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Information management in working memory: A collection of studies on encoding and updating processes

Surname: Baggini
Name: Davide
University of Milano-Bicocca registration number: 789839
University of Surrey registration number: 6841417

Tutor: Paola Ricciardelli

Co-tutor: Alan Wong

Coordinator: Simona Sacchi

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I think the human brain is fascinating.

A small organ that weighs less than 1,5kg has the power to create an entire lifetime of experiences, emotions, and memories. It produces colors, sounds, smells, and perceptions that allow us to make sense of the world. It makes us feel free when we look at a landscape, and it makes us feel fractured when we lose a person that we love. It can lead to the creation of art, music, or entire fantastic universes that never existed before. It can create abstract representations of objects, places, people, and even create abstract representations of other abstract representations. It can share its representations with other brains through many types of communication, and it has the ability to integrate others' representations with its own, creating new concepts. It can make decisions, and it can evaluate how bad those decisions are (unfortunately, most of the time, when it is too late).

What makes the brain so special is its ability to process information, and I find this concept extremely intriguing. One of the crucial elements of information processing in the cognitive system is the so-called working memory, a mental workplace that we use to manage an incredible amount of information in each moment of our lives, most of the time without even noticing. It is precisely this mental workspace that will be the core of the present dissertation.

Acknowledgements

Doing a PhD in cognitive science gave me the opportunity not only to study and understand more about a topic that I'm passionate about, but it also gave me the opportunity to add my small contribution to the knowledge in a field that still has a lot to be unraveled. That made me feel like I was an active part of the scientific process, and I am grateful that I had this opportunity.

I want to thank all those researchers who devoted an immense effort and spent countless hours of their lives addressing apparently insignificant questions that no one had answered before because they were considered of no practical interest. All the researchers who came before me, whose findings are now used as a solid base for creating new knowledge. All those researchers who have the courage to question their own results and who can accept failure and criticisms with honesty and humility. These people have made science one of the most precious tools for humanity.

I want to thank my teachers, from whom I have learned the value of curiosity and the importance of learning, and all the teachers who understand the importance of their role.

I want to thank my PhD supervisors, especially Professor Paola Ricciardelli, who patiently taught me how to take my first clumsy steps into the world of research.

I want to thank my family and friends for trusting and believing in me. Their support was essential throughout my journey, and they always provided it to the best of their abilities.

I want to thank all those people who did not believe in me, because, in a childish attempt to prove them wrong, I was pushed to do my best in many difficult situations.

Finally, I want to thank you, the reader, for taking the time to read this dissertation and, in doing so, indirectly becoming part of my journey.

Overview of the text

The present dissertation adopts the format of a collection of articles. It brings together a series of original studies on working memory that have been designed and conducted during the course of my PhD. All the articles presented are at different stages of the publication process. Each study is preceded by a brief clarification about the state of the research at the time of the submission of this thesis. Although the text has been adapted to present a coherent format throughout the chapters, the content remains identical to the standalone version of the papers.

In Chapter 1, a theoretical introduction to memory is presented. Memory is introduced as a non-unitary object, but a complex system of cognitive processes articulated in distinct but interconnected components. The main components of memory, long-term memory and working memory, are presented in detail. Particular attention is paid to the description of Working memory, since it plays a central role throughout the dissertation. Two different models of working memory are illustrated: a classic and well-known one, and another relatively new model that tries to find a solution to the limits of the former.

In Chapter 2, a study on the relationship between cognitive load and information storage is reported. The study attempts to test and extend the theoretical model of working memory called Time-Based Resource Sharing, introduced in the previous chapter. The results found in the study are extended through an additional experiment. An unexpected outcome of these experiments led to the design of the study presented in Chapter 3.

Chapter 3 presents a study that aimed at investigating the cognitive mechanisms underlying the processing of serial order information. More specifically, the objective of the study is to determine whether maintaining information about the items of a series and about their order are two separate operations or they are a unique process.

In Chapter 4, two related studies are reported. The studies aim at exploring the processing of social/emotive information in working memory. The first study is a validation of the stimuli used in the second study. An interesting difference between men and women emerged in how they reported perceiving emotion intensity. The second study aims to explore how different emotions are encoded and updated in working memory. In addition, the difference in processing emotive information between men and women is investigated.

Finally, Chapter 5 summarizes the main results of the studies collected in the previous chapters and points to possible future directions for the research topics.

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Chapter 1: The study of memory

"Memory is the ability to remember things that happened in the past."

"Memory is what you remember."

"Memory is being able to remember important things."

These are some of the answers some people gave me when I asked them to tell me what memory is. In many contexts, these definitions are more than enough to exhaustively describe memory. They are simple, intuitive, easy to understand, and they are definitely correct. When studying the human mind, on the other hand, these definitions are incredibly limited and vague, as they describe only how memory manifests itself in everyday life. A slightly more precise definition of memory can be: a series of mental processes that allow the cognitive system to encode, manipulate, store, and retrieve information. This latter definition of memory is more exhaustive than the former, although also more cryptic.

In 1980, the jazz guitarist Pat Martino underwent a left temporal lobectomy. After the operation, his memory was heavily damaged, and he presented a severe retrograde amnesia together with a loss of interest and capabilities in music (Galarza et al., 2014). With time, Martino re-learned to play guitar and regained his musical abilities and his status as a virtuoso, and, in 2007, his neuropsychological functions showed a remarkable degree of recovery.

In 1985, Cleave Wearing, a British musicologist and conductor, contracted a cerebral infection from *herpes simplex* (Wilson, Baddeley & Kapur, 1995). This event profoundly impaired his memory to the point that, similarly to what happened to Pat Martino, he couldn't remember more than a handful of episodes of his past. In this case, however, he did not just lose his memory of the past, but he also became unable to maintain new information in his memory even for very short periods, leaving him stuck in a sort of "eternal present". His condition persisted for the whole duration of his life, but the part of his memory devoted to music seemed to be spared from oblivion. He maintained the ability to direct a chorus, to read music, and to play the piano.

These two examples make clear that memory is far more complex than the definitions proposed at the beginning. The events reported, and the many other similar cases recorded in literature, are obviously devastating for the people involved and for their families, but at the same time, they can be of immense value for research, since they provide precious information on the functioning of our cognitive system. Studying what happens when a certain mental component breaks can lead to groundbreaking insights into the understanding of such a component and its relationship with the rest of the mind, and this was one of the main techniques psychologists had available when psychology was still a very young discipline. Clinical case observations are a powerful but not systematic source of information to study the human mind, since they must occur by chance, and they do not give the researchers the possibility to manipulate many variables. Fortunately, there are many other techniques that have been developed to study memory and cognitive processes that do not rely on brain damage, such as neuroimaging and behavioral studies that allow researchers to observe brain pattern activation or the behavioral outcomes of cognitive processes. Through the combined use of all these techniques across many years of study, it clearly emerged that memory is a complex system of interactions between cognitive processes and goals that are constantly changing and updating.

When talking about memory, the first thing to keep in mind is that we are not talking about a single unitary structure, but rather a collection of processes and components that interact with each other. From this interaction, a coherent representation of the world that is capable of guiding behavior and updating itself through time emerges. Memory is only perceived as a single and rather simple process because most of the interactions within this system are transparent to consciousness, and only their final outcome is visible.

Long-term memory

Long-term memory is where all the information we have is stored. Past information can be retrieved, and present information will be accessible in the future. The information stored in long-term memory can be of any type, such as knowledge about ourselves, others, or the environment, events that occurred in the past, thoughts we had, the smell of a flower, the taste of a food, and procedures on how to perform some activities.

In an attempt to put some order in this apparent hotchpotch of different information, Squire (1992) proposed a classification of different types and functions of long-term memory. A first distinction is between explicit or declarative memory and implicit or non-declarative memory. Declarative memory refers to all the information that explicitly reaches our conscious experience. Examples of declarative memories are events that occurred in the past that we can remember, or knowledge and notions that we learned on a topic. Non-declarative memory, on the other hand, refers to all that knowledge we learned that results in performance rather than in explicit memories. For example, juggling or riding a bike.

Declarative memory can be divided into two subtypes, namely, semantic memory and episodic memory. Semantic memory refers to all the knowledge we have about the world, regardless of the sensory modality. The meaning of words, the year in which America was discovered, the color of the grass, the taste of a pizza, and how to order one from a pizza restaurant are all examples of information stored in our semantic memory. This kind of memory is usually general knowledge that can be applied to different contexts (e.g., ordering a pizza from two different pizza restaurants might not be exactly the same sequence of actions, but, in general, the procedure will be very similar). Episodic memory, on the other hand, stores specific instances of past episodes. That one time I called the pizza restaurant to order a pizza, but nobody answered the phone, and the extreme sadness that followed right after realizing that the place was closed, is a very specific memory I have, not a general knowledge of not being able to order a craved pizza. Semantic and episodic memory are closely related to each other. In fact, it is possible to say that semantic memory is just the result of a collection of episodic memories wrapped up into a general rule. Nonetheless, it is still debated whether these two types of memory rely on the same mechanism to store information, as proposed by Tulving (2002), or whether they use separate processes that converge into a unitary storage, as proposed by Baddeley (2020).

Different types of memory

Until the ‘50s, memory was commonly considered as a unitary structure that approximately coincided with today’s concept of long-term memory. From the ‘60s, when an information processing approach based on the brain-as-a-computer metaphor arose, the idea of the existence of more than one kind of memory began to spread (Gardner, 1987). This idea was first formalized by Atkinson and Shiffrin (1968) in their multi-store model of memory (sometimes called the modal model). According to this model, information accesses the cognitive system from the environment through a temporary sensory memory system, a type of storage strictly linked to perception. From there, information is transferred to a short-term memory system, a storage that can hold information for very brief periods. Finally, information is passed on to long-term memory (Fig. 1.1). This model describes information flow as a straight pipeline where, to access a certain storage, information must necessarily go through all the previous ones. This model was widely accepted for many years, but it presented two main issues. The first issue of this model was the assumption that information was guaranteed to be transferred to long-term memory simply by holding it in the short-term storage. This was proved wrong by Craik and Lockhart (1972), who described the so-called level of processing effect, according to which the storage of information in long-term memory depends on how deeply information is elaborated, rather than its permanence in the short-term storage. A second issue of the multi-store model came from neuropsychological evidence, which seemed to indicate the existence of separate paths and stores for information. Amnesic patients, in fact, provided evidence for the presence of a distinct long-term store. The most famous case in neuropsychology literature is the patient known as H. M. (Corkin, 2013). He

suffered from a severe disruption of long-term memory that made it almost impossible for him to create new memories and acquire new information. Nonetheless, he showed normal performance in language production and short-term memory tasks such as digit span. A completely opposite pattern of effects was shown by the patient K. F. (Shallice & Warrington, 1970). K. F. showed a specific deficit in phonological short-term memory. The patient had a digit span of two and presented a significantly reduced recency effect in free recall tasks. His long-term memory, on the other hand, didn't show any impairment. These kinds of cognitive impairments demonstrate that these different kinds of memories can function independently. In addition, according to the multi-store model, a cognitive deficit in short-term memory, as the one shown by K. F., should have also impaired long-term memory because of the interruption in the pipeline of information flow from sensory input to long-term storage.

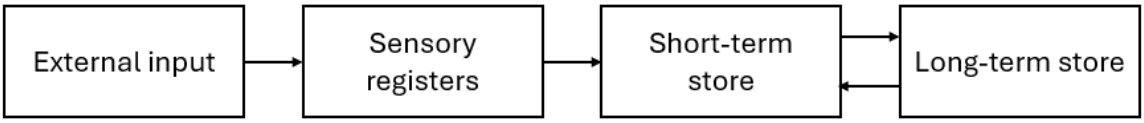

Figure 1.1. The modal model by Atkinson and Shiffrin

Working memory

It soon became clear that the multi-store model couldn't explain anymore many of the evidence that was accumulating. The concept of short-term memory itself became more complex and difficult to test, and the interest of many researchers shifted toward the study of long-term memory. In the same period, Baddeley and Hitch began to study the relationship between short and long-term memory, trying to understand what exactly the role of short-term memory was. It was generally accepted that short-term memory was somehow involved in information processing. Therefore, Baddeley and Hitch advanced the hypothesis that damage to short-term memory would have reflected in an impairment in comprehension, reasoning, and long-term learning (Baddeley & Hitch, 1974). Almost all the theories, at the time, agreed about the fact that digit span tasks, in which a series of digits is presented and must be repeated at the end of the presentation, were strongly linked to short-term memory, with the cognitive weight of the task increasing with the length of the series to be remembered. The authors decided to "simulate" patients with brain lesions by combining the digit span task with other reasoning or comprehension tasks that were assumed to rely on the same system. Participants were presented with a series of digits, and they were asked to repeat aloud the series while performing a second task. The authors varied the number of digits to be maintained in memory, therefore varying the load on the short-term memory system. The idea was that, if the short-term memory system had limited capacity and was involved in reasoning, the longer the sequence of digits, the greater the effect of interference on the second task. The authors observed that participants were able to perform the tasks even when they had to keep in mind a series of up to eight digits. The time required to perform the reasoning task increased proportionally with the length of the series to keep in mind, but the error rate remained constant regardless of the length of the series.

This result had a great implication for revising the concept of short-term memory. The fact that the error rate did not change, but the processing times did, suggested the existence of two systems involved in the tasks. One system was impaired by the concurrent maintenance of the digits, while the other system was not. This finding set the basis for the proposal of a new model of short-term memory.

Models of working memory: The multi-component model

Baddeley and Hitch (1974) proposed a new and more complex model of short-term memory that they called working memory. In this model, named the multi-component model, the emphasis was on its functional role in cognitive processes and information processing. In its first version, it was composed of three modules: the visuo-spatial sketchpad, the phonological loop, and the central executive (Fig. 1.2). The visuo-spatial sketchpad is in charge of maintaining in memory items and groups of items presented visually or spatially. The phonological loop is responsible for the maintenance of verbal and acoustic information. It comprises two distinct subsystems: a phonological short-term storage and an articulatory rehearsal process. The phonological storage, of limited capacity, encodes verbal input as memory traces that decay rapidly, typically within a few seconds. The articulatory rehearsal mechanism counterbalances this temporal decay by enabling the subvocal or overt repetition of the stored items, thereby refreshing the memory traces and prolonging their availability within the short-term storage. The central executive is a control structure with limited attentional resources that selects, filters, and manipulates the contents of the two other modules, acting more like an attentional control system rather than a memory system. In the multi-component model, this system operates as it was hypothesized by Norman and Shallice (1986), who suggested a dual-control system, with two different levels that differ in the degree of attentional resources involved. One is automatic and based on previous actions and experiences (e.g., driving a car), while the other is more mindful and attention-driven (e.g., how to react when an accident happens in front of us while driving a car). A fundamental function of the central executive, therefore, is to focus attention on the current task or manage attentive resources if there is more than one task ongoing. Baddeley and Wilson (1986) described the patient R.R., who, after a bilateral lesion on the frontal lobes, was unable to voluntarily focus attention on any single task and simply responded automatically to any object or environmental stimulus encountered. The authors named this attentional deficit dysexecutive syndrome (Baddeley & Wilson, 1988). Baddeley (1996) proposed that the central executive is in charge of shifting attention between two or more tasks, with some processes being more automatic, while others are more consciousness-driven and demand attention to be carried out (Allport, Styles & Hsieh, 1994; Monsell, 2005).

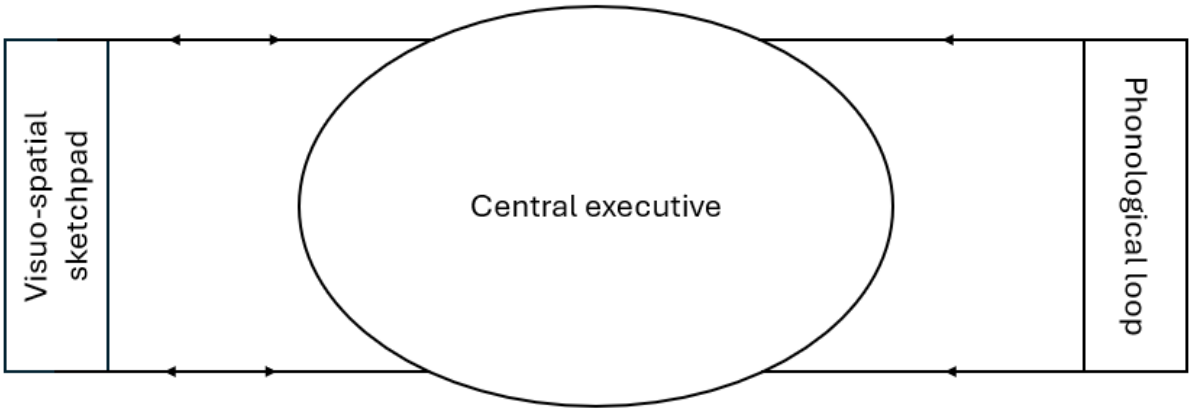

Figure 1.2. The first version of the multi-component model by Baddeley and Hitch

This first version of the multi-component model presented a great limitation: it did not explain how working memory is related to long-term memory. This issue arose from considering the memory span for words. When the words are not related in any way, the span is around five or six, but if the words are arranged into

grammatically meaningful sentences, it increases to about fifteen (Brener, 1940). This evidence made it difficult for the multi-component model to explain the span of fifteen words, since it is beyond the phonological loop's capacity. In fact, in a sentence, words are arranged according to grammatical rules, and it is the semantic relationships between them that facilitate the encoding of information through chunking, but both rely on previous knowledge that is stored in long-term memory. This raised the question of how working memory can access and use information stored in long-term memory. Baddeley and Andrade (2000) provided analogous evidence for visuo-spatial information, proving that processing of familiar images does not rely solely on the visuo-spatial sketchpad, but rather on the amount and quality of information stored in long-term memory.

In order to fill this gap, a fourth component was added to the model: the episodic buffer (Baddeley, 2000). The episodic buffer is a storage system with the capacity of approximately four chunks of multidimensional information. Each of these multidimensional chunks of information can carry material of different types, such as visual, semantic, and verbal information from different inputs like long-term memory, working memory, or sensory inputs (Fig. 1.3). Based on the idea that all this information must be bound together in order to create coherent chunks of information, Baars (1997; 2002) proposed that consciousness acts as a mental workspace where all this information is integrated into perceived objects and events through the rearrangement and convergence of the different input streams of information.

