0.131
Random effects	Variance	*sd*	
Intercept	2.534e+09	50342	
Residual	2.676e+09	51735	

Note: Group presented is the T1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Only the biased condition included different types of items so the model with information type predictor was analyzed in this condition. There was no significant effect of item type on reaction time change.

Table 36. Word problems reaction time change by information type

Reaction time change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-28754.9 (20062.2)	-1.433	0.189
Literal	-19475.2 (14505.3)	-1.343	0.181
Numerical	3177.4 (16057.6)	0.198	0.844
Random effects	Variance	*sd*	
Intercept	2.508e+09	50077	
Residual	3.368e+09	58038	

Note: Group presented is the T1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Figure 30. Word problems training group accuracy change by condition and operation type

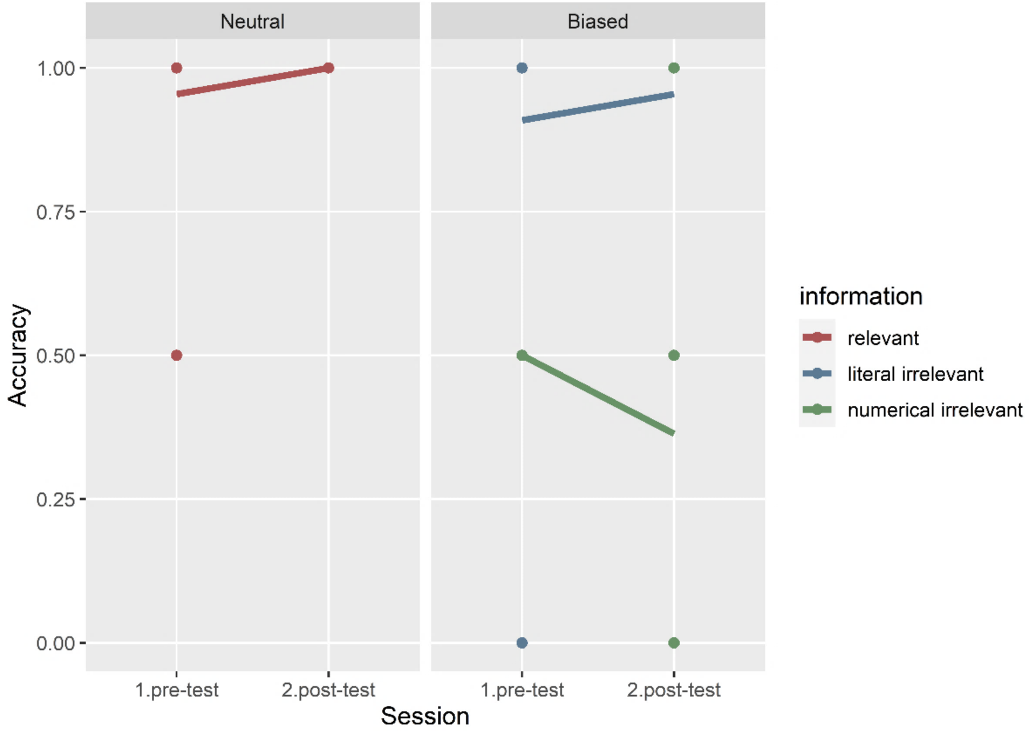
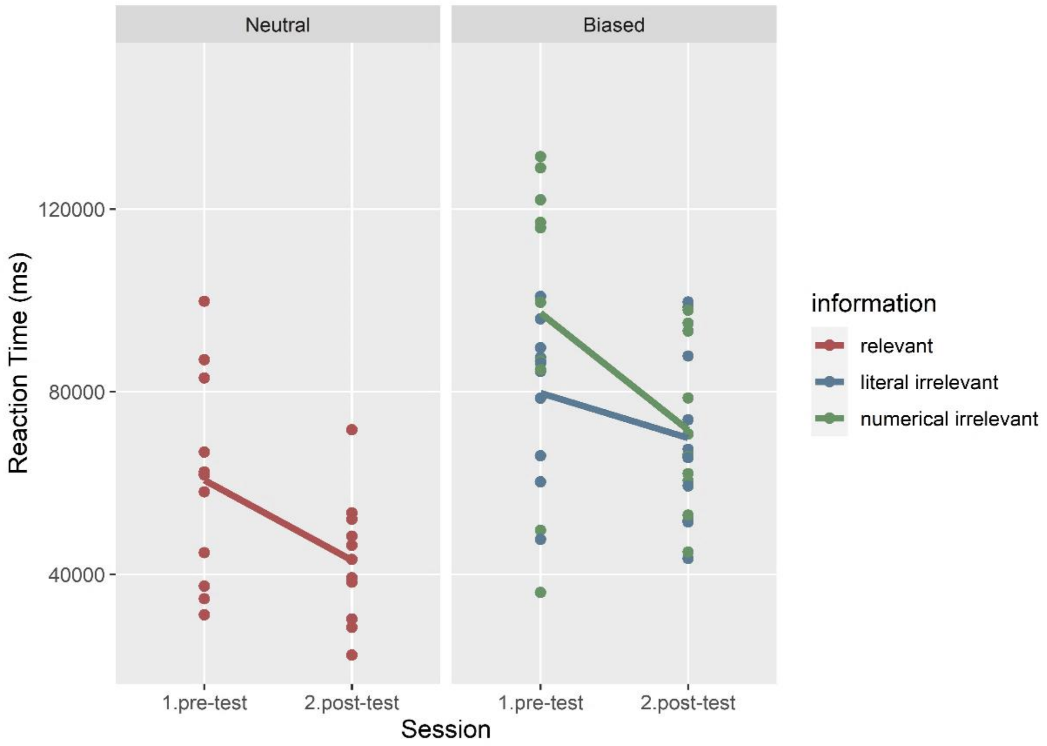


Figure 31. Word problems training group reaction time change by condition and operation type



4.3.2 Post-test performance

These analyses examined whether performance between training and control groups differed in post-tests after training. This investigation focused on four aspects of hypothesis 4. To examine this hypothesis for each task, the model included only the group as a predictor.

In order to study the performance patterns of two groups, T2 (training and post-tests) and C2 (only post-tests), on each task of the post-test battery, a set of analyses was conducted to address all five aspects of hypothesis 4. In these analyses, the post-test data for each task was examined individually, without aggregation. The accuracy data, which was categorized as either a correct or incorrect response, was analyzed using mixed-effects logistic regression models. This analysis specified the binomial family and the logit link function. The reaction time data, without aggregation, showed a skewed distribution. However, by applying a logarithmic transformation, the data was successfully converted into a normal distribution. After removing inaccurate trials and outliers from the dataset, the transformed data was analyzed using mixed-effects linear regression models with maximum likelihood estimation.

After comparing different models for each task, the appropriate model that included correlated random slope and random intercepts was selected, and this approach was followed for the analysis of each dataset.

n-back

The neutral condition of the 2-back task was examined for this analysis. For item type, the reference was new item. The results of analysis showed that while the main effect of group on accuracy performance was significant, there was no significant main effect of group in reaction time performance. T2 group's accuracy performance was higher in both new and target items than C2 group's (see Figure 32).

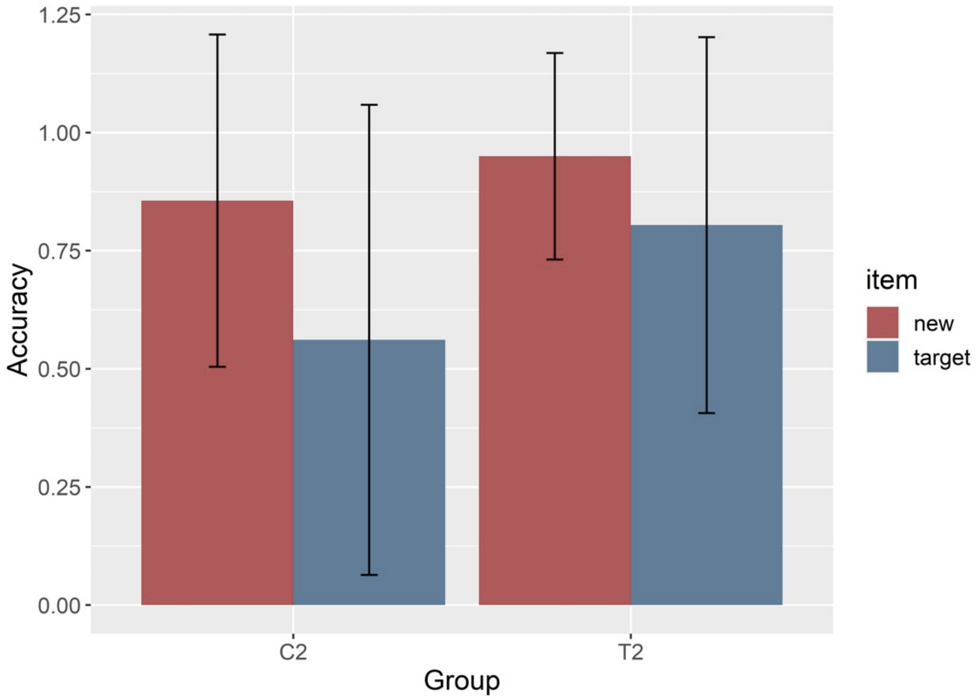
Table 37. Post-test *n*-back accuracy and reaction time predicted by group

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	5.873 (1.374)	4.274	**< .001**
Group	-1.704 (0.817)	-2.084	**< .05**
Random effects	Variance	*sd*	
Intercept	2.704	1.644	
Reaction Time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			

Intercept	665.2 (236.0)	2.819	< **.05**
Group	57.14 (149.3)	0.383	0.706
Random effects	Variance	*sd*	
Intercept	120778	347.5	
Residual	104619	323.4	

Note: Group presented is the T2 group (n = 11), reference group is the C2 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Figure 32. Post-test *n*-back task accuracy means by group



MDS Task

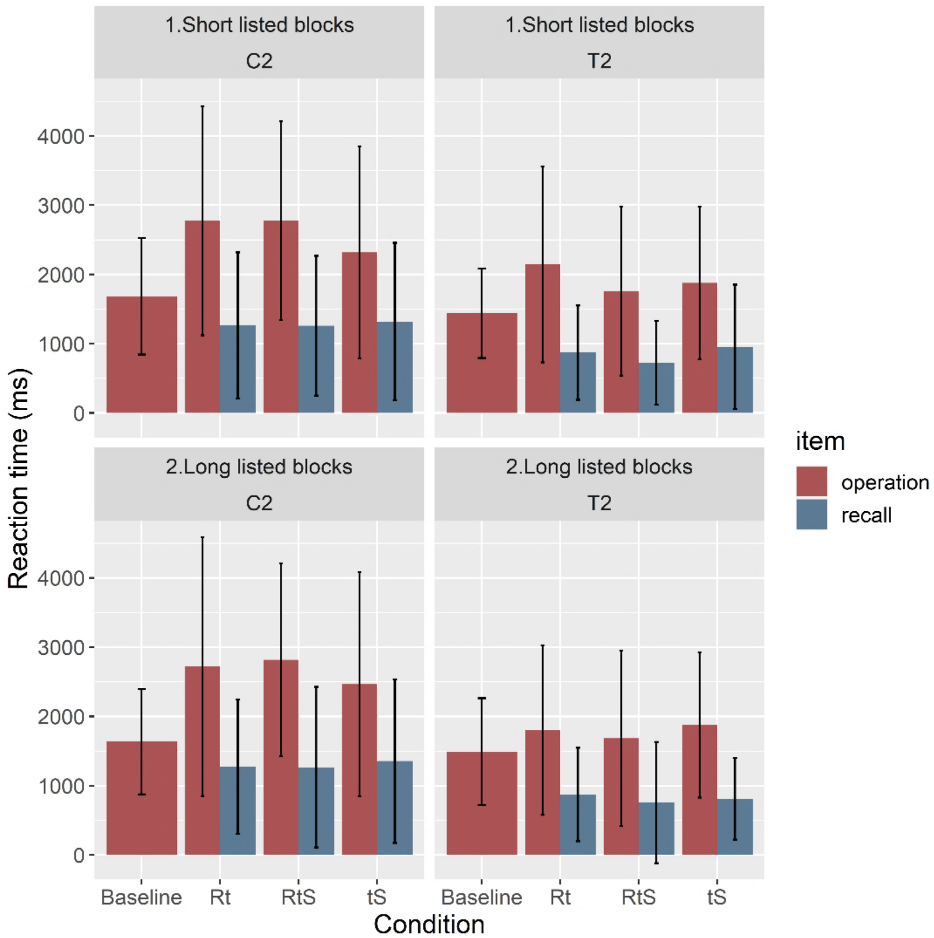
The RtS condition of the WM updating task was used as a reference to analyze the main effect of group. For item type, operation item type was chosen as a reference and the dataset was gathered from short listed blocks. There was no significant effect of group on accuracy performance at post-test. However, the main effect of group on reaction time performance was significant. The T2 group performed faster in the interference conditions of the WM updating tasks than the C2 group, while they performed similarly in the baseline condition (see Figure 33).

Table 38. Post-test MDS task accuracy and reaction time predicted by group

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	0.717 (1.552)	0.462	0.644
Group	1.359 (1.020)	1.332	0.183
Random effects	Variance	*sd*	
Intercept	4.164	2.041	
Reaction Time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	908.7 (537.1)	1.692	0.107
Group	907.9 (340.1)	2.670	**< .05**
Random effects	Variance	*sd*	
Intercept	574478	757.9	
Residual	1276718	1129.9	

Note: Group presented is the T2 group (n = 11), reference group is the C2 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Figure 33. Post-test MDS task reaction time means by group



Arithmetic operations

The interference condition of multiplication was chosen as an operation type for a reference. The analysis showed no significant difference between T2 and C2 groups in accuracy or reaction time performance. A total of 110 observations were analyzed with the dataset gathered from a total of 22 participants.

Table 39. Post-test arithmetic operations accuracy and reaction time predicted by group

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	8.597 (6.112)	1.407	0.160
Group	0.277 (3.566)	0.078	0.938
Random effects	Variance	*sd*	
Intercept	52.99	7.279	
Reaction Time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	32160 (9371)	3.432	**< .01**
Group	2414 (5927)	0.407	0.688
Random effects	Variance	*sd*	
Intercept	134069213	11579	
Residual	295629610	17194	

Note: Group presented is the T2 group (n = 11), reference group is the C2 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Word Problems

Numerical irrelevant information in biased condition was chosen as a reference for this task. There was no significant main effect of group in accuracy performance. Nevertheless, the main effect of group was significant in reaction time performance of the task. The mean of each group in reaction time performance did not differ significantly (see Figure 34)

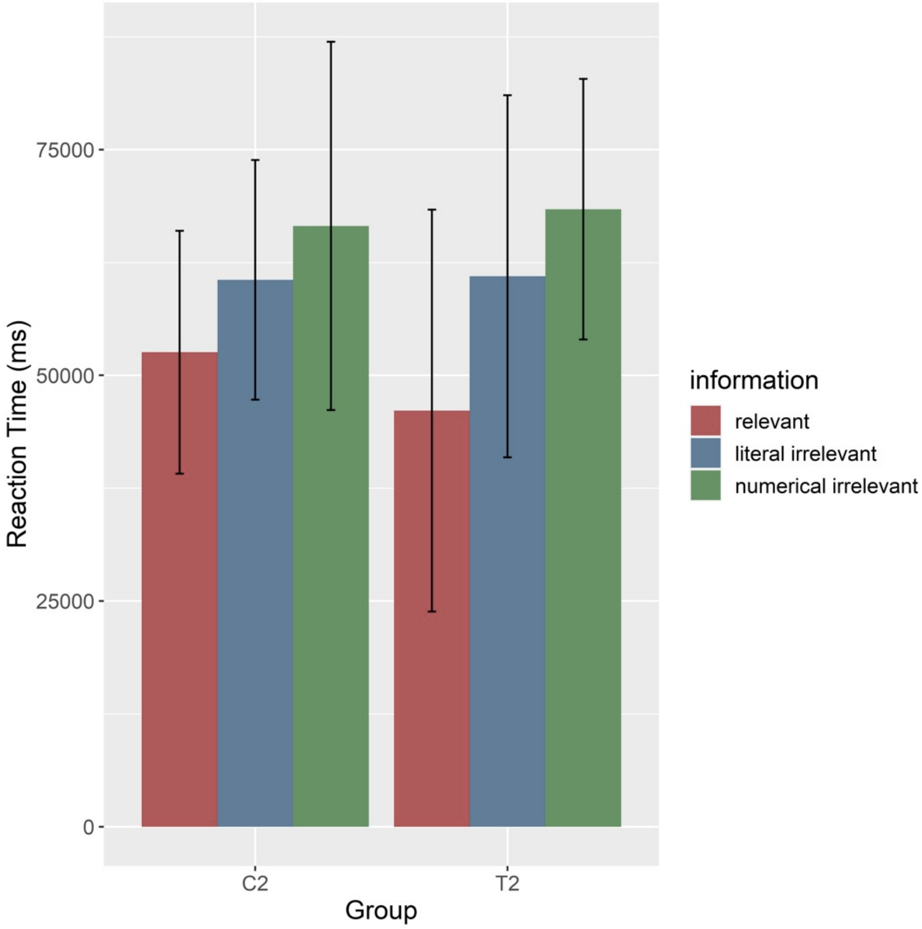
Table 40. Post-test word problems accuracy and reaction time predicted by group

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	0.762 (1.035)	0.736	0.462
Group	-0.963 (0.682)	-1.412	0.158
Random effects	Variance	*sd*	
Intercept	0.000	0.000	
Reaction Time			
Variable	Estimate (SE)	*t*	*p*

Fixed effects			
Intercept	30540 (24656)	1.239	0.223
Group	37379 (15481)	2.415	< **.05**
Random effects	Variance	*sd*	
Intercept	0.000	0.000	
Residual	2.455e+09	49548	

Note: Group presented is the T2 group (n = 11), reference group is the C2 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Figure 34. Post-test word problems reaction time means by group



4.4 Practice Effect

In this section, two sets of analyses were carried out to determine whether there was a practice effect on participants' performance in each test. As suggested by hypothesis 5, the performance change of the C1 group (pre- and post-tests) and the difference between the C1 and C2 (post-tests only) groups were analyzed to examine the practice effect.

4.4.1 Pre- to post-test change

In this part, a series of analyses were conducted to examine all four parts of hypothesis 5, which were formulated to understand whether the control group (C1) showed performance changes on each task at post-test compared to their pre-test performance. Accuracy and reaction time data set of each test were cleaned and transformed as differences between pre- and post-tests. As a last step, they were aggregated. The null models without predictors were analyzed and only the intercepts for accuracy reaction time change were used to understand whether there was a significant difference between pre- and post-tests of each task.

n-back

The neutral condition of 2-back task was conducted for this analysis. The intercepts for accuracy and reaction time change were not significant, so the performance on pre-tests was not significantly different than performance on post-tests.