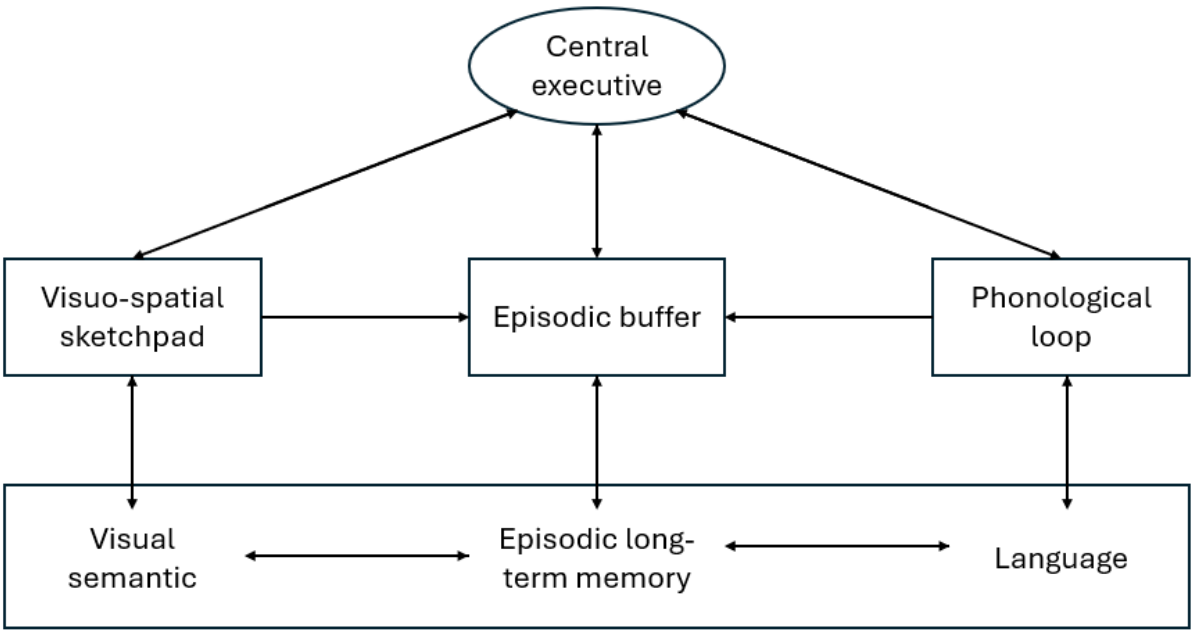

Figure 1.3. The multi-component model in its latest version

In its first version, the episodic buffer acted as an active system controlled by the central executive that could integrate different old concepts to create new ones, for example, integrating single words into meaningful sentences, or integrating color and shape to conceptualize objects (Baddeley, 2000). To test this hypothesis, Allen, Baddeley, and Hitch (2006) decided to overload the episodic buffer with simultaneous tasks in order to impair information integration. The authors observed that concurrent tasks that are cognitively demanding on the executive processes do impair overall performance, but they do not have a particularly

salient effect on the integration of information. Therefore, Baddeley (2007; 2012) proposed that integration is managed by different specialized sub-systems for different types of information, such as visual or linguistic. The integration of the episodic buffer into the multi-component model partially filled the gap between Baddeley and Hitch's model, which focuses on information storage, and other working memory models, such as Cowan's model (1999; 2005), whose focus was on attention. This drove the interest of many researchers toward the integration of working memory and long-term memory, producing more research on linking the multi-component model with visual attention and memory (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001).

Models of working memory. The time-based resource sharing model

The multi-component model is one of the most widely accepted models of working memory, but many alternative models have been proposed that were built driven by different assumptions, hypotheses, and architectures (for example, Cowan, 1999; Oberauer, 2002; Cornoldi & Vecchi, 2003). Among all these models of working memory, Barrouillet and colleagues (Barrouillet, Bernardin & Camos, 2004) proposed the time-based resource sharing model.

The time-based resource sharing model is based on four main assumptions (Barrouillet & Camos, 2015). The first assumption is that processing and storage, two of the main functions of working memory, are operated by the same limited-capacity attentional resource. The second assumption is that there is a cognitive bottleneck that prevents more than one operation from occurring at a time. Therefore, the attentional resources are shared on a temporal basis between processes. The third is that as soon as attention is not focused on a memory trace, the memory trace starts to suffer from a time-related decay that will lead to a loss of the trace. The fourth and final assumption is that decay can be prevented by refocusing attention on the memory trace. Therefore, maintenance is achieved through a rapid switch of attention between activities during the small pauses between processes.

The authors tested these assumptions with the use of the so-called complex-span task. In this task, participants are presented with a series of stimuli (typically letters) presented one at a time, and they have to recall all the letters at the end of the presentation. Each of these stimuli is followed by an equation that must be verified by the participant (e.g., 5 + 4 + 8 = 17). According to the model, participants try to maintain in working memory the series while performing the operations by rapidly focusing attention on the memoranda between the steps of the computation. In this way, although memory traces begin to decay during the processing of the equation, they are reconstructed when attention is focused back on them, and they are prevented from completely decaying.

One fundamental concept in the time-based resource sharing model is the cognitive load. In this model, the cognitive load is the proportion of time during which attention is occupied by processing information over the total time available for the task, impeding the refreshing of memory traces. In other words, cognitive load is the ratio between the amount of work that must be done and the time allowed to do it. This means that, in a task where all the processing steps have the same duration, reducing the total time available for performing the task, for example, by presenting items for shorter durations, would increase the cognitive load. This might sound counterintuitive because reducing the duration of the task means maintaining the items in memory for a shorter time, but it also means that there is less free time between processing steps to refresh items. The time-based resource sharing model predicts that recall performance does not depend on the duration or the number of processing steps, but rather on its cognitive load, with performance getting lower as the cognitive load increases in a sort of processing/storage trade-off. The authors tested this trade-off with the reading digit span task, a task very similar to the complex-span task, in which single digits have to be read aloud instead of equations to be checked (Barrouillet, Bernardin & Camos, 2004). In this type of task, the cognitive load can be varied in two ways: by changing the number of digits between memory items, while the total time remains the same, and by changing the duration of presentation of the stimuli, but

maintaining the same number of them. In their study, the authors combined three levels for each of these two variables (i.e., number of stimuli and time) into nine conditions and, in line with their model's prediction, they observed that recall performance was an almost perfectly linear function of cognitive load.

This model makes another counterintuitive prediction. If the recall performance is defined by the cognitive load, then it is possible to achieve the same performance by adjusting the cognitive load of any task. For example, a reading digit span task with two digits after each target, in which every item is presented for one second, would have the same cognitive load as a reading digit span task with four items after each target, in which items are presented for two seconds each. This would lead to a similar result in recall performance between the two tasks. Plancher and Barrouillet (2013) tested this idea and observed that the number of items between the memory items did not have any effect on recall performance, but there was a significant effect of cognitive load.

The latest version of the time-based resource sharing model (Barrouillet & Camos, 2015) includes a complete working memory architecture (Fig. 1.4). The authors suggested that information is represented in working memory as transient representations of mental models, and only a small number of these representations can be maintained at the same time in an episodic working memory buffer. These representations are manipulated through a production system, which creates a new transient representation by processing information or reconstructing older representations that have degraded through time, acting as a maintenance and temporal storage function. The new representations created are then manipulated again by the production system, repeating the cycle and creating an executive loop. This executive loop is the cognitive bottleneck that allows only one operation at a time in the model. In fact, if the loop is used to process information, it cannot be used for maintaining already existing representations. From this loop, it emerges what in the multi-component model is represented by the central executive. In the time-based resource sharing model, there is no structure devoted to focusing attention on a specific task or managing resources, but these outcomes will automatically emerge from the functioning of this loop.

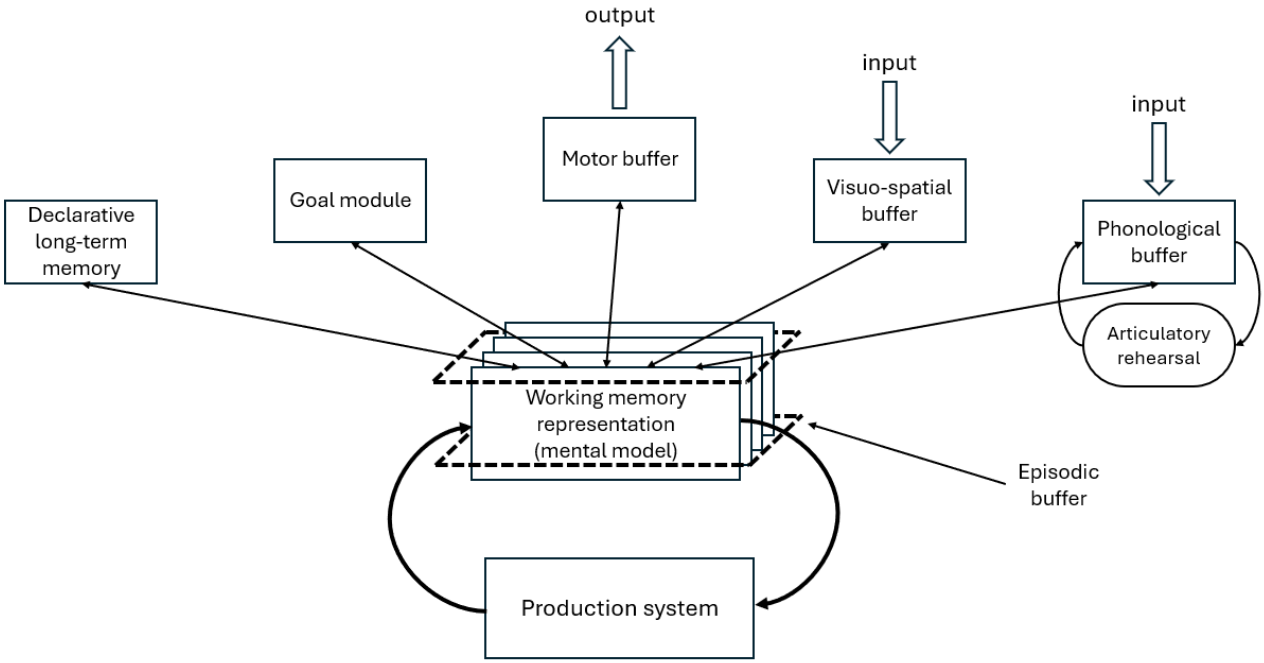

Figure 1.4. The complete cognitive architecture of the time-based resource sharing model by Barrouillet and Camos

While some models conceive working memory as an active part of long-term memory on which the attentional spotlight is directed (Cowan, 1999; 2005; Engle et al., 1999; Oberauer, 2002; 2009), in the time-based resource sharing model, these two elements must be distinct. The reason for this distinction lies in how the state of information is maintained in these systems. Working memory representations are transient and tend to fade with time if they are not actively maintained, suffering from time-related decay. In long-term memory, on the other hand, representations do not need to be actively maintained, and they don't suffer time-related decay, but rather from interference of new mental representations created in working memory.

Gaps in the knowledge

The two models presented (the multi-component model and the Time-Based Resource Sharing model) explain a complex and abstract concept, such as working memory, in a relatively simple way, and they are both based on plenty of supporting evidence. These are both necessary characteristics for a model to be a good model. The multi-component model is the most widely accepted among those who study working memory, and the time-based resource sharing model gives a representational description of working memory functioning at a more detailed level than the multi-component model does. Nonetheless, the existence of alternative working memory models based on different hypotheses and equally supported by empirical evidence suggests that those two models, despite being robust, are not perfect.

Something both models lack is a detailed description of the process of information transfer towards long-term memory. According to Baddeley (Baddeley, Eysenck & Anderson, 2020), the relationship between working memory and long-term memory is complex, flexible, and interactive. In his view, working memory represents a link between cognition and action that can acquire information at different processing levels and from different inputs, although not all information necessarily has to pass through working memory. The author confidently stated that working memory implies the activation of long-term memory to function, but he considered this statement more a challenge to further explore this complex relationship, rather than an explanation of its functioning. In the time-based resource sharing model, the passage of information from working memory to storage in long-term memory corresponds to the maintenance of memory traces in working memory. Therefore, the more a memory trace is reiterated through the maintenance/reconstruction cycle, the heavier the footprint that it leaves in long-term memory, but there is not enough empirical evidence yet in the literature to fully support this hypothesis.

Another missing explanation in these models is the mechanism used to remember serial information. Neither models describe this particular kind of maintenance of information that is tightly related to the passage of time during its acquisition phase. The majority of models proposed in the literature in an attempt to describe this process agree on the idea that remembering the order of a series does not happen through a chaining of elements, but rather through a more complex and dynamic relationship (for example, Burgess & Hitch, 1999; 2006; Page & Norris, 1998; Henson, 1998).

In the next chapters, a series of studies I conducted are presented. In these studies, I aimed at collecting evidence on some of the basic processes of working memory and their limitations. Specifically, the studies presented investigated the processes of maintaining verbal information presented serially (Chapter 3), the transfer of information to long-term memory (Chapter 2), and the updating of social information in working memory (Chapter 4). From these studies, new evidence has been added to the existing literature that enhances our understanding of how information is processed by the cognitive system, leading to improvements to existing models of working memory or, eventually, to the design of new ones.

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Chapter 2: Cognitive load and Working memory

The article “The effect of cognitive load on information retention in working memory: Are items and serial position different processes?” presented in this chapter has been submitted to Brain Sciences, and it has been accepted for publication after the peer review process.

The effect of cognitive load on information retention in working memory: Are item order and serial position different processes?

Davide Baggini[1 2], Paola Ricciardelli[1]

[1]Department of Psychology, University of Milano–Bicocca
[2]Faculty of Health and Medical Sciences, University of Surrey

Abstract

Background/Objectives: A central question in cognitive neuroscience is how information is transferred from working memory to long-term memory, and what factors influence this process. This study aimed to explore the role of cognitive load in the consolidation of information into long-term memory within the framework of the Time-Based Resource Sharing model of working memory. Methods: An exploratory study was conducted using a reading digit span task with delayed response, in which cognitive load was manipulated through Hebb repetition learning. Results: An improvement in the ability to remember the order of the elements was found with the decrease in cognitive load, consistent with the hypothesis that the transfer of information to long-term memory occurs during the maintenance process and involves cognitive load. However, no improvement in the recall of the total number of elements emerged, suggesting that different mechanisms and factors are at play in the process of information transfer. Conclusions: These findings shed new light on the complexity of interactions between working memory and long-term memory, paving the way for further systematic investigations into the nature of mechanisms responsible for transferring information from the former toward the latter.

Keywords: Working memory; Cognitive load; Time-based resource sharing; Serial order; Information storage

Introduction

The human cognitive system constantly collects, processes, and stores information. Most of this information is usually only maintained for a few seconds, but it can also persist for days, months, or even over the whole lifetime in long-term memory. In this study, we focused mainly on a specific model of working memory, the Time-Based Resource Sharing (TBRS) model (Barrouillet et al., 2004). One limitation of this model is that it does not properly integrate the relationship between working memory and long-term memory and how information is transferred from the former to the latter and vice versa. Since it is difficult to conceive that working memory has no functional connections with long-term memory, especially in cases where information depends on past experience, we decided to explore such a relationship in this study. The present research aimed to shed some light on the process underlying how information stored in working memory for a brief time is transferred to long-term memory.

The working memory theoretical construct has progressively replaced the outdated short-term memory concept to account for the retention and active processing of information in the short term (Baddeley & Hitch, 1974). It has been realized that the conceptualization of short-term memory was a conception of information storage that was too passive and did not take into consideration many cognitive processes, leading to poor predictions of real-world phenomena. Working memory, instead, is a richer cognitive construct that describes how immediate memory actively processes information and maintains it in the short term to deal with complex everyday tasks, such as for example problem solving and language comprehension, that require many different processes, constraints, and interactions between these processes (Aben et al., 2012). One of the most widely accepted models of working memory is the multi-component model proposed by Baddeley

and Hitch, in which working memory is described as a collection of sub-structures with different roles rather than a unitary system (Baddeley, 1986; Baddeley, 2000; Baddeley, 2007).

The initial version of the multi-component model faced a major limitation: it did not account for the relationship between working memory and long-term memory. Evidence from memory span tasks highlighted this gap. While unrelated words yield a span of about five to six items, grammatically structured sentences extend the span to approximately fifteen (Brener, 1940). Such findings challenged the model, as this exceeds the phonological loop's capacity. The increased span arises from chunking based on syntactic and semantic relations, processes that crucially depend on knowledge stored in long-term memory. This highlighted the need to explain how working memory draws upon and integrates long-term representations, and raised the question of how working memory can access and use information stored in long-term memory. Supporting evidence comes from the visuo-spatial domain: processing familiar images is not limited to the visuo-spatial sketchpad but is facilitated by the amount and quality of long-term memory knowledge (Baddeley & Andrade, 2000).

To address this limitation, a crucial component was introduced to the model: the episodic buffer (Baddeley, 2000). This system can hold about four chunks of multidimensional information, integrating inputs of different types (visual, semantic, and verbal) originating from long-term memory, working memory, or sensory sources. Since these inputs must be bound into coherent representations, Baars (1997; 2002) proposed that consciousness serves as a mental workspace, where streams of information converge and are integrated into unified objects and events.

In its initial formulation, the episodic buffer was conceived as an active system under central executive control, capable of integrating separate elements into coherent representations, for instance, combining words into sentences or uniting color and shape into object concepts (Baddeley, 2000). Allen, Baddeley, and Hitch (2006) tested this by overloading the buffer with concurrent tasks, finding that while executive demands impaired general performance, they did not strongly disrupt integration. This led Baddeley (2007; 2012) to argue for specialized subsystems managing different types of integration, such as visual or linguistic. Incorporating the episodic buffer thus helped bridge the gap between storage-focused accounts, such as Baddeley and Hitch's model, and attention-centered perspectives, such as Cowan's (1999; 2005). This shift stimulated research on how working memory interacts with long-term memory, particularly in relation to visual attention and memory (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001).

The multi-component model is not the only model of working memory, and alternative models, each based on different assumptions and trying to describe a different aspect of working memory, have been proposed in the last decades (e.g., Oberauer, 2002; Cornoldi & Vecchi, 2004).

TBRS is a working memory model developed to explain the mechanisms underlying the simultaneous processing and maintenance of information in working memory (Barrouillet et al., 2004). In relation to Marr's levels of explanation (Marr, 1982), one of the main differences between Baddeley's multi-component model and the TBRS model is that the former tries to describe working memory at a computational level, while the latter does it from a representational level, allowing quantitative predictions by accounting for the decay of information in the short term as a function of time. In the TBRS model, processing and maintaining information in working memory are two distinct activities performed within the same system. Processing is a function that results in the production of a new piece of information following a computation, whereas maintenance refers to the ability to hold and retrieve information after it has been encoded. The authors designed the TBRS model based on four main assumptions: *i*) Processing and maintaining information are active processes that both require attention, which is a limited resource. The two activities share the same pool of attentional resources. *ii*) A central bottleneck only allows the focus of attention to operate on one process at a time, so sharing attention is time-based. Attentional focus, therefore, must alternate between processing and maintaining information, since it cannot be split. *iii*) When attention is switched away from a to-be-recalled piece of information, its memory trace suffers from decay due to the passage of time (i.e., time-related decay). To avoid such a decay of information, refreshing the memory trace is necessary, but this

action requires attentional resources. *iv*) It is assumed that there are periods of time during which attention is totally engaged in information processing, hence preventing memory traces from being refreshed. Thus, attention sharing is achieved through rapid and frequent switching between processing and maintaining multiple memory traces during task completion. Because of these several alternating activities that depend on attentional resources, the functioning of working memory is time-based.