Table 41. *n*-back accuracy and reaction time change null model

Accuracy Change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-0.008 (0.035)	-0.22	0.828
Random effects	Variance	*sd*	
Intercept	0.000	0.000	
Residual	0.027	0.164	
Reaction time change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-73.15 (64.07)	-1.142	0.28
Random effects	Variance	*sd*	
Intercept	40908	202.26	
Residual	8503	92.21	

Note: Group presented is the C1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

MDS Task

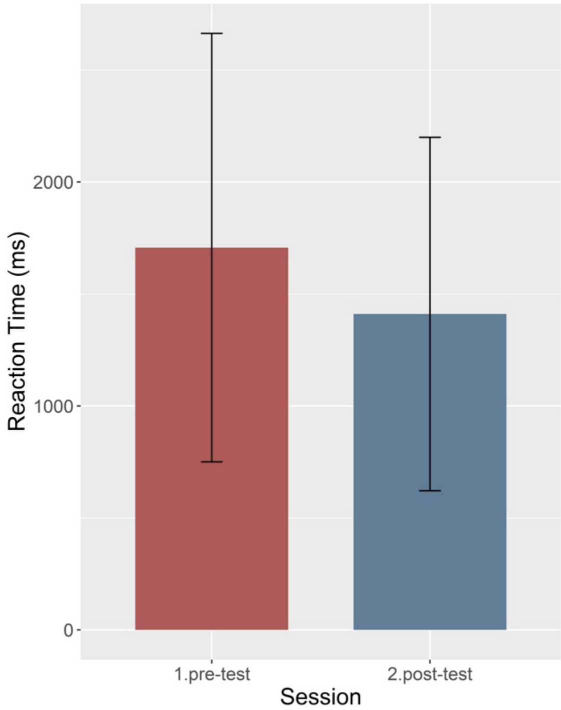
All conditions of this task were included for this analysis. While the intercept for accuracy change was not significant, the intercept for reaction time change was significant. The mean of reaction time in post-test is lower than in pre-test (see Figure 35 below).

Table 42. MDS task accuracy and reaction time change null model

Accuracy Change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	0.026 (0.038)	0.691	0.505
Random effects	Variance	*sd*	
Intercept	0.010	0.101	
Residual	0.074	0.273	
Reaction time change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-373.62 (128.17)	-2.915	< **.05**
Random effects	Variance	*sd*	
Intercept	171980	414.7	
Residual	119094	345.1	

Note: Group presented is the C1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Figure 35. MDS task reaction time means by sessions



Arithmetic operations

All conditions of this task were conducted for this analysis. The intercepts for accuracy and reaction time change were not significant, so the performance on pre-tests was not significantly different than performance on post-tests.

Table 43. Arithmetic operations accuracy and reaction time change null model

Accuracy Change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	0.007 (0.025)	0.300	0.770
Random effects	Variance	*sd*	
Intercept	0.002	0.047	
Residual	0.037	0.193	
Reaction time change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-1386 (2124)	-0.653	0.529
Random effects	Variance	*sd*	
Intercept	4511946	2124	
Residual	360922425	18998	

Note: Group presented is the C1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Word problems

All conditions of this task were conducted for this analysis. The intercepts for accuracy and reaction time change were not significant, so the performance on pre-tests was not significantly different than performance on post-tests.

Table 44. Word problems accuracy and reaction time change null model

Accuracy Change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-0.053 (0.065)	-0.813	0.425
Random effects	Variance	*sd*	
Intercept	0.000	0.000	
Residual	0.094	0.306	
Reaction time change			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-13307 (7307)	-1.821	0.083
Random effects	Variance	*sd*	
Intercept	0.000	0.000	
Residual	1.175e+09	34274	

Note: Group presented is the C1 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

4.4.2 Post-test performance

A set of analyses was conducted to address hypothesis 5a, which was built to interpret participants' performance on post-test tasks. Post-test data was not aggregated for any tasks before the analysis. Correct and incorrect answers in accuracy data were gathered as binary data and a mixed-effects logistic regression model was conducted in condition of family binomial and link logit. Unaggregated reaction time data which was normally distributed was transformed by removing outliers for each participant. A mixed-effects linear regression model was used with maximum likelihood estimation.

Hypothesis 5b postulated that C1 (control group complete pre- and post-tests) and C2 (control group completed only post-tests) groups would not significantly differ in any tasks of the testing battery showing that there was no practice effect for each task. This part was tested for each task by selecting a group as a predictor. The model of random effects with random slope and random intercepts was used for each part of the hypothesis since it is the strongest model for confirmatory hypothesis testing (Barr et al., 2013).

n-back

The neutral condition of 2-back task was examined for this analysis. The results of the analysis showed that the main effect of group on accuracy and reaction time performance was not significant.

Table 45. Post-test *n*-back accuracy and reaction time null model

Accuracy			
Variable	Estimate (SE)	z	*P*
Fixed effects			
Intercept	2.425 (0.757)	3.203	**< .01**
Group	-0.368 (0.472)	-0.781	0.435
Random effects	Variance	*sd*	
Intercept	1.076	1.037	
Reaction Time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	615.9 (194.1)	3.173	**< .01**
Group	88.66 (122.6)	0.723	0.478
Random effects	Variance	*sd*	
Intercept	81017	284.6	
Residual	125817	354.7	

Note: Group presented is the C1 group (n = 11), reference group is the C2 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

MDS Task

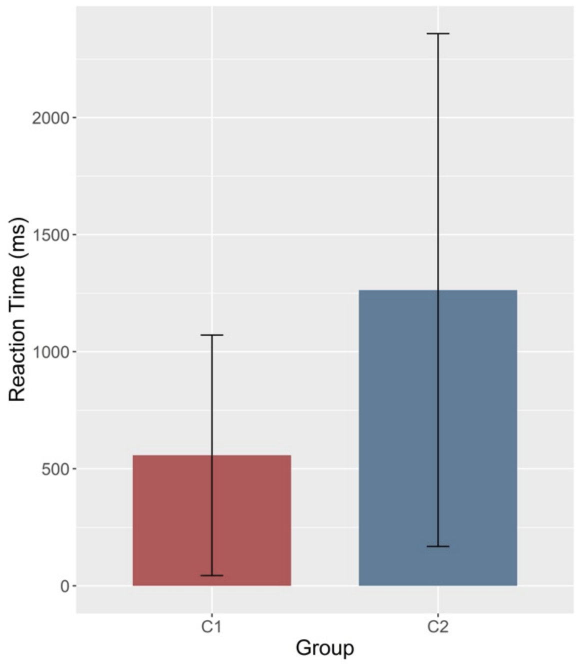
The RtS condition was chosen as a reference with recalling item type. There was no significant effect of group on accuracy performance at post-test. However, the main effect of group on reaction time performance was significant. Participants in C1 group were faster than participants in C2 (see Figure 36).

Table 46. Post-test modified digit span accuracy and reaction time null model

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	0.608 (1.407)	0.432	0.666
Group	0.749 (0.889)	0.842	0.400
Random effects	Variance	*sd*	
Intercept	3.700	1.923	
Reaction Time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	-147.6 (305.6)	-0.483	0.634
Group	706.7 (193.3)	3.656	< **.01**
Random effects	Variance	*sd*	
Intercept	176429	420.0	
Residual	570480	755.3	

Note: Group presented is the C1 group (n = 11), reference group is the C2 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Figure 36. Post-test MDS task reaction time means by group



Arithmetical operations

Interference condition of multiplication was chosen as a reference for this task. There was no significant main effect of group on accuracy or reaction time performance at post-test.

Table 47. Post-test arithmetic operations accuracy and reaction time null model

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	2.757 (1.679)	1.642	0.101
Group	0.668 (1.034)	0.646	0.518
Random effects	Variance	*sd*	
Intercept	2.528	1.590	
Reaction Time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	41615 (10980)	3.790	< **.01**
Group	-4662 (6944)	-0.671	0.510
Random effects	Variance	*sd*	
Intercept	206620479	14374	
Residual	586143528	24210	

Note: Group presented is the C1 group (n = 11), reference group is the C2 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Word problems

The reference was literal and numerical irrelevant information from the biased condition for this task. The main effect of group was significant on accuracy performance. C1 group had higher accuracy performance on this task than C2 group (see Figure 37). However, there was no significant main effect of group on reaction time performance.

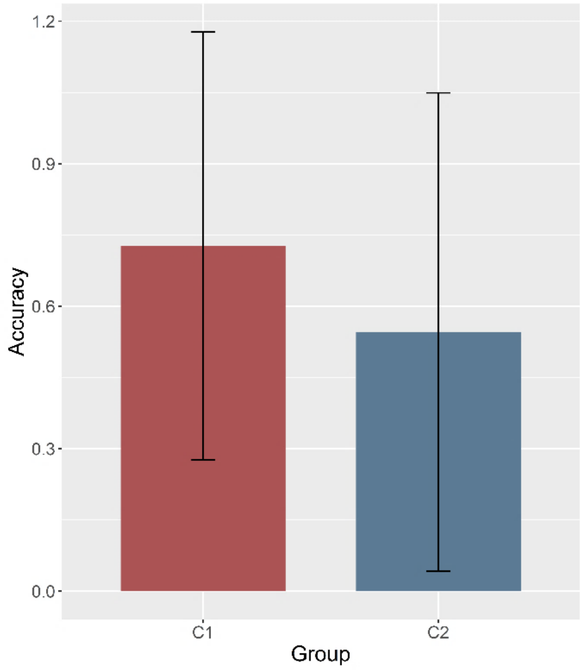
Table 48. Post-test word problems accuracy and reaction time null model

Accuracy			
Variable	Estimate (SE)	z	*p*
Fixed effects			
Intercept	2.251 (0.670)	3.361	< **.001**
Group	-0.846 (0.402)	-2.106	< **.05**
Random effects	Variance	*sd*	
Intercept	0.000	0.000	
Reaction Time			
Variable	Estimate (SE)	*t*	*p*
Fixed effects			
Intercept	48458 (18501)	2.619	< **.05**
Group	16146 (11701)	1.380	0.1828
Random effects	Variance	*sd*	

Intercept	5.359e+08	23150
Residual	1.303e+09	36091

Note: Group presented is the C1 group (n = 11), reference group is the C2 group (n = 11). The reported data for fixed effects consists of unstandardized coefficients, while for random effects, it includes variance.

Figure 37. Post-test word problems accuracy means by group



Chapter 5 Discussion

In this study, the impact of trained WM on cognitive and mathematical skills among school-age children was investigated within the interference theory as framework (Oberauer, 2001). This research was driven by the assumption that enhancing WM capacity through cognitive training may contribute to significant improvements in cognitive functions and performance in mathematics. Furthermore, the exploration using an interference framework of WM provided us with a better understanding of the individual differences in WM performance.

In this section, the connection between observed results of the study and prior research in the related fields is presented, based on the assumptions that have been made.

5.1 Training progress

The results pertaining to the relationships between participants' characteristics and their progress in the *n*-back training encompassed all five aspects of hypothesis 1. As outlined, for hypothesis 1a and 1b, participants engaged in the *n*-back training and completed it at different levels. The level of the *n*-back task completed varied among participants, with the minimum achieved level being the 2-back level with proactive interference lures, and the maximum achieved level being the 8-back level with proactive interference lures. This variability in training progress showed the differences in participants' ability to perform the task at higher levels with increasing cognitive load in memory. In this task, participants had to make recognition decisions on each item, accepting targets and rejecting distractors based on the *n*-back rule while increasing the load in the WM system at higher levels. Effective performance in this task requires the successful binding of each letter (content) to its specific temporal position (context), and the updating of these content-context associations as new information is presented (Oberauer et al., 2007). The findings of this study contribute to the extensive body of research which supports the interference framework as a dependable explanation for individual differences in WM performance, as well as performance on measures related to WM abilities (Cowan et al., 2005). It suggests that individuals with higher WM capacity may perform better at discarding distractors and focusing on relevant information and individual differences in WM performance are associated with efficiency in cognitive control processes.

As predicted by hypothesis 1b, participants demonstrated improvement throughout the training period. The analysis of the distribution of maximum *n*-level achieved in each session provided insight into the progression of participants' training over time. The training progress of participants in the training groups was not uniform or consistent. Among the participants, four individuals showed slow progress and only reached the 3-back level, while six other individuals initially progressed slowly but eventually completed the entire training up to the 4-back level. Two participants who were able to reach 7- and 8-back levels showed faster improvement in their performance. This can be attributed to the fact that they did not practice at any particular level for more than two sessions. Additionally, the quick adaptability and progression through levels exhibited by these two participants may have played a role in their superior overall performance compared to the others. In contrast, the remaining participants displayed fluctuating performance between the 5- and 6-back levels. Despite the fast improvement they experienced in the previous sessions, ultimately their performance stabilized within this range over multiple sessions. This indicates that they were able to maintain a consistent level of performance at the 5- and 6-back levels, even if they initially showed rapid improvement. This finding reinforces the idea that participants who show superior performance consistently show incremental improvements in their performance throughout each training session. Consistency in the higher levels highlights the importance of the training when increasing task difficulty. The consolidation and maintenance of improvement enable participants to reflect their cognitive gains by reaching and sustaining performance at these advanced levels (Klingberg, 2010; Cowan, 2001).

The findings confirm Hypothesis 1e, which posited that the initial cognitive resources of participants play a significant role in their training progress. The observations provide evidence that individuals whose performance in baseline cognitive tasks was higher achieved higher n-levels with the training. On the other hand, age, socioeconomic status (SES), and motivation did not predict their training progress. Participants' capabilities in the training might be relatively resilient to individual differences in these factors. This can support that the training program is efficient across a wide range of participants with different backgrounds (Klingberg, 2010). However, participants might use strategies to compensate possible deprivations because of age, low SES or low level of motivation. For example, participants with any disadvantages in these factors might develop resilience skills that may help them to perform better in the training tasks (Luthar et al., 2000). It is also possible that conducting this study in a controlled environment where participants had the same access to resources and support, reduced the influence of SES (Jaeggi et al., 2008). The results indicate that an individual's ability to benefit from WM training is influenced by their pre-existing level of cognitive abilities (Foster et al., 2017).

Hypotheses 1c and 1d identified four predictors of training progress: motivation, measured by Theories of Cognitive Abilities, and cognitive abilities, measured by nonverbal IQ, short-term memory capacity and semantic verbal fluency. However, due to the non-normal distribution of the digit span task, correlation analysis could not be employed as a method for assessing the short-term memory predictor. The results obtained from the Theories of Cognitive Abilities questionnaire indicated a relatively high level of motivation among the participants. However, it is not evident that the scores from the questionnaire exhibit a significant association with individual differences in training progress. The questionnaire might not be sensitive enough to capture slight differences among the participants. Since this scale included three items to reply to, most participants might likely have agreed with the statements, leading to a narrow range of responses and therefore less variability (Schwarz, 1999; Podsakoff et al., 2003). The analysis examined two variables, nonverbal IQ, and semantic verbal fluency, to explore their relationship with training progress. The findings did not support the hypotheses, revealing that nonverbal IQ and semantic verbal fluency were not significantly associated with individual progress in the training program. Previous research has consistently exhibited a significant correlation between IQ, specifically fluid intelligence, and WM (e.g. Engle et al., 1999; Kane & Engle, 2002; Gray et al., 2003; Alloway & Alloway, 2010). This moderate correlation between IQ and WM observed in this study could be attributed to various factors, such as complexity of the training tasks and the influence of statistical variables on outcomes. Overall, drawing definitive conclusions about how these characteristics predict training progress is challenging because of the small sample size and the narrow range of IQ and verbal fluency scores. Further research with a large number of participants is required to establish more conclusive findings.

5.2 Pre and post-tests

n-back

In this *n*-back training study, the *n*-back task was utilized for pre and post-test to confirm the trainability of the participants. It was hypothesized that the training group (that received training and completed the pre- and post-tests) and the control group (that completed pre- and post-tests without receiving training) would not differ in the pre-test battery, which evaluated the performance of the participants in different conditions and item types of the *n*-back task. The performance in 1-back and 2-back tasks consistently supported these assumptions within these groups. We will further discuss the performance of groups that completed pre-tests and the improvement shown by training groups, with consideration to the experimental manipulations of the task.

Hypothesis 2b proposed that participants would demonstrate better performance on new distractor items compared to target items in both the 1-back and 2-back conditions of the task. Additionally, it was expected that their performance on target items would be better than on interference items in the proactive interference tasks. WM tasks including proactive interference challenge individuals, since continuous updating is required while filtering out outdated or irrelevant information. Capability in these tasks relies on efficient interference control processes and updating skills (Jonides & Nee, 2006). To examine *n*-back performance within different conditions and items, in the 1-back task, participants exhibited significantly lower accuracy in the tasks, where possible proactive interference (PI) errors were available, compared to the neutral condition. Moreover, their reaction times were significantly higher in the PI condition compared to the neutral condition. In the 2-back task, participants demonstrated significantly higher accuracy and higher reaction times in the PI condition compared to the neutral condition. These findings support the assumptions about the impact of interference items on *n*-back performance, leading to longer reaction time in the PI condition compared to the neutral condition, but the assumptions about performance in accuracy contradict with the finding where the accuracy was higher in PI condition The reason might be related to the nature of the task, which was low level of *n*-back task and after practicing the 1-back tasks and the neutral condition of the 2-back task, the participants might have become better in performance. This can also be explained by the trade-off theory (Heitz, 2014) which suggests that decisions made with more accuracy require more time. Extensively, when participants in a WM updating task experience an increase in memory load, their accuracy in recognizing target items declines significantly (Johnson et al., 2022; Chen & Liu, 2021). This decline can be attributed to the fact that participants face greater difficulties in rejecting interference lures and correctly identifying target items compared to their ability to reject new distractors. In tasks where letters rapidly change positions, it is crucial to maintain the relevant context and continuously update working memory. These tasks have a dynamic nature that necessitates constantly updating the associations in the focus of attention and accurately recalling the correct item within the assigned temporal context defined by the task rules (Oberauer, 2005). Successfully completing such tasks relies on the ability to recall the correct item that is bound to the appropriate temporal context and to reject items that do not match the content-context binding. The capacity to adapt and update working memory representations flexibly is a critical aspect to achieve effective task performance.

Hypotheses 3a and 4a predicted the improvement of the training groups on post-tests. The results of the assumption which suggested a significant change in performance of the pre-test training group, proposed by hypothesis 3a, revealed that participants showed varying degree of performance change in terms of accuracy and reaction time across different *n*-back levels after they completed all sessions of the training. Based on the mean change in accuracy and reaction time, an insignificant mean change in accuracy and a significant decrease in reaction time was observed in 1-back task from pre to post-test. The ceiling effect in this task indicated that participants reached a maximum of correct responses; therefore, further improvement could not be observed in accuracy, but they became faster after the training. Furthermore, a significant increase in accuracy for target items and insignificant mean change in reaction time was noticed in the 2-back task. This suggests that the performance of the participants was similar in accuracy for the 1-back task at both pre and post-tests, while they improved their response time at the post-test. The shorter temporal span between the maintained and updated items, and the reduced cognitive load of the 1-back task likely resulted in quicker response times (Jaeggi et al., 2010). The results suggest that low-level *n*-back tasks with shorter temporal spans and reduced cognitive load contribute to quicker response times and more accurate answers. By minimizing the cognitive demands employed by the task, individuals can maintain better temporal context and allocate their attention more effectively. High-level *n*-back tasks (e.g., 3-back) require individuals to maintain and manipulate information over longer time-periods, making the task more challenging and cognitively demanding compared to low-level tasks. High-level *n*-back tasks can provide a more robust evaluation of an individual's WM capacity to process and update information efficiently. According to these findings, the 2-back task is considered more difficult than the 1-back task because the 2-back task requires holding and updating more information actively in WM for a longer time. As a result, this increase in cognitive demand often reveals decreased accuracy rates and increased reaction times compared to the 1-back task.

The additional analysis of the training effect supports Hypothesis 4a, which postulates *n*-back task performance difference between post-test training group and post-test control group, indicating an improvement in the training group. These findings are consistent with the hypothesis and show that the training had a positive effect, enabling the training to perform the *n*-back task more accurately. The participants in this training group showed higher performance in accuracy not only on the new items but also with the target items compared to the participants in the control group, however, the groups did not significantly differ in reaction time performance. The results suggest that the training might have underscored skills that were either acquired or improved, leading to better accuracy performance in the *n*-back tasks through enhancement of WM capacity. Participants performed more efficiently in accuracy without slowing down the decision-making process (Shipstead et al., 2012). While WM training enhances cognitive processes, such as interference control, it might not immediately translate into more rapid responses in related tasks (Diamond, 2013) This explains why the training speed of performance did not change significantly following the training.