According to the TBRS model, memory performance mostly depends on the cognitive load of the task. In fact, according to the TBRS model, no task is intrinsically easy or hard. What makes a task easy or hard to perform is the cognitive load level of the task, given by the specific circumstances in which it is carried out. In this model, cognitive load represents the proportion of time during which the focus of attention is captured by processing operations and, therefore, is not available for maintaining memory traces in an active state. It reflects the time taken by processing activities over the total time available for the task. In other words, the cognitive load of an activity increases proportionally with the ratio between the time used for processing and the total time available for the task, and it is given by the following formula:

$$\mathrm{CL} = \mathrm{aN/t}$$

where *N* is the number of processing steps, *a* is their average duration, and *t* is the total amount of time available for performing the task. To test the TBRS model, the authors used the reading digit span task (Barrouillet et al., 2004). This experimental paradigm consists of the serial presentation at a constant pace of to-be-recalled targets (i.e., letters), each followed by a series of stimuli to be processed (i.e., a series of digits) that compete for the same resources. Participants must process the interfering stimuli during the presentation (in this example, sum the numbers as soon as they appear) and then recall the targets at the end of the presentation (see Fig. 2.1).

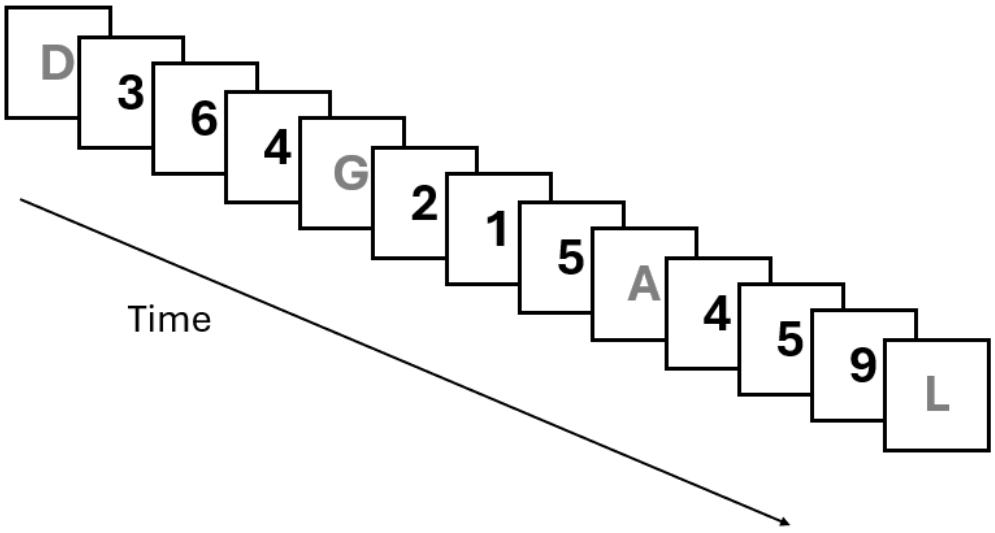

Figure 2.1. Example of the reading digit span task. Between the presentation of each target (the letters), a series of digits to be read aloud is displayed in sequence as an interference task. At the end of the trial, participants are asked to recall the targets in the correct order. The duration of the stimulus presentation can vary depending on the experimental design.

By manipulating the proportion between the free time (i.e., time not used to process new information) and the time occupied to process the interfering items, it is possible to vary the cognitive load of the task itself (see Fig. 2.2 for a graphical example). During the last few years, a remarkable amount of literature has been produced to support predictions of the TBRS model (Barrouillet et al., 2021). As predicted by the TBRS model,

memory performance is inversely proportional to the cognitive load of the task. This suggests that memory traces can only be refreshed during free time (i.e., when attention is not captured by the processing of interfering items).

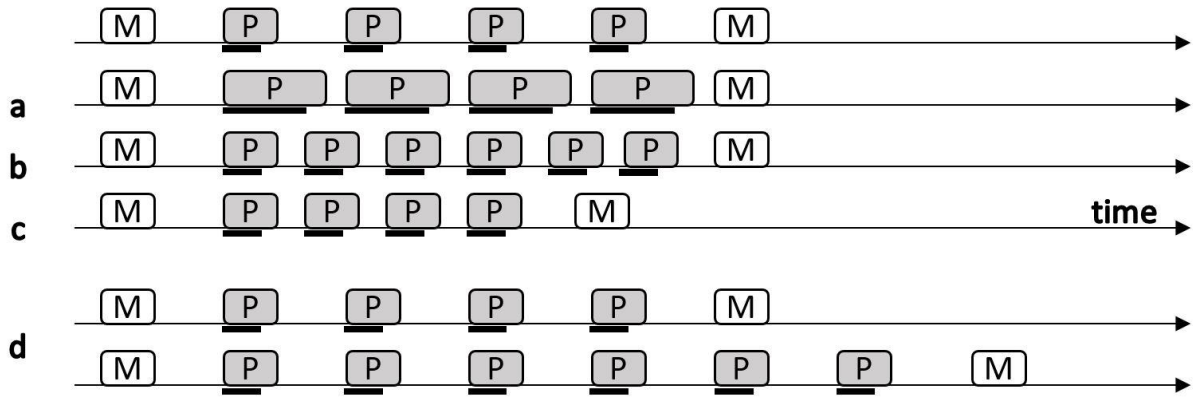

*Figure 2.2. Variations of cognitive load. The first row depicts successive screens on a computer-paced reading digit span task in which each memory item M is followed by a series of items to be processed P. Black lines beneath P items represent the portion of time during which processing occupies attention. Row **a** illustrates the increase in cognitive load resulting from an increase in the duration of attentional request (parameter a in the cognitive load formula) while the number of processing steps N (number of items to be processed) and the total time t allowed to perform them remain constant. Row **b** illustrates the increase in cognitive load resulting from an increase in the number of processing steps N while parameters a and t remain unchanged. Row **c** illustrates the increase in cognitive load resulting from a reduction of t while N and a remain constant. By contrast, increasing the number of processing steps performed at a constant pace leaves cognitive load unchanged (row **d**). (Image and caption adapted from Barrouillet & Camos, 2014).*

Some models conceptualize working memory as an activated subset of long-term memory under attentional focus (Cowan, 1999; 2005; Engle et al., 1999; Oberauer, 2002; 2009). In contrast, the time-based resource sharing model treats them as distinct systems, emphasizing differences in representational maintenance. Working memory traces are transient and subject to time-related decay unless actively refreshed, whereas long-term memory representations are more stable, decaying primarily through interference from new content generated in working memory.

A phenomenon that is usually considered a reflection of the gradual transfer of information from working memory to long-term memory is the so-called Hebb repetition learning effect (Mosse & Jarrold, 2008; Gaskell & Ellis, 2009; Majerus & Boukebza, 2013; Page et al., 2013; Hurlstone et al., 2014). Hebb repetition learning is a well-known sequential learning paradigm that is assumed to rely on the same cognitive resources as word-form learning, the ability to learn the phonological forms of newly presented words (Page & Norris, 2009; Smalle et al., 2016). A classic Hebb repetition learning paradigm consists of the immediate serial recall of presented sequences of items (usually characters or phonemes). The sequences can be either completely new (called filler sequences) or already presented in previous trials (called Hebb sequences). In this task, when recalling Hebb sequences, performance usually improves compared to when the filler sequences have to be recalled (Hebb, 1961). This is the case regardless of whether participants are aware of having seen the sequence before, as these repeated sequences become consolidated in long-term memory. This effect raises questions about how the TBRS model accounts for such a long-term learning effect. The primary aim of the present study was to investigate the mechanisms underlying information transfer from working memory to

long-term memory and to assess whether the TBRS model can also account for long-term retention of information. In particular, we focused on the role of cognitive load in the information storage process.

There is evidence in the literature suggesting how working memory performance is bound to a limited amount of available resources (for example, Cherry, 1953; Moray, 1959; Deutsch, 1958; Treisman, 1964; Rensink et al., 1997), but there is also evidence that, through repetition and practice, it is possible to reduce the involvement of working memory processes, since the process became automatic, thus requiring less or very little attentional resources (Anderson, 1993). It is also possible to improve performance in working memory tasks after training (Gathercole et al., 2019), suggesting that fewer resources might be required to perform the same task when gaining experience.

Baddeley and colleagues conceptualize the relationship between working memory and long-term memory as complex, flexible, and interactive (Baddeley, Eysenck & Anderson, 2020). The authors view working memory as a bridge between cognition and action, capable of drawing on multiple inputs and processing levels, while acknowledging that not all information must pass through it. Importantly, they argue that working memory necessarily involves the activation of long-term memory, framing this claim as a challenge for future research rather than a definitive explanation. In the time-based resource sharing model, consolidation into long-term memory is assumed to depend on the repeated maintenance of traces in working memory, with more frequent reconstruction leaving stronger imprints. However, empirical evidence for this account remains limited.

The present study aimed to answer the following research question: Does the cognitive load of an activity have an impact on the amount of information transferred from working memory to long-term memory? Our experimental hypothesis was that cognitive load influences the amount of information that can be transferred from working memory to long-term memory. More precisely, the higher the cognitive load, the less information it is possible to transfer. We expected such an effect because a high cognitive load task would require a greater amount of resources to be allocated to perform the task, thus leaving fewer resources to transfer information to long-term memory than a low cognitive load task.

Materials and methods

Participants

To determine the sample size, we relied on a classical study by Postman and Phillips (1965) that used a similar experimental paradigm. Since the effect sizes were not reported in the original article, we opted to double their original sample size. This approach aimed to ensure more stability and precision in parameter estimates and to reduce the risk of underpowered statistical tests, while maintaining continuity with prior literature. This rationale is a reasonable pragmatic strategy in replication and paradigm-extension studies when prior effect size information is unavailable.

A total of 70 participants, recruited among students at the University of Milano-Bicocca, voluntarily took part in the study. A group of 35 were randomly assigned to the experimental condition (Women = 20, men = 15, age M = 28, SD = 8,5) and the remaining 35 to the control condition (Women = 22, men = 13, age M = 24,4, SD = 4,2). All participants had normal or corrected-to-normal vision, and none of them had neurological or learning diseases. All participants consented to data treatment and received university credits for their participation.

The study was considered minimal risk (as defined by the National Research Council of the Academies of Science and, as such, was approved by the Committee for Research Evaluation of the Psychology Department of the University of Milano-Bicocca (protocol number N. RM-2023-619 approved on 02/08/2023) and was conducted in accordance with the Helsinki treaty.

Materials and stimuli

The authors of the TBRS model have widely used the reading digit span task for assessing their model; for this reason, we decided to stick to this paradigm even though in the present study it has been modified by pairing it with an n-back task.

The reading digit span task consists of a series of stimuli presented at a fixed pace on a computer screen. Some of the stimuli are targets that must be maintained in memory for recall, while the others are just distracting stimuli that must be processed but not remembered. In our study, the targets and the distractors for the reading digit span task were both letters that participants were asked to read aloud as soon as they appeared on the computer screen. The difference between the two categories of stimuli was that targets were depicted in red, while distractors were depicted in blue. Trials always began with the presentation of a fixation cross, followed by the first target. Four targets were presented per trial, and four distractors followed each target. Stimuli were presented at a constant pace of one per second. Participants were instructed to read aloud all the characters but only remember the red ones. In the response phase, the word "REPLY" was displayed on the computer screen, and participants were asked to type on a keyboard the red letters they remembered in the correct order they were presented.

In order to delay the response of the reading digit span task, an n-back task was added to each trial between the stimulus presentation and response phases of the reading digit span task.

The stimuli used in both the reading digit span task and the n-back task were Western upper-case letters depicted in different colors (red or blue for the reading digit span task and black for the n-back task). The stimuli were presented on a 17' monitor, and occupied approximately 2,5° of visual angle.

Procedure

The task was administered in a quiet room with controlled artificial light. To avoid any potential distraction, participants were asked to turn off all their electronic devices. The whole task was programmed and presented in Matlab (2023) using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997; Kleiner et al., 2007).

The experiment was structured as a between-subjects study. Participants were asked to perform a reading digit span task with a delayed response, meaning that between the stimuli presentation phase and the response phase, they were asked to perform a 2-back task. The n-back task is a commonly used paradigm in working memory studies. It is a demanding task in which information in working memory must be constantly maintained and updated. It consists of a series of stimuli presented one at a time, and participants must decide whether the currently displayed stimulus matches the *nth* previous stimulus. For example, in a 2-back task, the participant must decide whether the current stimulus is the same as or different from the stimulus presented 2 steps before (see Fig. 2.3 for an example).

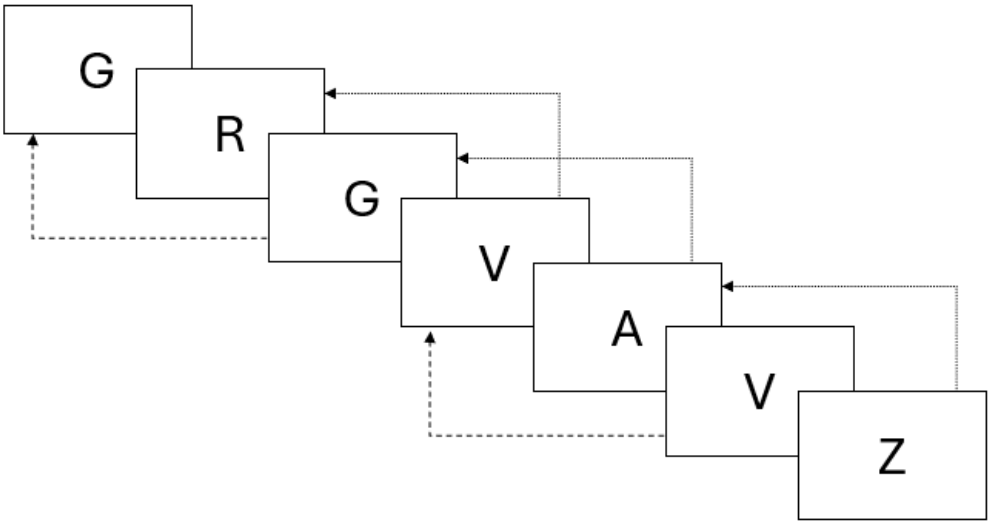

Figure 2.3: Example of the n-back task. Stimuli are presented one at a time, and participants must decide whether the currently displayed one was the same or not as the nth before. This example presents a 2-back task, meaning that participants must compare the currently displayed character with the character presented 2 positions before; dashed arrows represent "match" responses, and dotted arrows represent "mismatch" responses. Note that in n-back tasks, the first n stimuli (in this case, 2) do not have to be compared to anything, but they must be maintained in memory to be compared with the following stimuli.

The stimuli used in this study for the 2-back task were characters depicted in black, and participants were asked to decide whether the currently displayed character was the same or not compared to two characters before and give a response by pressing one of two keys on a QWERTY keyboard (Z for "same" and M for "different"). A 2-back series of fifteen stimuli was presented after each reading digit span task presentation. The 2-back task was self-paced, meaning that every stimulus appeared on the screen as soon as the answer for the previous stimulus was given. However, participants were instructed to answer as fast and accurately as possible without taking any breaks between stimuli or between the two tasks. Figure 2.4 represents the structure of a single trial. The general structure of the task is presented in Figure 2.5.

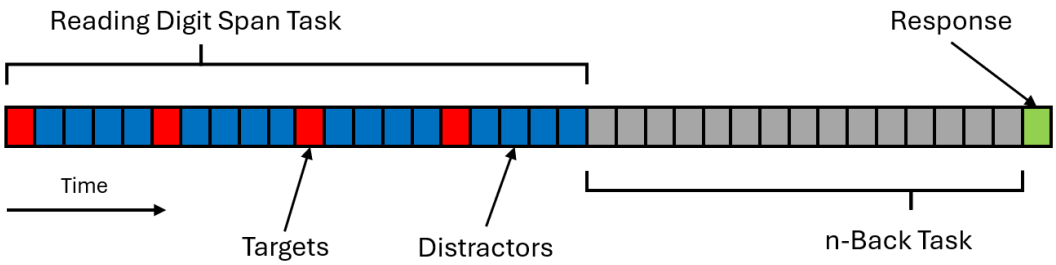

Figure 2.4: Schematic representation of the progression of a single trial of our experiment. Each cell represents a single stimulus presented on the screen. Red cells are reading digit span task targets, blue cells are reading digit span task distractors, grey cells are n-back task stimuli, and the final green cell represents the response phase.

Before the experiment began, participants signed the informed consent form and were then presented with a training phase to familiarize themselves with the task. They first made three practice trials with the reading digit span task alone, then three practice trials with the 2-back task alone, and finally three practice trials with both tasks in succession as described above. The experiment was divided into four blocks of 10 trials each, for a total of 40 trials. In the experimental condition, distractors (i.e., blue letters) remained the same across all trials within a block, while targets (red letters) and 2-back task stimuli were always randomly generated; therefore, targets were different in every trial. In the control condition, on the other hand, all the stimuli (i.e., targets and distractors) were randomly generated for each trial, meaning that they were always different. Participants were not aware of the division of the task into blocks in the experimental condition.

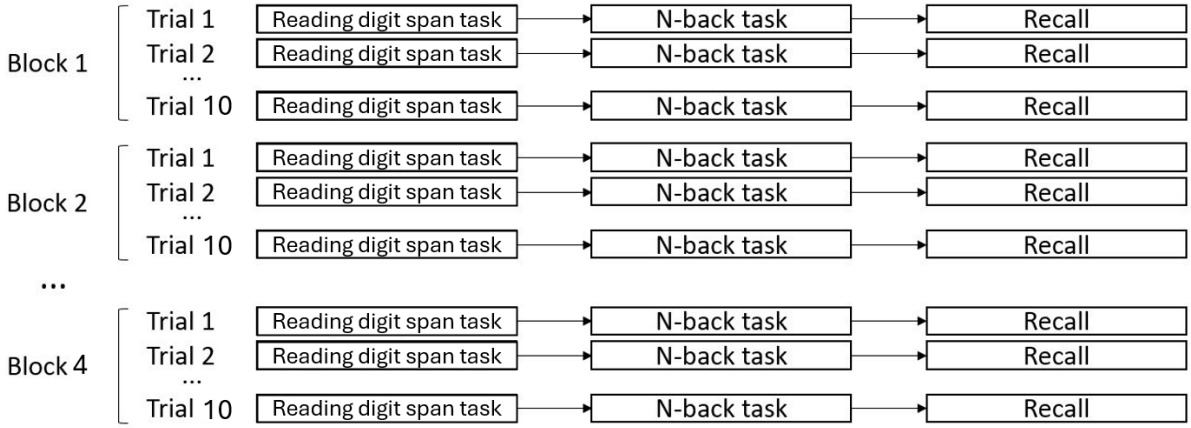

Figure 2.5: Representation of the experimental paradigm structure. Each trial was composed of three phases: a reading digit span task phase, an n-back task phase, and a recall/response phase. Within each block, the series of distractors used in the reading digit span task remained identical across trials until the end of the block.