Consequently, the *n*-back task plays a crucial role in this study to evaluate and challenge WM systems of school-age children by examining their performance in the task under different manipulations of memory load and interference conditions. It can be asserted that the successful performance in the *n*-back task requires individuals to update memory items and bind multiple features of representations accurately.

Modified digit span

The modified digit span (MDS) task which includes transformation, substitution, and retrieval components of the updating process was employed in this study. The purpose of this task was to observe performance on the task which requires retrieving numerical information from WM. As predicted by hypothesis 2a, which proposed that pre-test training and pre-test control groups would not differ in the pre-test battery, which evaluated the performance of the participants in different conditions with different item types. Both groups performed similarly on the task at pre-test. The performance of the groups that completed the pre-test, as well as the training groups' improvement was evaluated by different conditions and item types which were categorized as short-listed and long listed.

The investigation was based on the hypothesis 2c that participants would exhibit various performances in the conditions that required retrieval or substitution or both while performing basic arithmetic operations in all conditions of the MDS task. The participants were expected to perform better in the conditions where only transformation was employed as compared to the conditions in which they were engaged in retrieving and substituting items during the task. The results of this study were consistent with the hypothesis because the performance in accuracy for the retrieval and substitution-based condition (RtS) with both short and long listed block items was lower among other conditions, while performance in reaction time was significantly higher for both the transformation and substitution-based condition (tS) and RtS condition with long-listed block items for both. The challenge in the retrieval and substitution-based task highlights the role of WM systems in the retrieval process because information must be executed and manipulated while other information is being simultaneously retrieved from WM resources (Unsworth & Engle, 2007). This high demand on the WM system can explain the lower accuracy performance in retrieval and substitution-based tasks. It is the need to suppress irrelevant information with increased cognitive demands in substitution that may create interference among items that are being retrieved and transformed during task performance. Recalling items from WM is challenging in the presence of interference, which may result in lower performance accuracy when numerical information has to be updated and retrieved. This issue in retrieving information could be due to a weak binding between contextual cues (boxes) and the content (numbers) (Pelegrina et al., 2020). Here, the updating mechanism is more crucial to modify numerical information kept in WM to place new information continuously in each list of blocks because the ability to discard no-longer relevant (old) information is required to make room for the new information. Since old information has to be replaced with new information in this updating process, new bindings are built between boxes and updated numbers for effective retrieval (Oberauer, 2009; Miyake et al., 2000). The dynamic interplay between these cognitive functions underlines the complexity of the WM system in such tasks with a higher demand in WM.

The additional findings in this study point to the effect of item type categorized by operation and recall and to the length of each block in the task, separated into short listed and long listed blocks. It was assumed that participants would perform better in operation items compared to recall items in each task and their performance in short-listed block items would be higher overall, as posited by hypothesis 2c. The results partially confirmed the assumptions.

While the accuracy performance did not differ in any item type of tS and Rt conditions, the participants showed lower accuracy performance in long-listed operation items in RtS condition compared to short and long-listed recall items. This finding contradicts the hypothesis and suggests that arithmetic operation tasks with longer sequences may be more challenging than the tasks which require recalling processes. Long sequenced operations can create higher cognitive demand in WM since more complex problem-solving and manipulation of information is required (Unsworth & Engle, 2007). Additionally, participants demonstrated a longer reaction time in long-listed operation items for tS condition compared to other item types. This notion suggests that as more complex and longer tasks contain more interference, such tasks can require more time to process information (Oberauer & Kliegl, 2006). Interestingly, longer reaction time was found in both long-listed operation items and short-listed items for the Rt condition, whereas there was not significant difference between any item types for the RtS condition. According to these findings, item type and task length cannot solely determine the performance on different conditions of the MDS task, but multifaceted interplay of these factors may specifically influence the performance including other cognitive demands. For instance, tasks including both complex item type and longer length can challenge individuals' WM capacity limit due to high demand on cognitive resources (Oberauer et al., 2003). This high demand increases cognitive load which compels them to adopt strategies to manage in addition to the need for monitoring and updating (Miyake & Shah, 1999). Using strategies serves different processes and distinct functions within the WM system because individuals need to make decisions about when and how to allocate cognitive resources for better performance.

The results of performance changes in the training group provide insight into the near effects of the WM training. In this aspect, hypothesis 3b predicted that *n*-back training would contribute to significant improvement in performance on retrieval and substitution-based tasks compared to transformation tasks, reflecting near transfer effect to the updating processes of the WM system. The findings showed that the change in performance varied across the conditions of MDS task. The training group did not improve significantly on retrieval (Rt) and retrieval and substitution based (RtS) tasks. This outcome contradicts the predictions and supports the idea that trained cognitive skills may not directly adjust to the improvement in retrieval and substitution processes. Transfer effects of WM training can be more task-specific, bound to specific cognitive processes employed in the trained tasks (Dahlin et al., 2008). In order to achieve transfer, the training and the post-test tasks have to rely on the same underlying cognitive mechanisms. Unexpectedly, the change in both accuracy and reaction time performance was observed only in the long-listed transformation and substitution-based condition (tS). This finding suggests that *n*-back training may provide a positive effect on tasks where transformation and substitution of updating processes are utilized. Since individuals perform simple arithmetic operations in the tS task, it can be asserted that *n*-back training can have a broader impact on basic mathematical skills (Kane et al., 2005). The cognitive processes in the *n*-back tasks - where information has to be continuously updated and monitored - closely reflect the process of the transformation and substitution based arithmetic operation task. Participants need to maintain and manipulate numerical information, such as applying operation to a last result which must be remembered and updated for a following operation in the same list. The *n*-back training enhances cognitive flexibility and interference control, enabling individuals to adapt to changing task demands and focus on a current operation by suppressing distractions from previous steps. For instance, their enhanced WM capacity allows them to perform better in such arithmetic operations where intermediate results must be maintained though the problem-solving process. The improvement on recall items would be greater than on operation items in all conditions, as also posited by hypothesis 3b. The observations demonstrated that while the change only in reaction time performance was significant for recall items in the tS condition, the change in accuracy and reaction time performance was insignificant for either recall or operation items in the Rt condition.

It was also hypothesized that the improvement in performance in both solving arithmetic operations and recalling last items at the end of the list in which complex retrieval and substitution (RtS) are involved would be significant. However, intriguing results were found for the RtS condition where changes in both accuracy and reaction time performance were significantly higher for recall items than operation items. In this condition, remembering operation items is essential to enter recall items at the end of a list. If participants forget operation items which are recent results of each operation and are needed to be maintained to continue the sequence, recall items cannot be provided correctly at the end. This finding presents an argument that participants likely developed strategies for remembering recall items as an outcome of the training, such as verbal rehearsal and visualization, which were not effective for remembering operation items (Dunlosky & Kane, 2007).

As stated in hypothesis 4b, the post-test training group would perform better than the post-test control group in retrieval and substitution-based tasks as well as in operation and recall items in each condition, except the baseline condition. The training group did not improve performance significantly in accuracy, since groups did not differ at post-test in terms of accuracy. On the other hand, the training group showed faster response times in all interference conditions than the control group, but their performance in baseline condition was similar. This improvement only in response time might suggest that the training was related to certain cognitive processes more than others, such as complex retrieval and substitution. The nature of these cognitive skills is multifaceted and may necessitate additional interventions to improve those skills. This highlights the need for training programs which target a broad range of cognitive skills for enhancement to achieve far transfer effects (Melby-Lervåg & Hulme, 2013). Additionally, the training group's higher performance for operation and recall items in terms of reaction time supports that the *n*-back training can contribute to enhancement of speed in processing (Karbach & Verhaeghen, 2014).

Arithmetic operations

In the context of this study, arithmetic operations which consist of all four types of operations were used to test skills in mathematics under baseline and interference conditions. The purpose of using those tests is to verify whether there is a far transfer effect of the training on mathematical skills while solving large-size problems which create interference in memory. Similar performance was observed between the pre-test training and pre-test control groups in arithmetic operations, as anticipated by hypothesis 2a. The performance of participants in four arithmetic operations was used to interpret additional outcomes related to the hypotheses.

The assumptions based on the impact of problem size in the performance of arithmetic operations, especially in multiplication and division, supported the notion that larger-size problems would trigger more interference since the nature of the task required participants to recall procedures that were previously learned (Zbrodoff & Logan, 2005). As a result, while performance on accuracy was lower, it was higher on reaction time in the interference condition compared to the baseline condition. These findings are in alignment with the assumptions postulated in hypothesis 2d. Participants exhibited similar accuracy performance in the baseline condition across the operation types, the reaction time performance was higher in subtraction and multiplication. Participants were allowed to use any strategies to solve the problems, including auxiliary tools except for a calculator. They were likely able to perform addition and subtraction mentally, but for multiplication and division, they may typically use pen and paper, leading to longer time to complete the tasks due to increased the complexity of the calculations. Multiplication and division are more complex operations and involve larger numbers. Unlike addition and subtraction, retrieval of the multiplication table is required for those operations. Since participants shift from mental arithmetic to step-by-step process by using paper and pen, the likelihood of errors decreases, but reaction time increases (Ashcraft, 1992; LeFevre et al., 1996). This can be explained by Heitz's (2014) speed-accuracy trade-off theory suggesting that decisions made more quickly tend to be less accurate, however, decisions made with more accuracy require more time.

In the interference condition, the accuracy performance was lower across all operation types, but reaction time performance was higher in multiplication and division. The role of the monitoring skills becomes more crucial in complex tasks because more complexity in a task means that more steps are required which may lead to more errors at any given step. Controlling which steps are followed, which ones are left and whether the calculations at each step are correct pertains to good monitoring skills. However, monitoring may create a high demand in WM since evaluation of the quality of information is required alongside maintaining and manipulating the information (Morris & Jones, 1990). For example, when individuals are engaged in carrying and borrowing numbers in arithmetic operations, intermediate steps need to be monitored in the process where recalling and applying arithmetic procedures can be potentially disrupted by proactive interference.