Accuracy was measured for both the number of reading digit span task targets correctly recalled and their sequential order reported in the response. For measuring the presence of targets in the participant's responses, the response string was compared to the target string presented in the trial, and for each character in the response that was also in the target array, a score of 1 was assigned to the trial; 0 otherwise. To check for the correctness of their position, the two arrays of targets and response were compared, and only the characters in the response that were reported in the same position as in the target array were assigned a score of 1, and 0 otherwise. In this way, each trial has a score between 0 and 4 for both the presence of targets in the response and for their absolute position. Four targets were presented in each trial.

Analysis and results

First, we compared the first and last trials of each block, since they represent the highest and lowest cognitive load trials, respectively. A series of analyses was conducted using a linear mixed model to test performance on different parameters. In the first analysis, only the presence of a character in the response was tested, regardless of the correctness of its position. The dependent variable was the participants' accuracy in

remembering the target items. Condition, trial number, and block number were set as fixed effects, while subjects were clustered as random effects in order to account for interpersonal differences in performance. Estimates have been obtained through the REML method. Results showed a significant main effect of condition (β = .49, *SE* = .2, *t(*58.3) = 2.41, *p* = .019) and block (β = .09, *SE* = .04, *t(*389) = 2.3, *p* = .022) on accuracy, with an overall higher performance in the experimental condition compared to the control condition, and an increase in performance across blocks (Figure 2.6).

The same analysis was conducted using the accuracy in remembering the correct number of target characters in the correct position as a dependent variable. A significant main effect of condition (β = .54, *SE* = .24, *t(*62.4) = 2.28, *p* = .03), trial number (β = .03, *SE* = .01, *t(*389) = 2.93, *p* = .004), and block (β = .17, *SE* = .05, *t(*389) = 3.42, *p* < .001) emerged. The direction of the effects was coherent with those reported in the previous analysis, with a greater overall accuracy in the experimental compared to the control condition, an increase in accuracy across blocks, and an increase in accuracy across trials (Figure 2.6).

As an additional measure of accuracy, we computed the Damerau-Levenshtein distance between the correct responses and the responses given by participants, and we performed the same analysis using the Damerau-Levenshtein distance as the dependent variable. The results of this last analysis were in line with the previous ones reported. In fact, a significant main effect of condition (β = -.56, *SE* = .23, *t(*64) = -2.42, *p* = .018), trial number (β = -.03, *SE* = .01, *t(*389) = -2.38, *p* = .017), and block (β = -.14, *SE* = .05, *t(*389) = -2.78, *p* = .006) emerged once again (Figure 2.6).

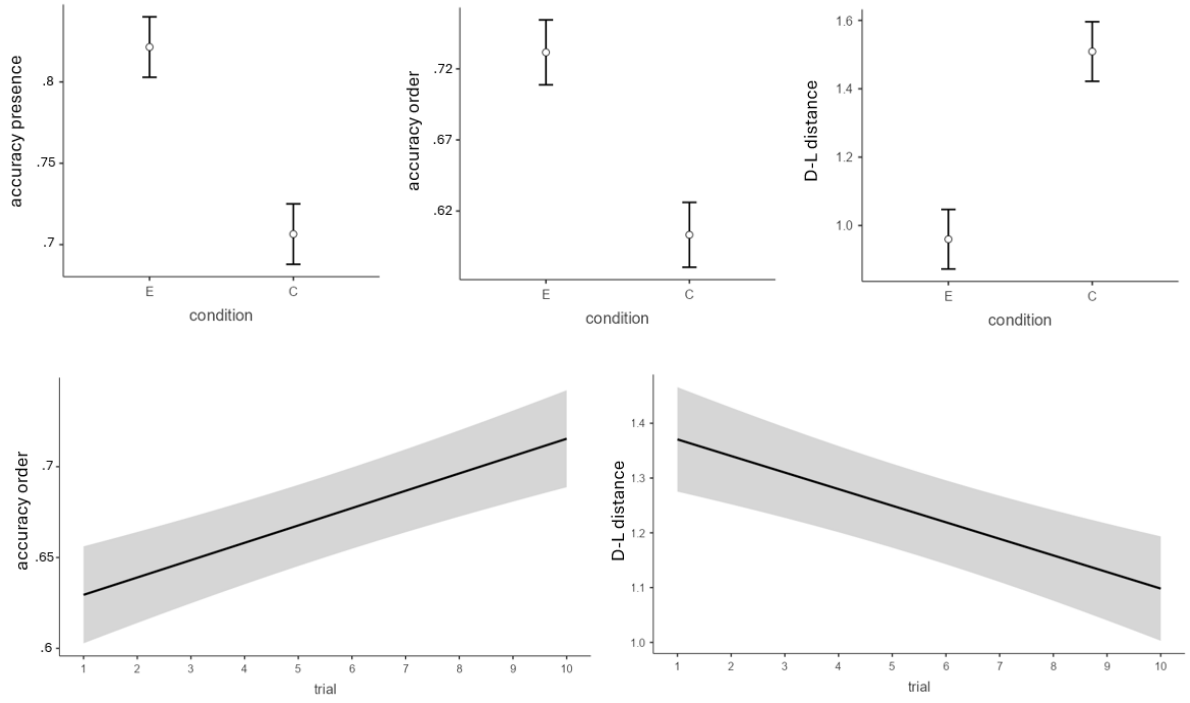

Figure 2.6: The top row represents the average accuracy for the two conditions for the three dependent variables considered. The bottom row represents the effect of trial on accuracy for remembering targets in the correct position and on the Damerau-Levenshtein distance. Only the first and last trials are considered.

To complement the earlier comparison between the first and last trials, the following analyses were conducted on the complete set of 10 trials per block. The same analyses have been conducted, with the only difference being that all the trials were included.

When considering the accuracy in remembering the presence of the target characters as a dependent variable, a significant main effect of trial (*β* = .01, *SE* < .00, *t(*2181) = 2.11, *p* = .035) and block (*β* = .04, *SE* = .01, *t(*2181) = 2.61, *p* = .009) emerged (Figure 2.7).

When the dependent variable was the accuracy in remembering the targets in the correct position, a significant main effect of trial (*β* = .02, *SE* < .00, *t(*2181) = 2.82, *p* = .005) and block (*β* = .07, *SE* = .02, *t(*2181) = 3.13, *p* = .002) emerged (Figure 2.7).

When the dependent variable was the Damerau-Levenshtein distance, once again, a significant main effect of trial (*β* = -.02, *SE* < .00, *t(*2181) = -2.58, *p* = .01) and block (*β* = -.04, *SE* = .02, *t(*2181) = -2.1, *p* = .035) emerged (Figure 2.7).

The average number of targets correctly recalled by participants was 2.96 (*SD* = .69), with *skewness* = -.98 (*SE* = .39) and *kurtosis* = .23 (*SE* = .77) in the experimental condition, and 2.88 (*SD* = .65), with *skewness* = -.61 (*SE* = .39) and *kurtosis* = -.38 (*SE* = .77) in the control condition. The average Damerau-Levenshtein distance was 1.35 (*SD* = .81), with *skewness* = .77 (*SE* = .39) and *kurtosis* = -.3 (*SE* = .77) in the experimental condition, and 1.5 (*SD* = .77), with *skewness* = .55 (*SE* = .39) and *kurtosis* = -.46 (*SE* = .77) in the control condition.

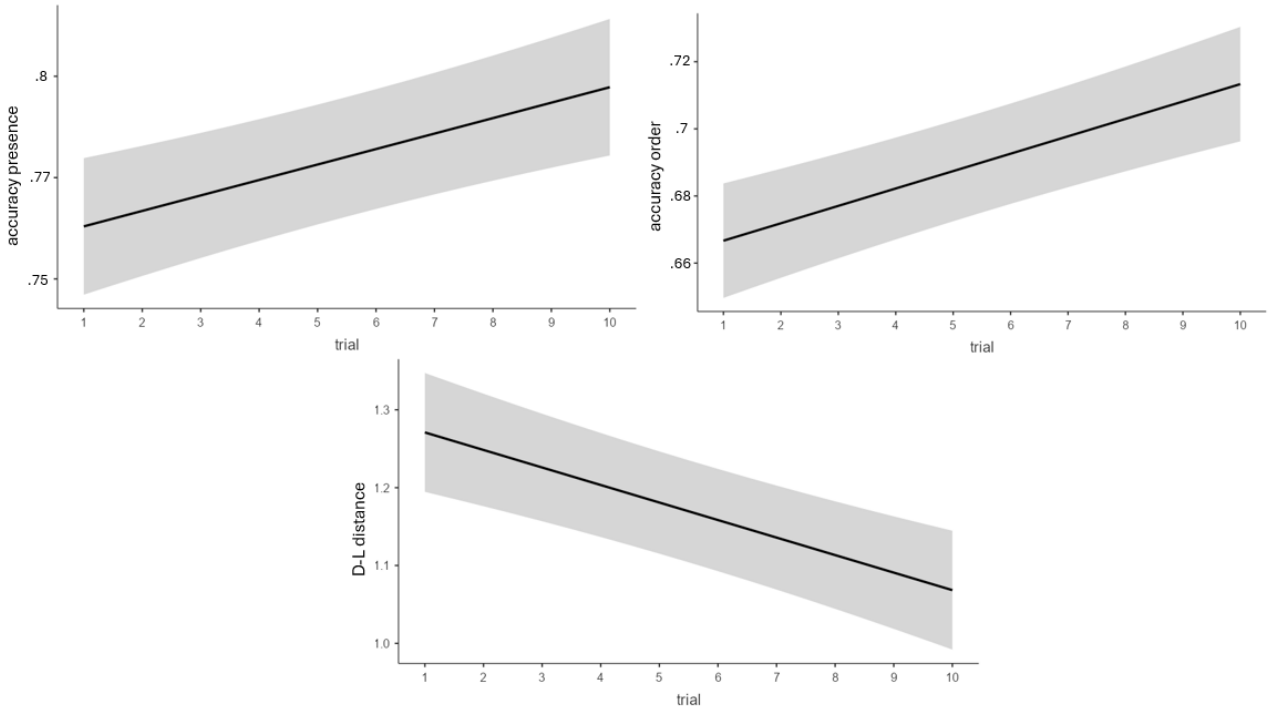

Figure 2.7: Effect of trial on accuracy for remembering the presence of targets regardless of their order, on accuracy in remembering targets in the correct position, and on the Damerau-Levenshtein distance. All the trials are considered.

Finally, we analyzed recall accuracy as a function of target position during presentation within each trial (i.e., whether the target appeared first, second, third, or fourth). A 2 (conditions) by 4 (targets) ANOVA revealed significant main effects of target position ($F(3, 11192) = 86.05$, $p < .001$, $\eta^2p = .023$) and a significant condition x position interaction ($F(3, 11192) = 4.88$, $p = .002$, $\eta^2p = .001$). A post-hoc comparison between conditions for each target revealed that the effect of condition alone was non-significant (Figure 2.8).

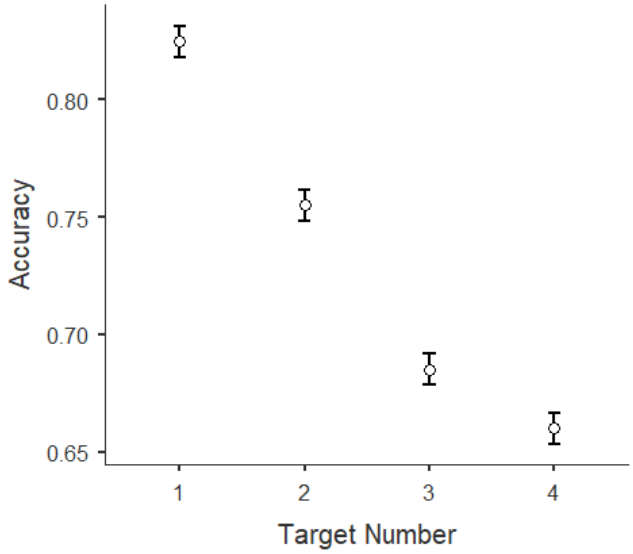

Figure 2.8. Accuracy in remembering the presence of a target. Accuracy is expressed as the proportion of responses that correctly included the target. On the x-axis is represented the position of the target in the presentation. Bars represent the standard error.

Discussion

In the present study, we tested the hypothesis that cognitive load affects the amount of information that can be transferred from working memory to long-term memory. We expected that a higher level of cognitive load would imply a lower amount of information stored in long-term memory due to a smaller amount of cognitive resources available for information transfer. The results partially confirm our hypothesis, since we found a significant difference in performance between the experimental and control conditions when considering only the first and last trials (i.e., the ones with the highest and lowest cognitive load, respectively), with the average performance in the experimental condition (where cognitive load decreases across trials) being higher. What was unexpected was that the difference in performance given by the trial number was only observed for remembering the order of targets, but not for their presence in the response. In other words, participants improved their performance in remembering the order of presentation of the reading digit span task's targets, but not in remembering a higher number of targets.

The reason for maintaining the same series of distractors between trials in the experimental condition in our experiment was to decrease the cognitive load of the task at each trial. Since the series was already encountered in previous trials within the same block, it became easier to process the information at every new trial due to Hebb repetition learning. By dividing the whole experiment into four blocks, we observed the effect of gradually decreasing the cognitive load on task performance four times per participant. In fact, thanks to Hebb repetition learning, cognitive load gradually decreased at each trial, but it returned to the starting level at the beginning of a new block of trials since the series of distractors was utterly new. In contrast, in the control condition, distractors were always new at each trial, resulting in a constant level of cognitive load across trials.

In the present study, the rationale behind the decision to use a delayed response paradigm was derived from the assumptions of the TBRS model itself. Specifically, the TBRS model has been widely tested using the reading digit span task and other similar tasks to assess working memory. However, in our study, we were interested in investigating the process of information transfer toward long-term memory. The 2-back task had

the purpose of occupying as many cognitive resources as possible and overwriting the content of working memory. According to the TBRS model, information maintained in working memory is refreshed only during periods when no other information is being maintained or processed. Otherwise, it decays as a function of time. Adding an n-back task between the presentation of the reading digit span task and the response phase forced participants to constantly maintain and update new information that was irrelevant to the reading digit span task. In this way, it would be theoretically impossible for participants, according to the TBRS model, to actively maintain the reading digit span task targets in working memory until the response phase. Therefore, the high demand for attentional resources and the delay created by the n-back task should have interfered with the maintenance process of targets enough to observe the effect of our interest.

An additional element that made it more difficult for participants to actively maintain targets in working memory was that they were instructed to read all the characters aloud as soon as they appeared on the screen. This ensured that they were paying attention to and processing all the stimuli and prevented them from refreshing the whole target series through articulatory rehearsal or subvocal repetition. This simple request to read aloud all the characters reduced the time available to participants for processing the targets and maintaining them available for recalling, since it increases the overall cognitive load of the task.

As mentioned above, in the experimental condition, the series of distractors in the reading digit span task always remained identical between trials within each block. In contrast, in the control condition, they were always randomly generated for each trial. This repetition of stimuli in the experimental condition allowed us to gradually decrease the cognitive load of the task by taking advantage of the Hebb repetition learning effect described previously. Thanks to this learning effect, it became easier for participants to process the distractors at every new trial within a block since they had already processed the same series in the previous trials. In other words, they needed a lesser amount of cognitive resources to process the distractors, and therefore, they had a greater amount of resources available to process the targets in the same time frame. According to the TBRS model, this would reflect in a change in the time proportions for processing/maintaining information in the reading digit span task: as trials progress, distractors are processed faster, and more time is available to process and maintain the targets (Barrouillet et al., 2004). At the end of the reading digit span task presentation, targets should have been better maintained in late trials compared to early ones. However, the long delay and the significant consumption of cognitive resources caused by the n-back task presented after each trial of the reading digit span task should have led the target memory traces to completely or almost completely decay (Portrat et al., 2008). This means that, according to our experimental hypothesis that the higher the cognitive load, the less information it is possible to transfer from working memory, if target information has been successfully maintained, it should not have been stored in working memory, but likely during the maintaining phase in working memory, it has been transferred to another structure functionally similar to long-term memory or, possibly, long-term memory itself, capable of holding information but where active maintenance of information is not required or, at least, is less demanding. This process, as expected, should manifest in a gradual improvement in performance across trials within each block. On the other hand, since in the control condition distractors were always different, the cognitive load did not change across trials, and no improvement was expected, except for the generic effect of practice. In other words, the expected finding was an improvement in accuracy when comparing the first (i.e., the highest cognitive load) and the last (i.e., the lowest cognitive load) trial of each block, as a consequence of Hebb repetition learning. In fact, in the first trial of each block, all the stimuli were new, but in trial 10, the series of distractors had already been encountered nine times. Specifically, according to our experimental hypothesis, we expected to find an increase in performance between trials 1 and 10 in the experimental condition group but not in the control group. Indeed, our results show a difference between the groups for the number of items remembered, but no difference was observed between these two trials. Despite not being exactly what we expected, this result is still partially in line with our hypothesis, since participants in the experimental group performed better than the control group, possibly due to the lower overall cognitive load of the experimental condition.

When examining accuracy for target order, we found a significant main effect of condition, trial, and block, although the main effect of condition was only observed when the first and last trials alone were considered

for each block. Performance improved from the first (high cognitive load) to the last (low cognitive load) trial within each block, in line with our prediction, suggesting that a lower level of cognitive load allowed for better processing of target information. These results indicate that participants gradually became better at remembering the order of presentation of targets with a decrease in cognitive load. However, they were not able to remember a greater number of items.

As an additional measure of performance, we computed the Damerau-Levenshtein distance between the correct and the given responses. This value represents the edit distance between two strings, expressed by the number of steps required to obtain the correct response starting from the given one, where each step can be the insertion, deletion, substitution, or transposition of characters. The analyses conducted on this metric confirmed the results reported above.

To summarize, a positive effect of the progressive number of trials on accuracy for remembering the order of targets was observed. In line with the main hypothesis, accuracy gradually increased with the number of trials performed within each block. The decrease in cognitive load through trials led to an improvement in performance in remembering the order, but not the total number of targets. Interestingly, if it is true that a greater amount of available cognitive resources is used to encode information in long-term memory, our results would suggest that encoding a series of elements and encoding their order can be two distinct operations.

A possible alternative explanation for not having observed any improvement in remembering the total number of targets can be the presence of a ceiling effect due to the small number of targets presented for this task, since the overall scores for character presence were relatively high, therefore not leaving much possibility to improve. An issue that should be addressed in future research.

In addition, the increase in accuracy from the first to the fourth block (i.e., the effect of block number) could be due to the practice with the task. In fact, in addition to gaining familiarity with the task itself, participants could have developed personal strategies to perform the task in more efficient ways. For example, they could have learned that exactly four distractors followed every target, so when they were presented with the fourth distractor after a target, they “prepared” for the presentation of a new target by shifting their attention toward an encoding process even before the target appeared.

Let us now consider the average accuracy in correctly remembering the targets by their presentation order. The first target presented in each trial is remembered more correctly than the second, the second more than the third, and the third more than the fourth. This is commonly known as the primacy effect (Glanzer & Cunitz, 1966). Such an effect was used by Glanzer and Cunitz (1966) as evidence for a short-term storage of information functionally distinct from long-term storage. In case we had observed a difference in the magnitude of this effect between the two conditions, with a higher performance in the experimental condition, we could have interpreted it as evidence of the effect of cognitive load on information transfer to long-term memory, but this is not the case. In the context of the TBRS model of working memory, this effect can be explained by the fact that the memory trace of an item had more occasions to be refreshed compared to those items presented later, but less time than those presented before. This effect can be interpreted as a reflection of different levels of decay of memory traces held in working memory. Still, an alternative interpretation can be given by the different levels of encoding of memory traces in long-term memory. The delay between the presentation of the last target and the response phase should have, at least in theory, updated the content of working memory, substituting the target memory traces with the n-back task-relevant memory traces that changed after each new stimulus. If targets were maintained entirely in working memory, it means that the cognitive resources available to participants were enough to both process and update the new information from the n-back task and maintain the targets from the reading digit span task, but in this case, we might expect that the proportion of the activation of the target memory traces would have balanced over time. On the other hand, if participants did not have enough available cognitive resources to process and update n-back information while maintaining reading digit span task targets, and information was

transferred to long-term memory during the processing and maintenance of the memory traces, it would be reasonable to expect that targets presented at the beginning of the series were better encoded in long-term memory, and, therefore, better recalled than the targets presented at the end. However, this interpretation needs to be corroborated further in future studies.

As already said above, our findings show a significant increase in accuracy from the first to the fourth block of trials, suggesting some possible effect of cognitive load. However, this improvement in performance could also be due to some practice effect. Either because participants got more familiar with the task (e.g., knowing that every four blue letters, a red one will appear) or because they became better at managing cognitive resources (for example, by finding strategies to cluster stimuli), or both. However, such explanations alone would not justify the difference in performance between the experimental and control conditions, which was overall higher in the experimental condition.

The unexpected difference in performance for remembering the targets' presence and order should be further explored in a new study, in which the two aspects of the series might be experimentally controlled. We suggest that a paradigm with two separate conditions should be designed in order to test the performance for each of these two aspects separately. In fact, by designing an experimental paradigm that allows participants to only process one of the two aspects (item presence and item order) at a time, it will be possible to observe the two processes separately. Another unexpected observation was the absence of interaction between condition and trial. The absence of such an interaction might be due to a multitude of different factors, but the evidence collected in this study does not allow us to formulate any valid explanation without being too speculative. This is an issue that should be addressed by future studies specifically designed to investigate this element.

Interestingly, a clear primacy effect for the order of presentation of characters was also found, and it can be interpreted as a proxy of the transfer of information from working memory to long-term memory.

Limits of this study

While this study provides useful insights into the role of cognitive load in information transfer and storage, the paradigm used does not allow a precise quantification of the variation of cognitive load among the different experimental trials. In other words, we know that the cognitive load in trial 2 is lower than in trial 1 and higher than in trial 3, but we cannot quantify such a difference. In addition, we do not know what type of mathematical function cognitive load follows in its decrease across trials. Therefore, we cannot say whether the difference in cognitive load between trial 1 and trial 2 is the same or not as the difference between trial 2 and trial 3. A new paradigm should be designed to take into consideration this element in a future study; in fact, a greater level of control on cognitive load would lead to a deeper understanding of its role in information transfer to long-term memory.

Conclusions

In conclusion, we found some evidence supporting the role of cognitive load and its effect on the amount of information transferred from working memory to long-term memory. Interestingly, it also emerged that the processes underlying remembering a certain number of items and their specific serial order might be two distinct processes. This hypothesis is not new in the literature, but still needs evidence and testing, and we will investigate this possibility in a future study.

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Experiment 2

To further investigate the results obtained in the presented article, we conducted a second experiment to collect more evidence on the subject. We used a paradigm similar to the one described in the article, but with a few variations in the design that allowed us to vary the cognitive load level of the task more and, consequently, make the effect manifest more clearly.

Materials and methods

Participants

Based on an a priori power analysis for a within-subjects ANOVA conducted on the G*Power software, 52 was the minimum sample size required to achieve a power of .8 (computed with an effect size of f = .2 and an α = .05). Fifty two participants (women = 35, men = 17, age M = 25,5, SD = 4,7) were recruited among the students at the University of Surrey and voluntarily took part in the study. All participants had normal or corrected-to-normal vision, and none of them had neurological or learning diseases. All participants consented to data treatment and received £30 as a reward for their participation. The study was approved by the ethics committee of the University of Surrey and was conducted in accordance with the Helsinki Declaration.

Materials and stimuli

The materials and stimuli used in Experiment 2 were identical to those employed in the article above, with one exception: a 20' monitor was used instead of a 17' monitor. To ensure consistency in the visual presentation, the distance between the participant and the screen was adjusted to maintain a visual angle of 2,5° for the stimuli.

Design and procedure

The procedure used in this experiment generally resembled the one described above, but with a few differences. First, this second experiment employed a within-subjects design, allowing us to compare the performance of the same participants in both experimental and control conditions. Second, we did not divide the experimental condition into blocks. This time, in the experimental condition, the distractors remained the same for the whole duration of the task in order to explore the effect of interest with more trials per condition, meaning a theoretically higher decrease in cognitive load between the first and the last trial that should have made the effects observed in the previous experiment more evident. On the other hand, nothing changed in the control condition, where distractors were still randomly generated for each trial. Finally, to avoid the possible ceiling effect observed in the first experiment, in both conditions, the number of targets per trial was increased to six, and the number of trials per condition was changed to 30. The same accuracy measures for target presence and order were recorded, with scores per trial ranging from 0 to 6.

Results

A paired sample t-test was conducted to assess the difference in average performance between the experimental and the control conditions; no significant difference was found. Similarly, an independent sample t-test revealed no significant effect of sex on average performance. However, linear regression analysis showed a small, but significant positive effect of age on both character presence (R^2 = .005, $F(1,$

3118) = 16.1, p < .001) and character order (*R^2 = .01, F(1, 3118) = 32.6, p < .001*), meaning that performance increased with the increase of participants' age.

As in the previous experiment, we first focused on comparing only the first and last trials, which represent the highest and lowest cognitive load, respectively. A 2 (conditions) by 2 (trials) analysis of variance revealed a significant main effect of trial on the number of items correctly recalled (*F(1, 204) = 4.52, p = .035, η^2p = .022*), with performance being lower in the last trial compared to the first (Fig. 2.9, left). No significant effects have been observed for the condition or the interaction between trial and condition. Additionally, no significant effects were observed for trial, condition, or their interaction on the accuracy for recalling item position.

When all thirty trials were included in the analysis, no significant effect of trial, condition, or their interaction was found for the number of items remembered. However, a significant main effect of condition was observed for the accuracy of recalling items' order (*F(1,3060) = 5.89, p = .015, η^2p = .002*) with participants performing better in the control condition regardless of trial number (Fig.2.9, right).

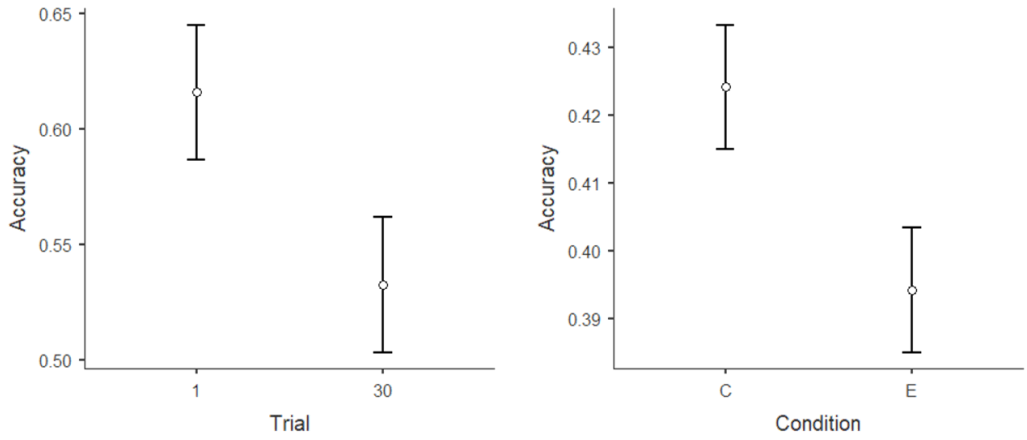

Figure 2.9. (left) Difference in average number of remembered targets between trial 1 (first, highest cognitive load) and 30 (last, lowest cognitive load). (right) Difference in average score for remembering the order of items between conditions (including all trials). Bars represent standard errors.

To further explore these effects, a generalized mixed model was used to assess the effect of trial number and condition on the accuracy of recalling both target presence and target position. In this model, each participant was considered as a cluster to account for individual differences and exclude random variance from the analysis. Regarding target presence, no significant interaction was found between trial number and condition. However, a significant negative effect of trial number alone emerged (*Marginal R^2 = .001, $X^2(1)$ = 3.97, p = .046*). In contrast, for target position, a significant negative effect of condition was observed (*Marginal R^2 = .002, $X^2(1)$ = 10.33, p = .001*), but no significant effect of trial number.

As in the first experiment, accuracy in recalling targets has been analyzed separately for each target position during the stimuli presentation. A 6 (target number) by 2 (condition) analysis of variance was conducted to investigate the effects of the target position, condition, and their interactions on the average accuracy for

each target. A significant effect of target number was found ($F(5, 18708) = 144.22$, $p < .001$, $\eta^2p = .037$) as well as a significant interaction between target number and condition ($F(5, 18708) = 3.03$, $p = .01$, $\eta^2p = .001$). However, no significant main effect of condition alone was observed. A post-hoc analysis revealed that the effect of the interaction between target number and condition was non-significant (Fig. 2.10).

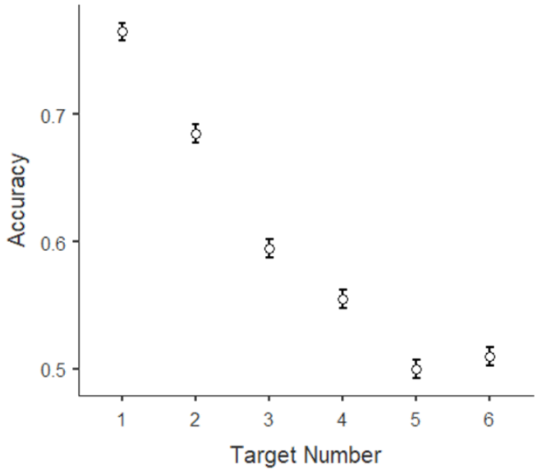

Figure 2.10. Effect of target position in the presentation on accuracy in correctly remembering each target. Accuracy is expressed as a proportion of responses that correctly had the target. Bars represent standard error.

Discussion

We decided to run a second experiment in which some details of the paradigm were changed in order to gather more data and try to overcome some of the limits of the previous experiment. We changed the experimental design to a within-subjects design to compare participants' performance between the two conditions, we increased the number of targets per trial to avoid the ceiling effect observed previously, and we decided not to divide the experimental condition into blocks, but rather to maintain the same series of distractors for the whole task in order to reach a lower level of cognitive load in the last trials compared to the first experiment.

From the results of this second experiment, age has been observed to positively correlate with accuracy for both target presence and target order, meaning that older participants performed, on average, better than younger ones. This might sound counterintuitive, and one might expect a negative correlation, with younger participants performing better than older ones, given the lesser cognitive decline in their cognitive functions. However, since the sample was generally young (18 to 35), we can interpret this positive correlation by considering that none of the participants has yet reached an age associated with cognitive decline. Older participants, therefore, had more life experience than younger participants, and assuming no cognitive decline at all, this might reflect in a better set of strategies to process and store information developed through the years. Therefore, this effect can be explained as a consequence of better cognitive control of executive functions given by experience.

When only the first and last trials were considered, since they were the two trials with the highest and lowest cognitive load levels, respectively, condition did not produce any significant effect on performance for both

the number and order of characters remembered. Also, no significant difference has been observed between trials 1 and 30 concerning the performance in remembering the order of characters. However, a significant difference emerged between the two considered trials for the number of items remembered, with higher accuracy in the first trial.

When all the trials are considered, the condition showed no significant effect on the number of targets remembered. However, a very small negative main effect of trial on the number of items remembered emerged when the random variance between subjects was removed. In addition, the condition proved to have an effect on the accuracy in recalling the order of targets, with performance in the control condition being higher than that of the experimental one. These last observations seem in direct contrast with the results discussed above when comparing just the two extreme trials. However, the effect of fatigue must be taken into account. In fact, despite having a smaller number of trials compared to the experiment presented in the article, in the present experiment, we used a within-subjects design. This means that in the first experiment, participants were asked to complete forty trials in total, while in this one, they had to complete thirty trials twice (once per condition), for a total of sixty trials. Therefore, it is not possible to exclude the possibility that the observed outcome is due to the high number of trials, which led participants to lose their focus on the task. However, this remains insufficient to explain the negative effect of trial on the presence of targets or the unexpected difference between conditions in remembering the order of targets, where participants performed better in the control condition, contrary to our hypothesis. A deeper explanation for these results is given in the general discussion section, where results from both experiments will be compared and discussed.

Finally, as expected and already observed in the first experiment, a clear primacy effect emerged when we consider the average accuracy in remembering the single targets in their order of presentation, but, once again, no difference in its magnitude between conditions was found.

General Discussion

The primary aim of the experiments presented in this chapter was to investigate whether different levels of cognitive load affect the amount of information that can be transferred and stored in long-term memory. To do so, we employed a reading digit span task with a delayed response paradigm. The paradigm was designed to manipulate cognitive load, decreasing it at each trial without modifying anything in the task itself, but making participants become more and more familiar with the set of stimuli used by taking advantage of the Hebb repetition learning effect. The temporal delay between the reading digit span task and the response phase was filled with a 2-back task, a demanding working memory task that requires constant processing and updating of new information. This n-back task served both to introduce a temporal delay between the reading digit span task and the response phase and to overwrite preexisting memory traces in working memory, preventing the maintenance of information from the reading digit span task. The idea underlying this paradigm was that information cannot be maintained in working memory if it is overloaded with new information. Therefore, if all or part of the old information is successfully maintained, it means it has been maintained by a different storage or using different cognitive resources. The main hypothesis in this study is that information is transferred and stored in long-term memory during the processing and maintenance phases of such information in working memory, and the amount of information stored in long-term memory is inversely proportional to the cognitive load of the task.

To investigate the effect of interest, two experiments were conducted using two similar paradigms. We asked participants from both experiments to perform the same task, but there were three main differences between the two. First, we asked participants from the first experiment to perform only the experimental or the control condition, while in the second experiment, they performed both. Therefore, we switched from a between-subjects design to a within-subjects one. The use of a within-subjects design allowed us to have an accurate measure of the difference between conditions for each participant, but a possible issue that might

arise from this type of design is the effect of task learning. Such an effect has been balanced by presenting the two conditions in a randomized order to participants. Nonetheless, it is something that must be taken into consideration while interpreting these results. The second difference lies in the number of targets that participants were asked to remember. In the second experiment, we increased the targets to six to avoid the ceiling effect observed in the first experiment, where the targets were only four. The third difference was that, in the second experiment, trials were not divided into blocks, and the number of trials was set to 30. With this last variation, we were able to let the cognitive load decrease through a higher number of trials in the experimental condition. Therefore, the effect of cognitive load level on information transfer should have been more evident.

Some of the results we obtained from the two experiments are coherent, while others seem to be in contrast with each other, and that might be due to the differences in design between the two experiments. Below is a summary of our results.

The comparison between the first and last trials, which represent the highest and lowest cognitive load, respectively, yielded different results across the two experiments. In the first experiment, a significant effect of condition and block on the number of items remembered was observed, while in the second experiment, a similar effect was attributed to the trial number. In the first experiment, accuracy in recalling target order was influenced by trial, condition, and block, while in the second, no such effect was observed. When all trials were considered, no significant effects of trial or condition were observed for the number of items remembered in either of the experiments. However, a significant effect for target order was found. In the first experiment, trial number influenced order accuracy, whereas in the second experiment, condition had a significant impact on order recall. These systematic differences in performance between remembering the number of items and their order suggest that two different mechanisms underlie the two processes, and it's something that might be interesting to explore in further studies.

In the first experiment, we observed a significant increase in accuracy from the first to the fourth block of trials. This improvement in performance can be attributable to the effect of practice. It is worth considering the possibility that this practice effect might be a result of better management of cognitive resources (e.g., finding strategies to cluster stimuli) and not just a mere consequence of familiarization with the task (e.g., knowing that every four blue letters, a red one will appear). If this is the case, it would have some interesting implications for working memory training, and it is certainly something that is worth investigating in future studies.

A strongly coherent result that emerged between the two experiments is the primacy effect. In both experiments and in both conditions we observed a clear primacy effect, that can be interpreted as a reflection of information transfer from working memory to long-term memory, but the absence of a significative difference between experimental and control conditions in both experiments (even when considering only the last trials, where theoretically the effect of cognitive load should have been stronger) suggests that cognitive load might not have an effect on information transfer to long-term memory, and this can be considered as an evidence against our experimental hypothesis.

It is noteworthy that the patterns of results between the two experiments were not entirely consistent. In the first experiment, the effects are generally in line with the experimental hypothesis, showing an increase in performance across trials and better performance in the experimental condition. On the other hand, in the second experiment, the pattern seems generally opposite, with performance decreasing across trials and the experimental condition showing a lower accuracy than the control condition. This incongruence in the result patterns between the two experiments might be due to the changes in the experimental paradigm between the two experiments.

Several factors may account for the differences in results between the two experiments. A first explanation for these differences can be given by task-related fatigue. In the second experiment, in fact, participants performed both the experimental and the control conditions. Therefore, they were asked to maintain focus

on the task for a longer time compared to the first experiment. This extended exposure may have contributed to performance decrement across trials, though it does not fully explain the superior performance observed in the control condition of the second experiment. Another difference between the two experiments that must be taken into account is the higher number of targets, and consequently the higher number of distractors, in the second experiment. The increase in the number of targets from four to six in the second experiment was intended to mitigate the ceiling effect observed in the first one. However, it is possible that the higher number of targets in the second experiment led participants to reach their working memory capacity limit, resulting in cognitive overload. The reach of such a limit could explain the difference in results between the two experiments and the decrease in performance in the second experiment. Further research should explore this hypothesis to determine whether the increased number of targets indeed exceeds participants' cognitive capacity for this task.

A further potential explanation for the observed differences between the two experiments involves the effect of interference between memory traces. In the first experiment, participants performed ten consecutive trials with the same distractor series, which changed with each new block of trials. In contrast, the second experiment involved thirty trials with the same series of distractors, and each trial contained six targets, each one followed by four distractors. Therefore, we cannot exclude the possibility that the longer and more repetitive distractor series in the second experiment may have resulted in interference during target encoding, impairing performance. The role of interference in information maintenance in working memory has already been taken into consideration in other studies and has become one of the main ideas on which different models of working memory are designed. Despite the results here reported being too weak to be considered proper evidence of the role of interference, they can provide a good starting point for further investigation on this topic.

One last alternative explanation that must be considered is that information has been transferred to long-term memory according to our hypothesis, but it was not possible to properly retrieve it in the response phase. The design of this study and the data collected do not allow us to adequately investigate this possibility, but it should be contemplated in future studies.