Binding and updating processes have also a significant role in explaining how large-size problems create proactive interference. In large-size problems, the complexity and quantity of information contribute to an increase in binding numerical values to their corresponding operation types (Oberauer et al., 2012). The increased binding of previous information can interfere with the bindings of the current information if there is not enough flexibility in the cognitive system. Updating is required continually while solving larger-size problems, in other words more complex tasks require the execution of various operations simultaneously, such as progressing problem steps, accessing new information, applying calculations, and improving the understanding of the problem (Ecker et al., 2010). This continuous updating may lead to proactive interference if similarity occurs between old and new information in complex forms.

Hypothesis 3c predicted a pattern change in both conditions of this task and enhancement in multiplication and division performance in the interference condition, leading to far transfer effect of the *n*-back training. Performance changes of the pre-test training group were observed only in reaction time in both baseline and interference conditions. Performance change in reaction time was significantly larger in the interference condition than in the baseline condition, suggesting that participants showed more improvement in the interference condition after the training. In the interference condition, participants are required to discard irrelevant information and update their WM with new relevant information. Enhanced WM capacity which can be obtained by cognitive training may provide more efficient processing and increased interference control to suppress distractors efficiently and respond quicker to stimuli (Klingberg, 2010; Shipstead et al., 2012). Further analyses showed that participants were faster at post-test than pre-test in all operations in both conditions, but the improvement from pre- to post-test was significantly greater for subtraction tasks in the baseline condition and for division tasks in the interference condition. Far transfer effect is not compatible with some cognitive tasks. In this study, no significant improvement was found in addition and subtraction under the interference condition, probably due to the lower complexity of the tasks than in multiplication and division. The intensity of the training and the involvement of more complex tasks enabled the participants to benefit more from the training in complex arithmetic operations such as multiplication and division (Passolunghi & Pazzaglia, 2004).

The improvement in subtraction performance in the baseline condition is in alignment with research suggesting that *n*-back training might serve near transfer effects (Soveri et al., 2017). This emphasizes the ambiguity in the literature regarding the transfer effect of training because it is difficult to determine whether enhancement in a task is because they improved their cognitive abilities or they used task-specific strategies or they were familiar with the task. In this study, problems of varying difficulty were included before and after the training period to measure participants' performance in arithmetic operations. Improvement across these tasks may demonstrate the enhancement in cognitive abilities rather than using task-specific strategies or task familiarity (Jaeggie et al., 2008; Shipstead et al., 2012). Foundational arithmetic skills, like subtraction, are closely integrated with basic cognitive functions and can benefit from broader cognitive enhancement without developing specific strategies (De Smedt & Verschaffel, 2010; Geary, 2011).

Another hypothesis on training effect proposed that the post-test training group would outperform the post-test control group in large-size arithmetic operations. Contrary to expectations, according to the analyses, no significant difference was observed in either accuracy or reaction time performance between these two groups. Individual differences may explain this outcome in how participants benefit from the training. Due to indeterminate differences between the participants, some of them might show more improvement following training, whereas others may not. This Variability within groups may lead to average outcomes presenting no significant difference between the training and the control groups. These findings are considered within the limitations of the study.

Word problems

Another test to measure participants' performance in mathematics was word problems under neutral and biased conditions. The primary purpose of implementing this test was to investigate the far transfer effect of the *n*-back training. This segment of the study aimed to furnish further supportive evidence for theories about the interference mechanisms within the context of solving word problems. The performance between group T1 (the pre-test training group) and group C1 (the pre-test control group) on word problems was similar. However, the findings revealed that the presence of irrelevant information, either literal or numerical, did not significantly influence the performance of participants in word problems. Group T1 did not exhibit a performance change in terms of accuracy and reaction time as a result of training, as proposed by hypothesis 2e. Groups T2 (the post-test training group) and C2 (the post-test control group) differed in only reaction time performance but interestingly group C2 performed faster than T2 in the problems which included numerical irrelevant information. Cognitive training might impact participants' strategic approaches in tasks where discarding of irrelevant information is required (Miyake & Shah, 1999). This can unintentionally slow down response times. The faster response time of group C2 might be attributed to their reliance on more familiar and less complex approaches while performing the task (Karpicke & Roediger, 2008; Dehaene, 2011). The contradiction between the assumptions and the findings in this part of the study might be caused by high individual differences and inadequacy of problem-solving skills due to the presence of younger children. The type and amount of irrelevant information alone cannot be indicative in determining performance in word problems with interferences. Participants are also required to be able to use cognitive strategies and to have reading comprehension and numeracy skills (Holmes & Adams, 2006). The training groups probably did not sufficiently address these multifaceted demands required for proficiency in word problems with irrelevant information. The findings suggest that the training might not effectively enhance participants' capability to ignore irrelevant information while solving word problems since there was no difference between the training and the control groups in the post-tests, and the training group did not improve their problem-solving skills following training. The *n*-back training improves certain aspects of cognitive skills (Shipstead et al., 2012) and it might not be efficient at allowing individuals to transfer its effect into word problem proficiency, especially problems including irrelevant data.

5.3 Practice effect

To evaluate the practice effect of repeated testing, two different sets of analyses were conducted within the control groups. It was anticipated that the pre-test control group would not show any improvement in tasks from pre-test to post-test, and no significant difference would be observed between the pre-test control group and the post-test control group at post-test.

The results of these two sets of analyses revealed complicated findings. The performance of the pre-test control group in terms of either accuracy or reaction time did not change in the *n*-back, arithmetic operations and word problems tasks from pre to post-test, but the reaction time performance in the MDS task was lower at post-test. As expected, without training, the participants did not exhibit significant improvement in the *n*-back task (Redick & Lindsey, 2013), nor in the arithmetic operations and word problems tasks (Karbach & Verhaeghen, 2014). Conversely, a decrease in reaction time in the MDS task at post-test, despite no training, could indicate a test-retest effect. The faster response might be a consequence of increased familiarity with the task.

The findings focusing on the differences between the pre-test and post-test only control groups were partially consistent with the assumptions. At post-test, while these two groups did not show significant difference in either the *n*-back or arithmetic operations tasks in terms of accuracy and reaction time performance, the pre-test control group performed faster in the MDS task and demonstrated higher accuracy in the word problems task. This supports the notion that repeated exposure to cognitive tests can contribute to improvement over time even if training was not received (Collie et al., 2003). This finding further supports the use of the Solomon 4-group design to control the practice effect. The increased accuracy performance in the word problems task might be explained by the fact that the participants in the pre-test control group received prior exposure to the task during the pre-test, which may have led to an improvement in their understanding of the task structure and problem-solving strategies.

Overall, the varying results in different tasks highlight that practice effect is nonuniform and can be task-specific (Melby-Lervåg & Hulme, 2013). A variety of factors, such as task type, testing interval, and individual differences may influence practice effect in a cognitive task.

5.4 Transfer effect of cognitive training

The primary aim of cognitive training studies is to discover whether improvements in performance can be transferred to areas that were not directly targeted within the training (Jaeggi et al., 2008; Melby-Lervåg & Hulme, 2013; Simons et al., 2016; Sala & Gobet, 2017b). While many studies have reported such transfer effects, there are a considerable number that failed to observe substantial changes (Sala & Gobet, 2019; Gathercole et al., 2019; Moreau et al., 2016) This contradiction contributes to difficulty in understanding the body of literature. Variations in research findings underscore the complexity and ambiguity of cognitive training outcomes. Recent research has not found a transfer effect from working memory training to mathematical and reading skills, despite some positive effects of training (Vernucci et al., 2023). It was asserted that since reading skills are complex, different interventions are required to improve those skills. Performance improvement in mathematics computation may have relied on strategy use and specific knowledge rather than WM resources. Again, if the training tasks did not target the most relevant underlying cognitive mechanisms that were needed for either the reading comprehension or the computations in mathematics, then no transfer should have been expected.

A meta-analysis of previous training studies also underscored that working memory training does not necessarily contribute to enhancement in arithmetic, word decoding, or verbal or nonverbal abilities (Melby-Lervåg & Hulme, 2013). This evidence supports the idea that due to the inefficiency of training in high-level cognitive abilities, far transfer effects are not typically observed (Shipstead et al., 2012). Another meta-analysis of training studies reports that while training is less likely to produce far transfer effects, near transfer effects may possibly be observed since the tasks are similar to the training tasks (Sala & Gobet, 2017a; Dahlin et al., 2008). On the other hand, there are several studies that demonstrate intriguing results on cognitive training studies. For example, dual *n*-back training improved fluid intelligence as evidence for far transfer effect (Jaeggi et al., 2008). This improvement specifically involved the cognitive skills related to reasoning and word problem-solving. Since multiple components of WM were simultaneously engaged in this training, it might contribute to more effectiveness to create transfer effect on fluid intelligence. Training demands may produce improvements in domain-general skills that can be transferred to fluid intelligence with improved attentional control by maintaining relevant items in active memory (Gray et al., 2017). Additionally, computerized adaptive WM training had a positive impact on WM and mathematical skills of school-age children with low WM (Holmes & Gathercole, 2013). Significant improvement in WM was observed in complex span measures which were correlated strongly with children's academic achievements in mathematics and literacy (Swanson & Siegel, 2001; Alloway et al., 2004).

These discrepancies might arise from methodological divergence among the studies or specific characteristics of the mathematics measures that were utilized. For instance, differences in duration, intensity, and type of WM training programs (Klingberg, 2010), as well as participants characteristics (Gathercole et al., 2019), sample size, and the statistical methods (Button et al., 2013) applied can separately or collectively lead to varying outcomes. Additionally, the context and format of mathematics problems presented in assessments can influence benefits from the training because training may enhance proficiency in problems including only numerical information more than problems where participants need to comprehend and solve problems presented in text (Raghubar et al., 2010).

All in all, studies on cognitive training exhibit multifaceted and complex findings which were gathered from different methodological approaches and designs. The degree of overlap between the underlying mechanisms that are targeted by the training and the outcome measures have a key role in obtaining a transfer effect to untrained tasks. In line with this, the current study provides significant insights to demonstrate training effects from a methodological perspective, and across the tasks designed to observe the transfer effect of the training. The Solomon 4-group design differentiated this study from previous research and provided advanced and extensive analyses of data gathered from distinct combinations of tasks to examine transfer effects of the training. Detailed analysis revealed that transfer effects of the training were observed in the cognitive tasks (1-back, 2-back and MDS) and arithmetic operations, particularly in the condition including proactive interference lures or possible errors. Participants demonstrated increased speed in those tasks despite the absence of significant improvement in accuracy. However, transfer effects in word problem-solving tasks were not observed in this study. These specific points provide an important contribution to exploration of the mechanisms which underlie transfer effects of *n*-back training.