Limits of this study

Although this study provides useful insights into the role of cognitive load in information transfer and storage, two limitations should be considered.

As already said in the discussion section of the above article, one limit of this study is that, in both experiments' experimental conditions, the cognitive load variations are relative to the previous trial but not defined by any absolute or proportional value. A new paradigm should be designed to take into consideration this element in future studies.

Another limit of this study is given by the differences in paradigms between the two experiments presented. Some of the results that appear to be confusing or even in contrast might be due to an excessive alteration of the design in the second experiment compared to the first. This methodological issue must be taken into consideration when reading and interpreting the results of this study, but it also acts as an incentive to replicate this study with a more robust design.

General conclusion

In conclusion, we found some evidence supporting our main hypothesis and some other factors against it. From what emerged from this study, it is not possible to state that cognitive load has a real effect on the amount of information transfer from working memory to long-term memory. To properly answer this

question, further research is needed, considering the series of different factors and limitations discussed above, and aiming for more consistent data. Interestingly, however, what also emerges in our study, which deserves further investigation, is the possibility that the processes underlying remembering a certain number of items and their specific serial order might be two separate processes in working memory.

Chapter 3: Serial order in working memory

The article “The problem of serial order. New evidence toward understanding how items and their position are managed in working memory” has not been submitted yet to any journal, since data collection is still in progress.

The problem of serial order. New evidence toward understanding how items and their position are managed in working memory

Davide Baggini[1 2], Paola Ricciardelli[1]

University of Milano-Bicocca, Department of Psychology
University of Surrey, Faculty of Health and Medical Sciences

Abstract

Working memory is responsible for the temporary maintenance and manipulation of information necessary for complex cognitive operations. It is still debated whether the maintenance of item identity and serial order relies on a shared process or two distinct cognitive mechanisms. The present study aimed at clarifying this issue by examining the interaction between item and order maintenance under different levels of cognitive load. Sixty-eight participants performed an immediate serial recall task in which they had to remember either the identity of items, their presentation order, or both simultaneously, with sequences of either three or seven digits. Results revealed a robust effect of cognitive load, with lower accuracy in high-load compared to low-load conditions. Performance was significantly higher when participants had to remember only the items than when they had to remember only their order or both. This result suggests that maintaining item identity may rely on a process that can operate independently from order maintenance, whereas serial order processing might depend on more specific item encoding. These findings partially support the notion of separable but interacting mechanisms for item and order maintenance in working memory and highlight a possible asymmetry in their cognitive management.

Introduction

General introduction and aim of the study

Baddeley and Hitch (1974) conceptualized working memory as a limited-capacity system responsible for the temporary storage and manipulation of information necessary for the execution of complex cognitive tasks, such as comprehension, learning, and reasoning. As such, one of the primary functions of working memory is the maintenance of information for immediate and short-term use. In everyday life, individuals constantly rely on working memory to retain information required to complete ongoing tasks. Most of the time, the information to be maintained does not consist of just one single item, but rather of a collection of items that, taken together, create meaningful information. In some cases, the mere presence of these items is enough to give the information needed and guide behavior. For instance, in a grocery list, the order of the items is typically not relevant (assuming that the goal is not to optimize the tour of the market). On the other hand, there are some cases in which remembering just the presence of the items is not enough to have all the information that is needed, but also their order and temporal relation are required. In these contexts, the order in which items are presented is of critical importance. A salient example is the use of GPS navigation, where the sequence of instructions (e.g., “go straight for 300 meters and then turn left”) must be maintained to ensure one follows the right path; altering the order in which one follows these instructions results in performing actions that lead to entirely different (and potentially disastrous) outcomes. The ability to maintain a series, conceived as a succession of items with a specific temporal order, is thus essential for many working memory tasks and executive functions. Accurate serial recall requires not only the retention of the individual items that make up the sequence but also the preservation of their relative order. The present study sought to investigate the cognitive mechanisms involved in the maintenance of serial information, focusing specifically on the processes underlying the retention of item identity, serial position, and the interaction between these two processes. In addition, their interaction with cognitive load, which represents the cost of a mental operation in terms of attentive and computational resources, was also tested. In

particular, we aimed at determining whether the retention of item identity and that of their serial position are two distinct processes that involve two different mechanisms, or instead are part of the same unitary process.

Maintaining information in STM

The maintenance of information has long been a central topic of interest in cognitive psychology. Even prior to the introduction of the working memory model by Baddeley and Hitch (1974), numerous studies had already examined the fundamental mechanisms of short-term memory and its capacity limits. In his pivotal and classic study, Miller (1956) proposed that memory capacity should not be defined by the absolute number of items retained, but rather by the number of meaningful “chunks" into which these items could be organized. Subsequent research confirmed the effectiveness of chunking as a memory strategy, highlighting that chunking improves recall performance regardless of the number of items per chunk, with groups of three items being particularly efficient (Ryan, 1969; Wickelgren, 1964). In the same period, studies involving immediate serial recall tasks revealed that recall errors in a series of letters occurred when the items were similar in sound, although the presentation was visual. This finding suggests that linguistic/verbal information, even when presented visually, is encoded and maintained in shoert-term memory in a phonological form. For example, participants were more likely to confuse the letter "P" with "V" rather than "R", despite the greater visual similarity between "P" and "R" (Conrad, 1964; Conrad & Hull, 1964). Further studies demonstrated that the duration of short-term retention is limited to approximately 15–20 seconds in the absence of active rehearsal, particularly when attention is diverted from the to-be-remembered material (Brown, 1958; Peterson & Peterson, 1959).

Maintaining information in working memory

Empirical evidence accumulated over the years led to a reconceptualization of the structure devoted to temporary information storage. The previous notion of short-term memory as a passive repository proved insufficient to account for the range of observed phenomena. Baddeley and Hitch (1974) introduced the concept of working memory, proposing a dynamic and multi-component system designed not only for the temporary storage of information but also for its active manipulation. Unlike the unitary and passive models that preceded it, their framework conceptualized working memory as a set of functionally distinct subsystems, each specialized in handling different types of information and cognitive operations. Over time, this model was progressively refined and expanded to incorporate additional components on the basis of emerging empirical findings (e.g., Baddeley, 1986; 1996; 2000; 2019).

While the multi-component model of Baddeley and Hitch remains the most widely adopted framework to describe working memory, alternative models have also been developed. These include, among others, the embedded-processes model (Cowan, 1999), the dual-component model (Unsworth & Engle, 2007), and the time-based resource-sharing model (Barrouillet, Bernardin, & Camos, 2004) (see also: Towse & Hitch, 1995; Oberauer & Hein, 2012). Although all the above models differ in their theoretical assumptions and emphasize distinct aspects of working memory function, they converge on a critical point: the maintenance of information in working memory is not a passive process but requires the continuous involvement of cognitive and/or attentional resources.

Remembering order

Within the framework proposed by Baddeley and Hitch, one of the core components of working memory is the phonological loop, which is responsible for the maintenance of verbal information. This system comprises two distinct subcomponents: the phonological short-term storage and the articulatory rehearsal process. The phonological storage is characterized by a limited capacity and encodes linguistic and verbal input as memory traces that decay rapidly, typically within a few seconds. The articulatory rehearsal mechanism serves to counteract this temporal decay by enabling the subvocal or overt repetition of the stored items, thereby refreshing the memory traces and prolonging their availability within the short-term storage.

The phonological loop is an extremely useful tool for understanding and studying how verbal information is maintained in working memory and prevented from decaying. Nonetheless, in its original conceptualization, it presents a strong limitation when it comes to describing the processing of serial order information. Specifically, the model lacks an explanation of how the serial order of verbal items is encoded and subsequently retrieved from the phonological storage (Baddeley et al., 2020). To fill this theoretical gap, different models of the phonological loop have been proposed. For example, Burgess and Hitch (1999; 2006) proposed that information about the order of a series is bound dynamically to a variable context related to time progression, and such a context is then used as a clue for recall. Another example is given by the primacy model (Page & Norris, 1998), where each item receives progressively less activation than the previous ones. During retrieval, the item with the highest activation is recalled first and then inhibited, allowing the next most strongly activated item to be recalled. All these models share the assumption that the phonological storage is separate from the mechanism responsible for serial order. In addition, they also agree that retrieval from the storage is affected by the similarity between items. All these phonological loop models raised the issue of whether there is only one generic serial encoding mechanism or whether there are similar but separate modality-specific mechanisms for verbal and visual stimuli (Hurlstone et al., 2014).

Maintaining different types of information

Depoorter and Vandierendonck (2009) tried to answer this question. The authors investigated how serial order is encoded in working memory, testing whether such encoding is dependent or independent from sensory modality (i.e., verbal and visuo-spatial). Using four dual-task paradigms involving both verbal and visuo-spatial stimuli, they observed a cross-modal interference between tasks that require recalling order, regardless of the sensory modality. This evidence supports the idea of a unique modality-independent mechanism for maintaining serial order that is shared among different sensory modalities, suggesting that order is represented in working memory in a unitary way, rather than by modality-specific systems. Other evidence in favor of the unitary nature of the serial order maintenance system in working memory is provided by Abrahamse and colleagues (2017). In their review, the authors reported studies that show how the retrieval of verbal sequences affects external spatial attention, supporting the interconnection between verbal and visuo-spatial processes. Based on this series of evidence, the authors hypothesized the existence of a “mental whiteboard”, a visuo-spatial mental framework on which serial order is represented in the same direction as one’s writing system. In this way, temporal information is converted into spatial information (i.e., the position of items on the whiteboard). Another review by Hurlstone and colleagues (2014) examined the serial order recall of information. Based on the results of many previous studies, the authors support the idea of a common mechanism shared by different sensory modalities, but they also note that, due to the lack of consistent evidence, especially in the visuo-spatial domain, it cannot be excluded that this shared mechanism is supported by other separate modality-specific processes. Complementary evidence comes from Saito and colleagues (2008), who explored the effects of visual and phonological similarity in short-term retention of Japanese characters. Their results revealed that both types of similarities affect recall, but through different mechanisms. In fact, phonological similarity decreases performance in the absence of articulatory suppression, while visual similarity has an effect even when articulation is suppressed. These findings support the hypothesis that visual and phonological codes for serial information are separate, and they are supported by different domain-specific systems. In a study conducted by Davis and colleagues (2013), serial recall of

visuo-spatial and verbal information was explored with and without interference from a secondary visuo-spatial or verbal task. Results showed that verbal and visuo-spatial interference selectively influence the recall of stimuli of the same category, suggesting the existence of separate processes for each domain. However, they also observed a generalized interference that highlighted an overlap between the two mechanisms. This evidence supports the existence of a combination of domain-general and domain-specific processes for maintaining serial information.

Unitary or separated operations for items and order? Debate and diverging evidence

In their study, Chubala and colleagues (2019) compared two commonly used tasks to study short-term retention of verbal information: immediate serial recall and immediate serial recognition. In the former, participants are required to recall a series of elements in the exact order of presentation, while in the latter, they must determine whether the order of a list of elements matches that of a previously presented one. While immediate serial recall requires actively maintaining in working memory information about both the elements presented and their sequential order, immediate serial recognition needs to actively maintain exclusively the order of presentation of the elements. The authors demonstrated that both tasks were sensitive to concreteness and acoustic similarity of the words used as stimuli, but effects such as word frequency and semantic relationships among the words in the sequence only affect the serial recall task. This evidence suggests that the two tasks involve partially different cognitive processes, and the maintenance of items and that of their serial order might be separate operations. In a study published in 2007, Cattaneo and colleagues explored the picture superiority effect in working memory for spatial and temporal order (Cattaneo et al., 2007). In this study, the authors presented participants with a series of items depicted as words or images in random locations of a screen and then asked them to recall just the presentation order of items, just their position, or both. The authors observed that participants recalled more accurately both the spatial and temporal position of items when they were presented as icons rather than as words. However, performance dropped significantly when both information types (i.e., spatial and temporal) had to be recalled simultaneously, implying that the two types of information, temporal and spatial, compete for attentional resources. This result supports the idea of at least partial independence between spatial and temporal memory systems.

Evidence for spatial and temporal information being managed by separate processes in working memory is not a novelty. In fact, early evidence was provided by Bjork and Healy (1974), who investigated how order and items for verbal information are maintained in working memory. In their study, participants were asked to retain series of four consonants to recall after different temporal delays. The authors observed that temporal information degraded more rapidly than information about the items that had been presented. They also observed that transposition errors (i.e., switching the places of items) were quite common, even when there was no acoustic confusion between the items. In the same year, Healy (1974) conducted a related study in which participants were asked to read aloud and recall series of letters. In one of the two experiments, they were asked to remember just the items, while in the other experiment, just their presentation order. The author observed two different error patterns across the two experiments. Such difference between the results of the two experiments provided further support for the hypothesis that item and order retention rely on different cognitive processes. Baggini and Ricciardelli (currently under revision) provided further evidence in support of the separation of the processes for maintaining items and order in working memory. In their study, the authors tested participants through a complex-span task with a delayed response involving verbal material at different levels of cognitive load (i.e., series of random letters of different lengths). They observed that the accuracy in remembering the order of the items was significantly more sensitive to variations in cognitive load than the accuracy in remembering the presence of the items.

On the other hand, several studies support the existence of a unitary cognitive system responsible for maintaining both items and their order information in working memory. For instance, Bahramisharif and

colleagues (2018), using intracranial recordings from neurosurgical patients engaged in sequence-based working memory tasks, reported patterns of synchronized but anatomically distinct neural oscillations, which they interpreted as evidence for a unified representational mechanism. Indirect evidence for a unitary system also comes from De Belder and colleagues (2017). They based their study on the assumption that serial order is maintained in working memory through the creation of position markers, to which items to be maintained are bound. The authors demonstrated the fundamental role of time in creating these position markers for serial verbal information, suggesting a close relationship between temporal and spatial information maintenance mechanisms. Majerus (2019), in a comprehensive review, discussed findings from brain lesions and neuroimaging studies suggesting that item and order information are processed via partially distinct neural substrates. However, the author also reported the existence of neural circuits supporting both item and serial order maintenance. Based on this body of evidence, the author suggests that serial order information is represented in working memory through multiple processes: some are specific to items or order, while others operate in a more general way and can process both types of information.

There is still uncertainty about the nature of the serial information maintaining mechanism in working memory, and the debate is still far from reaching a conclusion. The present study aimed to contribute to this ongoing debate by providing new empirical evidence on the relationship between item and order maintenance in working memory. The primary aim of this study was to shed light on the underlying mechanisms of a process that is typically attributed to working memory, namely, serial learning. More specifically, the main focus of the present work was to investigate how the cognitive system manages the temporary and short-term storage of elements in a series and their order in working memory. Our experimental hypothesis was that, if remembering the items of a series and remembering their order are two separate cognitive processes, performing only one of these two processes at a time would lead to a better performance than performing them together, because in the former case all the available resources can be devoted to a single operation (i.e., remembering only items or only order), while in the latter the cognitive resources available for the two processes must be shared (i.e., remembering both items and order). To answer this main question, an immediate serial recall task was used. The immediate serial recall task is a well-known task that has been widely used in cognitive psychology to assess various aspects and effects of information processing in working memory and short-term information retention. It consists of a series of stimuli (that can be of any nature, such as, for example, numbers, words, or faces) presented in series. Participants are asked to recall the stimuli after the presentation of the series, sometimes after a delay, or after performing another task. In this experiment, a simple version of the immediate serial recall was used that did not involve any delay or interference task. Stimuli were presented in series to participants, and they were asked to recall them in the correct order as soon as the presentation ended.

Materials and methods

Participants

A priori power analysis was conducted using the software MorePower 6.0.4 in order to define the minimum sample size for the experiment to reach a power of .8, with an $\alpha = .05$. The minimum sample size required was 78.

However, due to time constraints, a total of 68 participants (women = 32, men = 36; age M = 28.4, SD = 8.11) voluntarily took part in this study. All participants had normal or corrected-to-normal vision, and none of them had neurological or learning deficits. All participants gave their informed consent and consented to data treatment. They received university credits for their participation.

The study was considered minimal risk (as defined by the National Research Council of the Academies of Science and, as such, was approved by the Committee for Research Evaluation of the Psychology Department

of the University of Milano-Bicocca (protocol number N. RM-2025-952) and was conducted in accordance with the Helsinki treaty.

Materials and stimuli

The stimuli used in the series presented in the task were Arabic 1-digit numbers in Calibri font printed in black on a light gray background. The task was presented on a 17' monitor, adjusted to approximately 60cm from the participants, in order for the stimuli to occupy a visual angle of 2,5°. Participants gave their response on a QWERTY keyboard. The task was administered in a quiet room with controlled artificial light, and to avoid any potential distraction, participants were asked to turn off all their electronic devices. The whole task was programmed and presented in Matlab (2023) using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997; Kleiner et al, 2007).

Design and Procedure

Two independent variables were manipulated in this study: the cognitive load of the task and the dimension of the series to remember (i.e., the items of the series or their order in the series). We decided to include the manipulation of the cognitive load in our study to compare and integrate the results reported in our previous study (Baggini & Ricciardelli, under revision). The cognitive load was manipulated by changing the length of the series of stimuli presented. In the low cognitive load condition, the series had a length of 3 items, whereas in the high cognitive load condition, the length of the series was 7 items. To separate the two dimensions, three conditions were created by making one of the two aspects predictable and inferable. In the "items" condition, the series was composed of randomly chosen digits, but they were arranged in ascending order during presentation. In the "order" condition, items were presented in random order, but they were always numbers from 1 to 3 or from 1 to 7, depending on the cognitive load condition. In the "both" condition, items were chosen and presented randomly (Figure 3.1). Through this experimental paradigm, the processing of the two dimensions was tested separately in the first two conditions (i.e., "items" and "order" conditions), allowing the measurement of performance in only a specific dimension (i.e., item identity or sequential order of the items) of the to-be-remembered series. The third condition (i.e., the "both" condition) acted as a control condition. Since in this condition none of the dimensions of the series was predictable, it allowed us to study the participants' performance when a series of unknown elements and their unknown order had to be learnt. The dependent variable was the accuracy of participants' responses.

The experiment used a 3(dimension) by 2(cognitive load) within-subjects design. All participants were aware of the ongoing condition, so they knew whether to focus on the maintenance of one, the other, or both dimensions of the series, and they knew what information, if possible, could have been inferred in the recalling phase, with no need to store it during the presentation (e.g., in the 3-digit-order condition, if the participant recalled the first two digits as 3 and 1, the third one would necessarily be 2).

Each condition was composed of 30 trials. At the beginning of each condition, an introductory screen instructed the participant about what condition they were going to perform and the length of the series they were going to see. Each trial was composed of a series of digits presented one at a time at the constant pace of one per second. Participants were asked to read aloud all the digits as soon as they appeared. Once the whole series was presented, participants were asked to type the series they had just read on the computer keyboard.

The experimental session always began with the presentation of the task instructions displayed on the computer screen, followed by a brief practice to familiarize participants with the task. After this phase, participants began the task. Once the whole session was completed, a debrief phase followed. The whole procedure took approximately 30 minutes.