5.5 Individual differences

The outcomes of this study contribute to a large body of literature about individual differences in WM performance within an interference model (Kane & Engle, 2003; Conway et al., 2002; Unsworth & Engle, 2007; Oberauer et al., 2012; Redick, 2019). In this line, the study underscores the importance of the interference framework of the WM system for consistent explanations of why individuals differ in performance across different WM measures and which specific WM functions are crucial for task-oriented skills Performance differences observed across tasks consisting of different conditions and item types can be attributed to interference control skills. Completing these task goals successfully depends on the ability to use binding and updating mechanisms to maintain and manipulate information amidst interference. For instance, these mechanisms allow individuals to connect numerical data, gathered from a problem-solving context, with computational steps and adjust them to new data during mathematics problem-solving process.

To understand how cognitive abilities might be improved through WM training, the two concepts of domain-general and domain-specific WM should be clarified extensively in interpreting individual differences based on the interference framework. The mechanism of interference control is identified as the domain-general process that supports the ability to resist interference in WM across all tasks. For example, numerical tasks used as arithmetic operations and word problems in this study involve domain-general processes in WM, attention, and problem-solving skills. Training these skills lead to far transfer effects on domains to varying extents depending on the nature of the transfer domains (e.g., tasks similar to training content, numerical tasks, nonnumerical cognitive tasks) and individual differences (e.g., motivation, educational background, personal adapted strategies). The nonnumerical tasks requiring verbal skills, such as reading comprehension and improving vocabulary, incorporate both domain-general and domain-specific components of WM. In some instances, domain-specific skills can bolster domain-general abilities, such as binding and updating, which can then be transferred to a wide range of tasks, especially to mathematics tasks. The training implemented in this study has possibly engaged domain-general WM processes since the improvement in arithmetic operations does not directly relate to the training content, but these operations have been demanding cognitively. Furthermore, the consequent transfer effects may suggest that these processes do not consistently impact verbal and nonverbal domains. Here, involving the interference theory in this study provides an innovative approach (Marton et al., 2014) which sheds light on the interdisciplinary context by connecting cognitive processes to educational settings to understand how enhancing interference control skills can potentially improve cognitive skills and mathematics proficiency.

Individual differences stem from various factors including cognitive elements like working memory (WM) capacity and attentional control, as well as non-cognitive components like motivation and anxiety (Cirino, 2011). As a result, it is a big challenge to reach overarching conclusions about the relationship between mathematics and cognition. In this study, there was substantial variability in performance of mathematics and cognitive measures, even though participants came from a similar background in mathematics. However, comparison of patterns of performance among different conditions and item types in each task which were developed within the interference framework revealed evidence about performance differences in both mathematics and cognitive tasks after training. For example, performance pattern changes of the training groups from pre-training to post-training helped identify improvement in those tasks following the training. Furthermore, performance change of the C1 (pre-test control group) from pre- to post-tests and the performance comparisons of the C1 and C2 (post-test only control group) in post-tests indicated the practice effect of the tests.

5.6 Limitations

The present study has notable limitations that need to be acknowledged. Most prominently, the study lacks an appropriate sample size. Despite the use of the Solomon four-group design, which allows for comparisons between different groups and assessing the test re-test effect on performance, the relatively small sample size may have influenced the results. Forty-four participants were divided among the four groups and each group included only eleven participants. It was possible to conduct research with such a sample size, but this could potentially impact the statistical power of the findings and generalizability. Additionally, conducting multiple analyses within the framework of this design has introduced a degree of complexity in both the implementation and interpretation of the results. This increased complexity has resulted in difficulties and challenges encountered when dealing with the complex data analysis and discussing the findings derived from the various combinations of groups.

One limitation of this study is the potential bias introduced by the phrasing of items in the "Theories of Cognitive Abilities Scale" to measure the training groups' motivation before the training. Specifically, all three items used contained negative phrasing, which may have suggested to participants that intelligence and cognitive abilities are fixed traits. This could have influenced their responses, leading to a lack of variability in the results. Previous research has shown that item phrasing can significantly impact survey outcomes (Schwarz, 1999; Podsakoff et al., 2003). Future studies should consider using a mix of positively and negatively phrased items to obtain a more balanced and accurate assessment of participants' beliefs (Dweck, 2006).

Another significant shortcoming of this study is the potential impact of test-retest effects. Even though a significant test-retest effect was not found in the *n*-back and the arithmetic operation tasks, it was observed that the C1 (pre-test control group) improved in the performance of MDS task and word problems tasks. These non-uniform and task-specific changes in performance can underline that indeterminate factor such as task type, testing interval, and individual differences may influence practice effect in mathematical and cognitive tasks. Therefore, it cannot be concluded that all changes in performance among the training groups were due to the training itself. An inadequately implemented control design may have led to this test-retest effect. For example, during the training period, the control group was not engaged in any tasks, which may have created an invalid comparison point to the experimental group (Morrison & Chein, 2011). This situation probably prevented controlling variables properly like exposure to the test conditions or the time period, leading to observed improvement in the control groups. Its impact on validity of the findings needs to be considered while interpreting the results. While the Solomon Four-Group Design conducted in this study provided a comprehensive evaluation by examining both training and practice effects, the increased variability in complex data can lead to challenges to find significant differences and interpret data accurately. A larger sample size may eliminate such problems in the future and may increase internal validity (Shadish et al., 2002).

Lastly, the mathematics proficiency assessments utilized in this study can also be considered as limitations of the study. Specifically, the arithmetic operations task may not have incorporated manipulation explicitly. The task did not directly assess the participants' performance to manipulate target distractions as irrelevant stimuli. Only task complexity as determined by problem size and similarity-based interference (De Visscher & Noël, 2014) was assumed to create memory load which causes interference during performing the task. For instance, when finding the answer of 3x9, the combination 2–3 has been found in four previously learned problems (3x2=6, 3x7=21, 4x3=12, 3x8=24), the combination 2–7 has been found in two problems (2x7=14, 3x7=21), and similarly for the combination 2–9 (2x9=18), 3–7 (3x7=21), 3–9 (3x3=9). In this study, similar or same digits in large size were used as possible interference items, leading to the same response of a given problem. Furthermore, the presence of irrelevant information in the word problems task was expected to cause interference, but its nature is not completely clear. Numerically and literally irrelevant information in word problem were assumed to create interference in WM but the contradiction of the assumptions and insufficient findings did not support these factors as indicator to determine the performance in word problems with interference. Factors such as teaching strategies, the nature of problems and problem-solving skills can affect how irrelevant information interferes with problem-solving. A comprehensive perspective is required to understand the interference framework in this context because various elements can have substantial effects on results.

5.7 Future Research

This study has provided significant contributions to the understanding of the findings gathered from innovative approaches for the methodology and the in- depth analysis to find answers to the research questions. Despite the limitations, the present research and the suggestions provided here can be considered as a potential avenue to extend this field of study and highlight new questions for further research.

One important suggestion would be to recruit participants through an additional process which could include a measure to assess their mathematics proficiency in different subject areas. This idea would broaden the research questions to evaluate how training influences individuals with varying levels of mathematical skills. It is important to get information about participants' existing mathematics proficiency level before interventions to identify the differential effects of the training (Dowker, 2005). This was achieved by the pre-testing in this study but there was no assessment to examine participants' strategy use. The effects of the training could have been better understood by examining their strategy use in mathematics problems before and after training. As a benefit of training, improvement in mathematics skills should be attributed to training rather than to other potential factors such as developed strategies (Thompson et al., 2013). This modification can provide deeper understanding into the specific areas of mathematics where the training is more effective and how the impact of the training could be optimized for diverse learners.

Another logical suggestion for further studies would be to work with three groups which constitute a training group, an active control group and a post-test only control group. This active control group would engage in training which does not target any transfer effects, over the same number of sessions as the training group. That training would be unrelated to tasks that enhance cognitive skills as benefits from a WM training program, such as perceptual training (e.g., pattern identification, completing puzzles), or motor skills training (e.g., eye-hand coordination). This approach would enable researchers to control non-specific effects and isolate the specific effects of the training given to the training group. Performance change between the training and active control groups can occur after the training due to the training itself rather than any other factors.

5.8 Implications

The findings of this study have implications for research in cognitive skills and education, as well as practical applications in educational settings. The observations that predict mathematics performance based on cognitive abilities provide a steppingstone for developing educational strategies and interventions aimed at improving mathematics performance (Bull & Lee, 2014). These findings also highlight the necessity for early intervention in children with low working memory (WM) capacity or poor interference control. Since these cognitive skills are essential for success in mathematics, interventions designed to enhance these abilities can yield long-term efficacy not only in mathematics but also in other academic disciplines (Holmes & Adams, 2006). This study can provide evidence to enhance children’s cognitive abilities to maintain and process information in cognitive related tasks and may contribute to the identification of special educational strategies for children with learning difficulties or cognitive impairment. To achieve this, further research is required for better understanding of which specific tasks can be tailored to diverse cognitive abilities.

The findings of this research provide substantial evidence to endorse the use of working memory (WM) training for the improvement of children's cognitive and mathematics skills. With additional investigation into their relationship, practical applications can be established for learners. Educators, especially curriculum developers, can utilize these findings to devise mathematics programs and integrate principles about cognitive skills with mathematics programs. Such interventions might be promising for mathematics learning, as they can render the curriculum more effective and responsive to individual needs (Sternberg, 2003). Meanwhile, this cognitive-based approach requires teacher training to incorporate these elements into their instruction. From this perspective, teacher education programs could be designed to include training modules with cognitive development implications for mathematics teaching (National Council of Teachers of Mathematics, 2000).