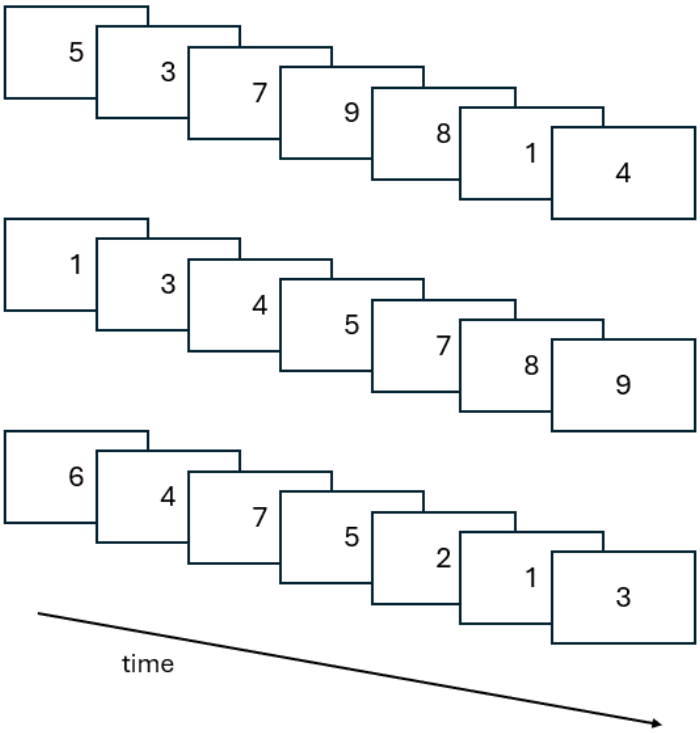

Figure 3.1. Example of the screen succession for the task. The three rows represent three different dimension conditions in the high cognitive load condition (series of length 7). The first row represents the "both" condition, the second row represents the "items" condition, and the third row represents the "order" condition.

Analysis and results

A 2 (cognitive load) by 3 (dimension) analysis of variance was conducted to examine the effect of the cognitive load, the dimension of the series to remember, and their interaction on task performance. The analysis revealed a significant main effect of the cognitive load ($F(1, 402) = 607.9$, $p = <.001$, $\eta^2p = .602$), as well as a significant main effect of the dimension ($F(2, 402) = 22.3$, $p = <.001$, $\eta^2p = .1$). The interaction between cognitive load and dimension was also significant ($F(2, 402) = 17$, $p = <.001$, $\eta^2p = .078$). Post-hoc comparison with Bonferroni correction confirmed the strongly significant effect of cognitive load (t (402) = -24.7, $p < .001$, $d = -2.44$). Regarding the effect of the dimension, post-hoc analysis revealed a significant difference between the "items" and "order" conditions (t (402) = 5.98, $p < .001$, $d = .72$) and between the "items" and "both" conditions (t (402) = 5.55, $p < .001$, $d = .67$), whereas no significant difference emerged between the "order" and "both" conditions. Finally, the post-hoc analysis of the interaction between the two factors confirmed the significant effects for all the combinations, except among the three low cognitive load conditions and between the "order" and "both" conditions under high cognitive load (Figure 3.2).

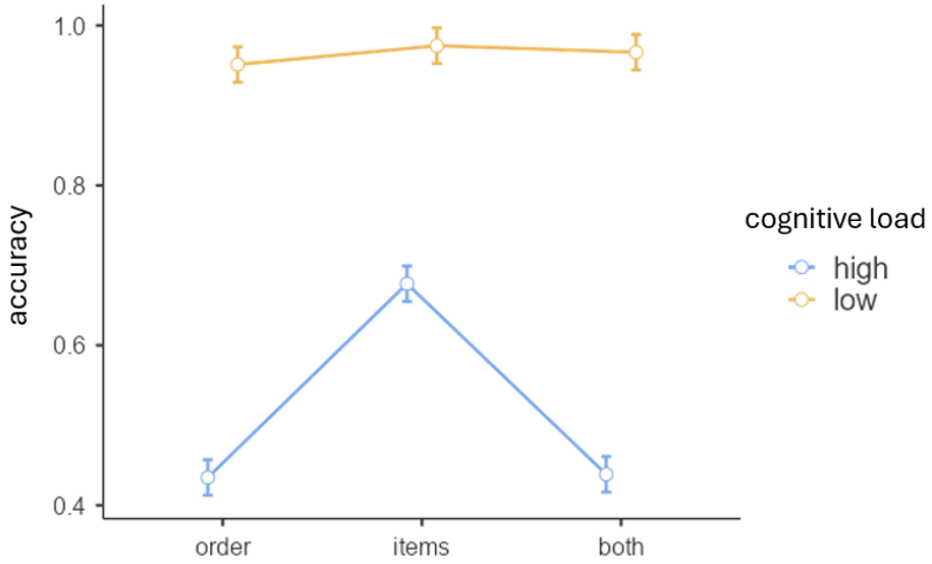

Figure 3.2. Accuracy, expressed as a proportion of correct responses, for each condition of the task. Bars represent standard error.

Discussion

In the present study, we aimed to investigate the cognitive mechanisms involved in the maintenance of serial order information, with the main focus on the processes underlying the retention of item identity, serial position, and the interaction between these two processes. We aimed at determining whether the retention of item identity and that of their serial position are two distinct processes that involve two different mechanisms, or instead are part of the same unique process. To do so, an immediate serial recall task was used, a task in which a series of stimuli is presented to participants one at a time and they are asked to recall the complete series at the end of the presentation. The experimental paradigm adopted in this study allowed for modulating the dimension of the series to remember (only the items of the series, only their presentation order, or both) and the cognitive load of the task (low or high). To modulate the dimension of the series that participants had to maintain in memory, we created three conditions. In the "items" condition, items were digits between 0 and 9 selected randomly at each trial but always presented in ascending order. In the "order" condition, items were digits between 1 and 3 or 7, based on the length of the series, and they were always presented in a random order. In the "both" condition, items were digits between 0 and 9, always selected and presented randomly. These three different conditions allowed us to test both separately and together the retention performance of participants in maintaining these different types of information. Cognitive load was also manipulated by changing the length of the series presented. In the low cognitive load condition, the series had a length of three digits, while in the high cognitive load condition, they had a length of seven digits.

Our hypothesis was that, if the two types of information are encoded or maintained by two different cognitive processes, performance in the "items" and "order" conditions should have been higher than performance in the "both" condition, since in the latter condition two processes are performed at the same time, while in the former two conditions only one process is required.

The present findings only partially confirmed our hypothesis. In fact, in the high-load condition, we found a significantly higher performance in the "items" condition compared to the "both" condition, which is

perfectly in line with our prediction, but we did not find any differences between the “order” and the “both” conditions. Unfortunately, the low-load condition turned out to be too easy to observe any actual effect of the three different dimension conditions, since the overall proportion of correct responses was close to 1 in all of them. Since the “items” condition did not require the encoding and maintenance of the order in which items were presented, a lesser amount of minimum cognitive resources was required to perform the task compared to the “both” condition, and more resources were allocated to the maintenance process of the memoranda, resulting in a higher accuracy. Nonetheless, this interpretation of the results does not fully explain the absence of difference in performance between the “order” and “both” conditions. In fact, if the two processes of remembering items' identity and order were completely independent, we should have observed on the “order” condition the same increase in performance observed in the “items” condition. This asymmetrical effect between the two single-feature conditions opens the possibility of the idea that maintaining the identity of the items in a series involves a process that can occur without the activation of the process devoted to remembering their order, but the opposite case is not possible, with the process in charge of the maintenance of order that can only be activated in conjunction with the process for remembering the items. If this is the case, it would not be entirely correct to say that the two processes are separate. It would be more cautious to say that the process for remembering items is a basic process that is always necessary and can be integrated into another process when it is required to remember the serial order of the items. Further studies should corroborate the present findings and address this specific hypothesis.

An alternative and more speculative explanation for these results is that the two operations are not separated at all, but the encoding of the items, which here were verbal material, is supported by another process, such as a visual encoding, since they were presented visually on a computer screen. Under this account, the enhanced performance observed in the “items” condition would not reflect a greater availability of cognitive resources, but rather the combined contribution of verbal and visual encoding processes, without the interference associated with maintaining serial order. This interpretation, nonetheless, still does not fully explain the results. In fact, if this were the case, we should have observed a similar increase in performance in the “order” condition, since the same logic can be applied to the order maintenance process.

In any case, such an interpretation of our results can lead to new possible research hypotheses: the first one is that the two processes of encoding visual and verbal information in working memory can synergize to achieve the maintenance of the same set of elements. This redundancy makes information more stable and easier to reconstruct in case one of the two representations (visual and verbal) is disrupted. The second, and even more interesting one, is that the same information integration and redundancy does not happen for serial order. This is an interesting possibility that future studies should investigate.

The present results are also in line with those reported by Baggini and Ricciardelli (under revision), in which the authors provided evidence in support of the separation of the processes for maintaining item identities and serial order in working memory. In their study, they reported a different impact of cognitive load on the ability to remember items and order, with the latter being significantly more sensitive to variations in cognitive load than the former. Their result, together with the results provided in the present study, suggests that serial information might not benefit from a multi-representation integration as the information about the identity of items does.

In conclusion, the higher performance in remembering the items of a series compared to their order or both the things together, supports the idea that the process of remembering the items of a series is at least partially independent from the process of remembering the order of items.

Limits of this study

A limitation of this study is that in the low cognitive load conditions (i.e., the series of three items), participants' accuracy was generally too high to observe any error pattern or effects given by the task. A new study with a similar paradigm and aim, but different cognitive load conditions, should be conducted. We propose to add another level to the cognitive load variable, bringing it to three: a low cognitive load condition, with a series length included between four and six, a medium cognitive load condition, with the same length as the high cognitive load condition presented here, and a high cognitive load condition, in which series are purposefully too long to maintain in working memory. In future research, avoiding the ceiling effect in the low load condition would help understand better the modulatory role of cognitive load on the processes devoted to maintaining the different dimensions of a series.

Conclusion

In this study, we brought evidence supporting the possibility that remembering item identity and serial order are two distinct processes. However, our findings did not fully confirm this possibility, as we observed no difference in performance between recalling only the items' order and recalling both their identity and order together. Crucially, in the high cognitive load conditions, a clear difference emerged between remembering only the items' identity and both identity and order recall. This result provides new insights into the ongoing debate on which cognitive processes or mechanisms the maintenance of item identity and serial order relies on in working memory.

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Chapter 4: Social stimuli in working memory

The article “Gender differences in the perceived intensity of emotions expressed by faces” Has been published on Giornale Italiano di Psicologia (Italian Journal of Psychology) in 2025.

The article “Encoding and updating of emotional information in working memory: Sex and emotion-based differences in performance” has not been submitted yet to any journal, since data collection is still in progress.

Gender differences in the perceived intensity of emotions expressed by faces

Davide Baggini[1 4], Paola Ricciardelli[1], Paola Palladino[2] e Caterina Artuso[3]

[1]University of Milano-Bicocca
[2]University of Foggia
[3]University of Genova
[4]University of Surrey

Abstract: In this study, aiming to validate a set of stimuli, a questionnaire was presented to participants. The stimuli used are faces taken from the Radboud Faces Database expressing three different emotions combined with the same number of gaze directions. The results showed that, although the emotions expressed by the faces and those perceived by the participants matched, females reported perceiving them significantly more intensely than males. Also, regardless of the gender of the participant, faces expressing fear or with their gaze directed towards the observer, have been reported as more intense in the emotion expressed.

Keywords: Emotion recognition, emotion intensity, gender differences, emotive faces

Introduction

Faces represent a category of stimuli that holds particular relevance for human beings. Through them, it is possible not only to obtain information such as an individual's identity, but also to anticipate their behavior and communicate one's own intentions. Faces are, in fact, a specific category of social stimuli that, in order to be adequately processed and convey coherent information, require all their constituent elements and features to be integrated with one another. For instance, an angry face looking directly at us and the same face with the gaze averted in a different direction convey two markedly different types of social information. In the former case, we are dealing with an individual expressing hostility toward us, thus representing a potential threat to which we must react promptly and with an appropriate behavioral response. In the latter case, the threat is not directly addressed to us; consequently, the reaction will differ in both form and salience. In other words, the social information conveyed by faces can regulate social interactions by facilitating or inhibiting them.

According to the cognitive appraisal theory, the combination of emotion and gaze direction signals to the observer their relevance to the individual expressing the emotion, thereby enabling inferences about that person's behavior and intentions toward oneself (Adams & Kleck, 2003; Adams & Kleck, 2005; Adams et al., 2010; Mumenthaler & Sander, 2012; N'Diyae et al., 2009). Approach-oriented facial expressions, such as anger or joy, are intensified when associated with a direct gaze. Similarly, avoidance-oriented expressions, such as fear or sadness, are perceived as more intense when the gaze is averted away from the observer. These emotion–gaze combinations facilitate the evaluation of behavioral tendencies (Adams & Kleck, 2003; Adams & Kleck, 2005; N'Diyae et al., 2009). The effect of this combination has been observed in various cognitive functions, such as attention and short-term memory. Faces expressing anger with an averted gaze have been found to produce lower memory performance than angry faces with a direct gaze toward the observer (Nakashima et al., 2012). Moreover, angry faces with a direct gaze do not produce an attentional blink, as this combination is processed rapidly and automatically (Ricciardelli et al., 2012).

Artuso et al. (2012) examined the effect of these combinations in a working memory updating task—that is, the mechanism that allows relevant information to be maintained while inhibiting information no longer

pertinent to the task goals. In their first study, the authors reported that emotion–gaze direction combinations that enhance emotional perception (e.g., joy–direct gaze, fear–averted gaze) produce faster responses (i.e., shorter reaction times) during face processing compared to weak combinations characterized by low congruence according to the cognitive appraisal theory (e.g., joy–averted gaze, fear–direct gaze). A similar effect was observed during working memory updating: faces with strong, highly congruent combinations required less time to be updated than those with weak combinations. Conversely, the opposite pattern was found in the encoding phase, with strong combinations requiring more time to be memorized than weak ones (Artuso et al., 2015).

In all the studies mentioned above, neither the effect of participants' gender nor the possible interaction between participants' gender and the sex of the presented stimuli has been examined.

The present study represents the first phase of a broader project aimed at investigating the effect of the emotion–gaze interaction on the processing, maintenance, and updating of social information in working memory. The specific goal of this initial phase was to validate the stimuli that will be used in subsequent experiments. In particular, we aimed to ensure that the emotions expressed by the selected faces were correctly and unambiguously perceived. The results showed that, overall, the stimuli were effective in conveying the target emotion. However, they also revealed an unexpected difference in perceived intensity between men and women, which does not appear to be attributable to the emotion–gaze interaction described above.

Materials and methods

Participants

Sixty adults (31 females, 29 males) aged between 19 and 53 years (M = 30.4; SD = 9.07) voluntarily took part in the study. All participants provided informed consent in digital form prior to the start of the experimental session, agreeing to the processing of their data. No monetary compensation was provided for participation. The study was approved by the Research Evaluation Committee (CRIP) of the Department of Psychology, University of Milano-Bicocca, under protocol number RM-2016-69.

Materials and Stimuli

The stimuli used in this study consisted of faces taken from the *Radboud Faces Database* (Langner et al., 2010). The set included faces from ten different models (five male, five female), each represented in nine variants obtained by combining three emotional expressions (joy, fear, anger) and three gaze directions (frontal, right, left), resulting in a total of 90 stimuli. All faces were photographed in frontal view against a neutral background. The models were all Caucasian, wore no makeup or glasses, had their hair tied back, and were dressed in plain black T-shirts without decorations. The experimental task and data collection were conducted using Qualtrics (Qualtrics, 2023). Statistical analyses were performed with the software *jamovi* (The jamovi Project, 2024).

Procedure

The study was conducted in the form of an online questionnaire accessible via a link. The questionnaire lasted approximately 15 minutes and could be completed using a computer, smartphone, or tablet. Before beginning the questionnaire, participants were shown a screen containing the consent form for personal data processing. Once they provided consent to participate and to the processing of their data, the task instructions were displayed, after which the questionnaire began.

Each trial consisted of a screen displaying a randomly selected face from the 90 stimuli (without repetition) along with two questions. The first question was “Which emotion is expressed by the face in the image?” with the response options “Joy,” “Fear,” and “Anger.” These three options were always presented in random order and on separate lines. The second question was “How intense is the emotion expressed by the face in the image?” to which participants responded by selecting one of five options: “not at all,” “a little,” “moderately,” “very,” or “extremely” (Figure 4.1). The task was administered in Italian to Italian-native speakers. The questionnaire ended after 90 trials, ensuring that all faces were evaluated by each participant. Stimuli were presented in a random order without repetitions.

Figure 4.1. Example of the questionnaire screen used in the study. The three alternative emotions were always presented in random order, while the five intensity options remained fixed. First question says “Which emotion is expressed by the face in the image?”, second question says “How intense is the emotion expressed by the face in the image?”. Below each question, the relative answers are displayed.

Analysis and results

To verify that the emotions expressed by the facial stimuli corresponded to those perceived by the participants, we first analyzed the distribution of responses to the question *“Which emotion is expressed by the face in the image?”* for each stimulus. All stimuli received at least 97% of responses consistent with the intended emotion.

Two main analyses were subsequently conducted. First, we tested the effect of gaze direction and emotion type, as well as their interaction, on the perceived intensity of the emotion. Then, we examined potential differences between male and female participants to investigate whether participant gender influenced the perceived intensity of the emotions.

To test the first effect, an analysis of variance (ANOVA) was conducted on the mean intensity ratings across the stimuli. Fixed factors were emotion (joy vs. fear vs. anger) and gaze direction (direct vs. averted), and the dependent variable was perceived intensity. A significant effect emerged for both emotion type ($F(2, 84) = 16.36$, $p < .001$, $\eta^2p = .28$; joy: $M = 3.27$, $SD = .425$; fear: $M = 3.49$, $SD = .41$; anger: $M = 3.03$, $SD = .461$) and gaze direction ($F(1, 84) = 4.3$, $p = .041$, $\eta^2p = .049$), but not for their interaction. Post hoc comparisons with Bonferroni correction revealed that faces expressing fear were perceived as significantly more intense than those expressing joy ($t(84) = 5.64$, $p < .001$, $d = 1.54$) or anger ($t(84) = 3.64$, $p = .001$, $d = .99$), while no significant difference was found between happy and angry faces (Figure 4.2).