5.9 Summary and Conclusion

The present study explored the cognitive and mathematical performance enhancement in school-aged children resulting from adaptive *n*-back training based on binding and updating processes in working memory. The participants showed an improvement in task performance, albeit not entirely, in tasks designed to assess the training's efficiency. Evidence of the near transfer effects of the training was observed in the performance pattern on a modified digit span task, particularly in terms of processing speed under conditions of interference. Far transfer effects of the training were evident in arithmetic operation performance, but only for subtraction under baseline conditions and division under interference conditions, again in terms of speed. These results affirm that the interference model of working memory can provide an effective framework for identifying individual differences in working memory settings. Furthermore, this study suggests that the design of tasks, which are derived from a theoretical basis and include manipulations of the targeted mechanism, is crucial to demonstrate the impact of cognitive training. Overall, this study supports the connection between mathematical proficiency and cognitive skills in school-aged children and encourages the continuation of this research path to foster an interdisciplinary approach by incorporating similar cognitive manipulations with mathematical implications for learners.

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APPENDICES

APPENDIX A

*Note: It was translated into Turkish.

DWECK'S THEORIES OF COGNITIVE ABILITIES SCALE

Read each sentence below and then circle the one number that shows how much you agree with it. There are no right or wrong answers.

1. You have a certain amount of intelligence, and you really can't do much to change it

1. Strongly agree
2. Agree
3. Mostly agree
4. Mostly disagree
5. Disagree
6. Strongly disagree

2. Your intelligence is something about you that you can't change very much

1. Strongly agree
2. Agree
3. Mostly agree
4. Mostly disagree
5. Disagree
6. Strongly disagree

3. You can learn new things, but you can't really change your basic intelligence

1. Strongly agree
2. Agree
3. Mostly agree
4. Mostly disagree
5. Disagree
6. Strongly disagree

APPENDIX B

INFORMED CONSENT FORM

Proje Başlığı: Çalışan Bellek Eğitimi: Okul Çağı Çocuklarında Bilişsel ve Matematiksel Çıkarımlar
Birincil Araştırmacı: Selma Boz, Doktora öğrencisi, Özel Eğitim Bölümü, Eötvös Loránd Üniversitesi (ELTE)
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Birincil Danışman: Klara Marton, Ph.D, Özel Eğitim Fakültesi, Eötvös Loránd Üniversitesi (ELTE)
Çalışmanın yapılacağı yer: Türkiye

Genel Bilgi: Çocuğunuz bir araştırma projesine katılmaya davet edilir. Bu çalışmanın amacı, çalışan bellek eğitiminin okul çağındaki çocukların hem çalışan bellek, hem de matematik görevlerindeki performansını nasıl etkileyebileceğini incelemektir. Bu çalışmanın sonuçları, bellek ve matematik performansındaki bireysel farklılıkların ve sınırlamaların doğasını daha iyi anlamamıza yardımcı olabilir.

Prosedür: Bu çalışmaya yaklaşık 40 çocuğun katılması beklenmektedir. Tüm testler ve bellek eğitimi online ses ve video kayıt ile uygulanacaktır. Yarısı bir dizi bilişsel ve matematik testi tamamlarken, diğer yarısı bu testleri tamamlamanın yanında çalışan bellek eğitimi alacaktır. Çocuğunuz eğitim gruplarından birine seçilirse, her biri 30 dakika süren 16 seansa katılacaktır. Çocuğunuz kontrol grubuna seçilirse, çalışmanın başlangıcında ve sonunda 1-2 seansa katılarak çalışmayı tamamlayacaktır. Çocuğunuz sessiz bir odada oturacak ve ondan onay alınacaktır. İlk olarak, çocuğunuz standartlaştırılmış testleri kullanarak bir zeka ve hafıza testine katılacaktır. Ardından bazı bilgisayarlı görevleri yerine getirecektir. Örneğin, bazı soyut figürler veya tek tek harfler görecek ve belirli bir şeklin veya harfin daha önce sunulup sunulmadığını değerlendirecektir. Her öğrenci, araştırmacı tarafından online olarak, tüm dikkat dağıtıcı unsurların ve gürültünün ortadan kaldırılacağı sakin bir yerde test edilecek ve eğitilecektir. Görev gruplarına bağlı olarak, eğitim döneminden önce ve sonra, test oturumları ve 16 eğitim oturumu alacaklar. Araştırmacı, her öğrencinin oturumlara katılacağı kesin zamana karar verecek ve öğrenciye uygun bir program planlayacaktır. Bir öğrenci herhangi bir eğitimi kaçırırsa, telafi oturumu düzenlenecektir.

Olası Rahatsızlıklar ve Riskler: Bu çalışmaya katılırken, olası küçük yorgunluk dışında bilinen veya beklenen risk veya tehlike yoktur.

Faydalar: Gönüllülüğün size veya çocuğunuza doğrudan bir faydası yoktur. Fakat, sonuçlar çocuklarda çalışan bellek ve matematik arasındaki ilişkiyi daha iyi anlamamıza yardımcı olabilir. Ayrıca, çocuğunuzun standartlaştırılmış testlerden elde ettiği sonuçlar talep üzerine size sunulacaktır.

Gönüllü Katılım: Bu projeye katılım isteğe bağlıdır. Çocuğunuz herhangi bir faaliyeti durdurmakta veya herhangi bir soruya cevap vermeyi reddetmekte özgür olacaktır. Çocuğunuzu herhangi bir ceza olmaksızın geri çekmekte özgürsünüz.

Gizlilik: Çocuğunuzun adı ve tüm tanımlayıcı bilgiler kesinlikle gizli kalacak ve araştırmacının bilgisayarında tutulacaktır. Yalnızca bu projenin Birincil Araştırmacısı Selma Boz ve Baş Danışmanı Klara Marton toplanan verilere erişebilecektır. Yetkili bir psikolog danışmanlığında bir dizi zeka ve hafıza testleri uygulanacak ve bir araştırma görevlisi çocukların test puanlarının hesaplanmasına yardımcı olacaktır. Tüm çocuklara, test sayfalarında ve elektronik belgelerinde kullanılacak kod numaraları verilecektir. Bu proje sırasında toplanan bilgiler sunulabilir veya yayınlanabilir, ancak sizi veya çocuğunuzu tanımlayabilecek hiçbir veri dahil edilmeyecektir.

İletişim Soruları / Kişiler: Bu proje hakkında şu anda veya gelecekte herhangi bir sorunuz olursa, Birincil Araştırmacı Selma Boz ile iletişime geçmelisiniz, e-posta: selmaboz85@gmail.com, telefon: +90 536255 93 17.

Bu araştırmanın bir katılımcısı olarak haklarınızla ilgili sorularınız için, Eötvös Loránd Üniversitesi Bárczi Gusztáv Özel Eğitim Fakültesi Etik komitesi ile +36 1 358 5500 numaralı telefondan iletişime geçebilirsiniz.

Lütfen istenen tüm bilgileri doğru ve eksiksiz bir şekilde doldurunuz.

Çocuğunuzun bu araştırmaya katılmasını kabul ediyorsanız lütfen aşağıdaki açıklamayı okuyarak kutuyu işaretleyiniz.

- ❑ Bu araştırmanın yukarıdaki açıklamasını okudum ve anladım. İlgili riskler ve faydalar konusunda bilgilendirildim ve tüm sorularım memnuniyetle yanıtlandı. Ayrıca, gelecekteki sorularımın da çalışmanın birincil araştırmacısı tarafından yanıtlanacağından emin oldum. Çocuğumun bu çalışmaya katılmasını gönüllü olarak kabul ediyorum.Bu kutuyu işaretleyerek, aksi takdirde hakkım olacak hiçbir yasal hakkımdan feragat etmedim. Bu beyanın bir kopyası bana gönderilecektir.

Öğrencinin adı ve soyadı:

Öğrenci velisinin adı ve soyadı:

Lütfen onayladığınız tarihi doğru seçiniz.

Appendix C

Demographic Information and Socio-economic Status (SES)

Çocuğun adı ve soyadı:

Çocuğun Ebeveyninin / Velisinin Adı ve Soyadı:

Yakınlığı:

Aşağıdaki soruları size uygun bir şekilde yanıtlayınız.

1. Evinizde kaç kişi (kendiniz hariç) yaşıyor?
2. Çocuğunuzun BİRİNCİL ikametgahı olan evde veya dairede kaç yatak odası (misafir yatak odaları, ofis olarak kullanılan yatak odaları vb. dahil) var? Birincil ikametgahı yoksa cevabınızda belirtiniz.

3. Aşağıdakilerden hangisi, tamamladığınız en yüksek eğitim düzeyini en iyi tanımlar?

- ❑ Liseyi Bitirmedi.
- ❑ Liseyi Bitirmedi, ancak bir teknik / mesleki programı tamamladı.
- ❑ Lise Mezunu veya GED (Genel Eğitim Diploması)
- ❑ Bitirilen Lise ve bir teknik / mesleki program
- ❑ 2 Yıldan Az Üniversite
- ❑ 2 Yıl veya daha fazla Üniversite / ön lisans veya eşdeğeri dahil
- ❑ Üniversite mezunu (4 veya 5 yıllık program)
- ❑ Master derecesi (veya diğer lisansüstü eğitim)
- ❑ Doktora derecesi (PhD., MD, EdD, DVM, DDS, JD, vb.)

İleri eğitim için sağlam planlarınız var mı? (Kendiniz için)

- ❑ Evet
- ❑ Hayır

Varsa nedir? Belirtiniz.

4. Mevcut çalışma durumunuz nedir? Tüm seçenekleri kontrol ediniz.

- ❑ Ücret karşılığında tam zamanlı çalışma
- ❑ Ücretli yarı zamanlı çalışma
- ❑ Şu anda çalışmıyor, iş arıyor.
- ❑ Emekli
- ❑ Ev Hanımı
- ❑ Engelli (kalıcı veya geçici engellilik nedeniyle çalışmıyor)

Cevabınız "Diğer" ise lütfen belirtiniz.

Çalışıyorsanız haftalık çalışma saatinizi belirtiniz.