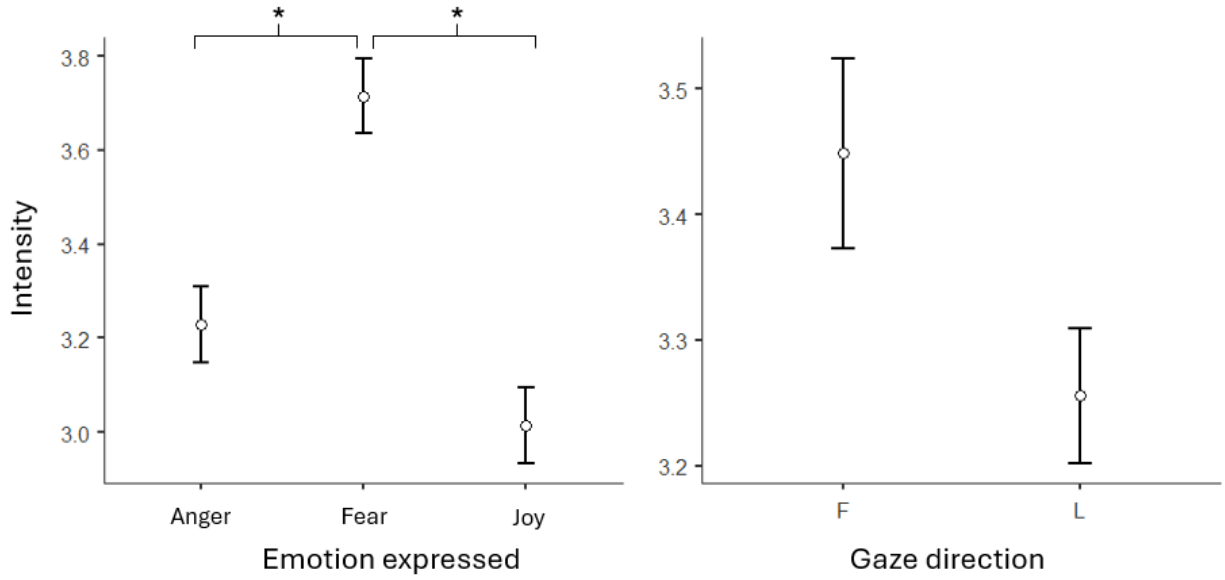

Figure 4.2. (Left) Mean intensity ratings of the emotions expressed by the faces, as reported by participants. Fearful faces were perceived as significantly more intense than the others. (Right) Mean intensity difference as a function of gaze direction (F = frontal, L = lateral). Note that the two graphs use different y-axis scales. Error bars represent the standard error.

In the second analysis, we investigated potential differences in perceived emotional intensity as a function of participant gender. Specifically, we tested whether the mean intensity ratings differed between male and female participants. An independent samples *t*-test revealed a significant difference, with females reporting higher perceived intensity than males ($t(58) = -4.58$, $p < .001$, $d = -1.18$; males: $M = 3.11$, $SD = .30$; females: $M = 3.52$, $SD = .38$) (Figure 4.3). Based on the observed effect size ($d = -1.18$), a post hoc power analysis was conducted using G*Power 3.1.9.7, with $\alpha = .05$, which yielded a power value of .99.

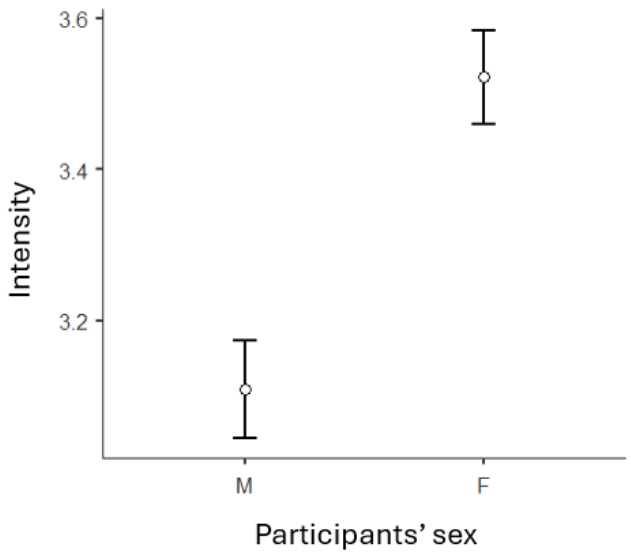

Figure 4.3. Mean perceived emotional intensity ratings reported by male and female participants. Error bars represent the standard error.

Discussion

The main objective of this preliminary study was to determine whether the selected stimuli effectively conveyed the intended emotion and to what degree of intensity. The analyses revealed that the emotions expressed by the stimuli were consistent with those perceived by the participants. However, the reported intensity differed significantly between males and females, with females indicating that they perceived the facial expressions as more intense than males did. When considering the interaction between emotion type and gaze direction, no significant difference was observed. This result appears to contrast with previous studies (Adams & Kleck, 2003; Artuso et al., 2012; Artuso et al., 2015), in which the interaction between gaze direction and emotion type seemed to play a role in perceived intensity. More specifically, a direct gaze has been found to enhance the perception of approach-oriented emotions such as anger or joy, whereas an averted gaze intensifies the perception of avoidance-oriented emotions such as fear. A possible explanation for this unexpected finding may lie in the fact that in the previously mentioned studies (e.g., Artuso et al., 2012; Ricciardelli et al., 2012), participants were not explicitly asked to identify either the type or the intensity of the emotion. Thus, the observed effect may have emerged implicitly. For now, however, this remains a tentative interpretation, and further research will be necessary to verify its validity.

It is important to note that the emotion intensity measures collected in this study were obtained through a self-report questionnaire. Consequently, they represent subjective measures and are therefore not immune to participants' biases or expectations. It is essential, when interpreting these findings, to bear in mind that the results discussed above do not demonstrate that females perceive emotions more intensely than males; rather, they indicate that females *report* perceiving emotions as more intense than males do.

In conclusion, these findings provide an assessment of the subjective perception of emotions expressed by faces. In a subsequent study, the same stimuli will be used to investigate the cognitive costs associated with processing emotional facial expressions, and the resulting data will be compared with the present findings to

explore the relationship between perceived emotional intensity and the cognitive cost of processing such stimuli.

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Encoding and updating of emotional information in working memory: Sex and emotion-based differences in performance

Davide Baggini[1 4], Paola Ricciardelli[1], Paola Palladino[2] e Caterina Artuso[3]

[1]University of Milano-Bicocca
[2]University of Foggia
[3]University of Genova
[4]University of Surrey

Abstract

This study investigated how different emotional facial expressions influence working memory performance and whether such performance is affected by participants' sex. Using a *n*-back paradigm, 35 participants were asked to maintain and update only the face identity, only the emotion expressed (happiness, fear, anger), or both across three levels of cognitive load (1-, 2-, and 3-back). Results revealed significant main effects of sex, cognitive load, and the type of facial feature maintained. Men outperformed women in both accuracy and response speed, regardless of cognitive load or task condition. Accuracy was, in general, significantly lower when participants were required to maintain emotional expressions alone, compared to identity or combined identity–emotion information. It was also observed that response time negatively correlated with accuracy, supporting a time-related rather than interference-based decay of information in working memory. These findings highlight sex-based differences in the processing of emotional facial information and suggest that emotional content is harder to maintain in working memory when not bound to facial identity cues. In addition, we provided evidence in support of the time-related decay of information in working memory hypothesis.

Introduction

Social interactions are a primary part of human life. Living in a society often means dealing with tens or even hundreds of people every day. While some of them directly communicate with each other through verbal means, many of them do not actively interact, but this doesn't mean that they are not carrying social information. In fact, there are many ways in which social information can be transmitted, such as through gestures or behavior, and it is fundamental to being able to correctly process and respond to such stimuli. One of the most salient categories of social stimuli is faces, and being able to process faces correctly is a necessary ability to live and navigate in a social environment. A crucial element in face processing is facial expressions. Through facial expressions, individuals can communicate their intentions and attitudes toward others. According to Zebrowitz (2006), faces provide important information about opportunities for social interactions. Face perception, in an ecological context, is therefore directly linked to action.

The relevance of emotional faces is supported by a great number of studies that have demonstrated how this type of stimulus is processed with greater speed and accuracy compared to other objects (Jenkins, Lavie, & Driver, 2005; Reinders, den Boer, & Büchel, 2005; Ro, Russell, & Lavie, 2001). As with any other element of the environment, in order to be perceived, social stimuli must be processed so as to create an appropriate representation of the environment and produce an adequate behavioral response. Therefore, working memory is an essential cognitive system involved in this processing, and, given the importance of correctly processing social stimuli, it is not surprising that the focus of some of the cognitive processes carried out by working memory concerns the processing of social information.

One of the key mechanisms of WM functioning is updating, which can be defined as the ability to maintain goal-relevant information while modifying some outdated parts or integrating new ones (Morris & Jones, 1990; Palladino et al., 2001; Oberauer, 2005). Updating becomes fundamental when it comes to processing social stimuli such as faces. Facial expressions, in fact, are dynamic stimuli. Indeed, they tend to change often and suddenly during social interactions. Therefore, being able to detect these changes and keep track of the previously encountered ones is crucial to properly understand and react to the social environment. Therefore, it is not surprising that the working memory updating function is involved in many social tasks, but despite having been widely studied in more abstract and conceptual contexts, its role in social functions still needs more research.

Only a limited number of studies have examined how the combination of facial expression and gaze direction is updated in working memory, either using sequences of faces with different identities (Artuso, Palladino, & Ricciardelli, 2012) or with repeated presentations of the same identity (Artuso, Palladino, & Ricciardelli, 2015). Therefore, the present study aimed to investigate the mechanisms of facial emotion information processing in working memory. More specifically, whether and how the type of emotion expressed by a face affects performance in maintaining and updating information in working memory. In addition, it was investigated whether the sex of participants influences performance.

Emotions: Definitions, functions, and expression in social contexts

Emotions can be described as intense, temporary affective states. In many social contexts, it is necessary to make other individuals aware of one's emotional state. In humans, emotions are predominantly conveyed through facial expressions, which serve as channels for the transmission of social information (Darwin, 1998; Langfeld, 1918; Ekman, 1992). Emotions are characterized by brief temporal duration and involve coordinated modifications in both motor output and cognitive processes (James, 1884; Hess & Thibault, 2009). Typically elicited by salient environmental stimuli, they are central to the regulation of behavior and the facilitation of adaptive interactions with the environment.

The Basic Emotions Theory, as advanced by Ekman (1992), posits the existence of a limited set of biologically rooted and evolutionarily selected and conserved emotions (happiness, sadness, anger, fear, surprise, and disgust), each associated with distinct, universally recognizable facial expressions. These emotions are considered the basic elements of affective experience, with cross-cultural consistency in emotional expression and perception. In addition to this categorical distinction, the theory integrates a dimensional perspective, wherein emotions are situated along continuous axes such as valence (i.e., positive vs. negative), arousal (i.e., high vs. low physiological activation), and intensity (Ekman, 1992; Russell, 1980; Lang, 1995). Emotions can also be differentiated based on duration, complexity, expressiveness, and subjective experience. From a functional standpoint, they are commonly classified into negative and positive. Negative emotions, such as anger, fear, or disgust, typically arise in response to aversive stimuli or perceived threats. In contrast, positive emotions, such as happiness, gratitude, or pride, are generally elicited by reward, achievement, and social connection. Both categories of emotion play critical roles in shaping cognition and behavior, functioning as internal signaling mechanisms that support decision-making, facilitate social communication, and contribute to psychological well-being (Ekman, 1993; Izard, 1994).

Emotional experience is accompanied by physiological markers like galvanic skin response, respiration and heart rate variability, and muscle activity and by behavioral changes like facial expressions, paralinguistic vocal characteristics and postural changes (Banse & Scherer, 1996; Barrett et al., 2011; DePaulo & Friedman, 1998; Ekman, 1993; Ekman & Rosenberg, 2005). These indicators often function as observable cues that convey emotional states to others, regardless of the individual's communicative intent. Within social contexts, emotional expressions are frequently interpreted as communicative acts, and such interpretations can play a pivotal role in modulating behavior in dynamic environments. In fact, emotions are widely

recognized to have fundamental evolutionary, social, and psychological functions, since they produce coordinated psychological and physiological response patterns that facilitate adaptive behavior in response to environmental demands (Frijda, 1986; Cosmides & Tooby, 2000; Brosh et al., 2013). From a social-functional standpoint, in fact, they promote adaptive behaviors such as avoiding danger or seeking social support. Emotional expression is also shaped by developmental and cultural influences, evolving across the lifespan in response to social reinforcement and experience (Dollard & Miller, 1950).

Appraisal theories of emotion suggest that behavioral responses, such as those associated with fight-or-flight reactions, do not have a unique emotional valence. Instead, their valence is influenced by the perceived relevance of emotional stimuli to the individual's personal goals and concerns (Mancini et al., 2020). In contrast, categorical models grounded in discrete emotion theory posit that emotions are biologically based and expressed through innate, universally recognizable patterns (Izard, 1994). According to this view, specific environmental events elicit prototypical physiological and behavioral responses that are reliably associated with particular emotional states across different cultures.

Certainly, the ability to accurately recognize and interpret emotional expressions is critical for social functioning, as it enables appropriate responses to the affective states of others and guides social behavior. Some facial expressions, for example, can evoke empathic and compassionate responses, thereby promoting social connection and prosocial behavior (Singer & Lamm, 2009). Emotional contagion, a process by which observers involuntarily adopt the emotional states of others, further contributes to shared affective experiences and modulates social dynamics (Hatfield et al., 1993; Adelhöfer et al., 2019). However, some facial expressions can elicit different types of responses. Negative facial expressions have been shown to diminish trust and cooperation, likely due to their role in signaling threat or interpersonal conflict (Dong et al, 2018).

Negative facial expressions: fear and anger

Among the emotions that can be expressed by faces, fear and anger are central to the detection and avoidance of potential threats, serving critical functions in both individual survival and adaptive behavior (Marsh et al., 2005). These emotions carry relevant information about environmental dangers, allowing individuals to anticipate potential threats and, therefore, adjust their behavior (Gonzalez-Garrido et al., 2013). Negative facial expressions are particularly salient, as they rapidly capture attention and modulate decision-making processes related to approach-avoidance behavior (Marsh et al., 2005). Rapid identification of emotional expressions, in fact, enables the assessment of both immediate threats and social context, promoting adaptive behavioral responses. Evolutionary models suggest that attentional mechanisms are biased toward emotionally salient stimuli, thereby enhancing preparedness to respond to threats signaled through social cues. Fear and anger are considered particularly salient due to their prominent roles in communicative signaling and survival (Darwin, 1998; Hampson et al., 2006).

Evidence from developmental research further supports the early emergence of sensitivity to threat-related emotional cues. Arterberry and Bornstein (2023) reported that five-month-old infants exhibit preferential attention toward novel fearful facial expressions compared to familiar static happy faces, indicating an early-developing capacity for emotional discrimination. This heightened attentional bias toward fear-related stimuli is consistent with findings that fearful expressions enhance vigilance and promote environmental scanning (Dennis & Chen, 2007; Beauregard et al., 2001). Peltola et al. (2008) demonstrated that fearful faces modulate gaze duration and disengagement patterns in seven-month-old infants, underscoring their influence on attentional control mechanisms. Neurophysiological evidence indicates that fearful expressions are detected within 150–200ms after presentation (Kiss & Eimer, 2008) and can be rapidly categorized even under peripheral presentation (Rigoulot et al., 2011). Moreover, fearful faces have been shown to facilitate spatial attention shifts, especially when gaze direction matches with a potential threat location (Adams et al,

2003; Carlson & Reinke, 2010). Ellena et al. (2021) extended this effect to peripersonal space, revealing that fear-related stimuli have a greater impact on spatial processing when presented in near space. Jiang et al. (2018) showed that subliminally presented fearful expressions influence attentional resource distribution, as evidenced by modulations in steady-state visual evoked potentials. Together, these findings highlight the salience of fearful facial expressions on attentional mechanisms and spatial perception.

Working memory for emotional faces

Evidence on the importance of maintaining facial information for driving social behavior, such as judgment formation and social perception, has long been present in the literature (e.g., Hastie et al., 1980; Srull & Wyer, 1989). More recently, the role of working memory in social cognition gained popularity, and a growing body of research began investigating the capacity to maintain and manipulate social information, such as other people's beliefs and mental states (Meyer et al., 2012). The so-called social working memory, then, became a central element in social cognition, since it allows navigation in our social environment (Spreng, 2013). In fact, in a social environment, one needs to maintain, retrieve, and update information about others in order to be engaged in a social interaction in which the actors might not be consistent over time.

Facial information is spread along different dimensions, such as emotion expressed, gaze direction, and identity. All these dimensions must be taken into account in working memory when social information is maintained or manipulated. Pehlivanoglu and colleagues (2014) demonstrated that, while facial identity extraction occurs automatically, recognizing emotional expressions is cognitively demanding and requires additional processing time. Moreover, evidence from Vermeulen and colleagues (2014) suggests the existence of emotion-specific cognitive resources distinct from those used for processing identity-related information. Therefore, being a particularly dynamic category of stimuli, faces require both their invariant (e.g., eye color) and changeable (e.g., expression) features to be processed (Haxby, Hoffman, & Gobbini, 2000).

The effect of emotional facial expressions on behavior has been explored by numerous studies (Tyng et al., 2017; Adams et al., 2006; Stins et al., 2011). Appraisal theories of emotion (e.g., Mumenthaler & Sander, 2012) highlight how the combination of gaze direction and facial expression conveys to the perceiver the degree of self-relevance of the observed face. For example, from an evolutionary perspective, the self-relevance of a fearful expression increases when the gaze is averted, as this signals a potential threat located in the surrounding environment. In contrast, an angry face with direct gaze is perceived as more personally relevant, since the gaze orientation suggests a threat directed at the observer. Thus, the appraisal of facial expressions not only serves emotional evaluation but also provides crucial social information that must be processed and integrated into subsequent behavioral responses.

It emerged that, in general, positive emotional states are associated with approach behavior and increased risk-taking, whereas fear and anger are typically linked to avoidance responses (Seidel et al., 2010). Nonetheless, in some cases, faces that express fear can also promote approach tendencies, particularly when linked to affiliative motivations or perceptual cues that resemble infant-like facial features (Marsh et al., 2005; Hammer & Marsh, 2015). Behavioral responses appear highly sensitive to the surrounding emotional context. Both fear and anger are more likely to elicit avoidance when contrasted with positive expressions (Paulus & Wentura, 2016). Fearful facial expressions have also been shown to modulate motor control, enhancing motor inhibition and leading to increased reaction times and error rates in tasks requiring rapid responses (Mancini et al, 2020; Mirabella, 2018).

Artuso and colleagues (2012) presented participants with sequences of faces depicting different identities, in which facial expressions and gaze direction were combined in line with predictions from appraisal theories. They found that updating was faster—reflected in shorter response times—when facial features were arranged in highly salient configurations, such as an angry face with direct gaze or a fearful face with averted

gaze. In a subsequent study, Artuso et al. (2015) replicated these findings using sequences of faces sharing the same identity, further supporting the role of emotion–gaze congruency in working memory updating.

Emotional information is known to have mixed effects on working memory performance. While some studies report facilitating effects (Erk et al., 2007; Levens & Phelps, 2008; Lindström & Bohlin, 2011; Exp. 1, Pessoa et al., 2012), others observed an impairment (Kensinger & Corkin, 2003; Gotoh, 2008; Lindström & Bohlin, 2012; Exp. 2, Pessoa et al., 2012; Kopf et al., 2013), especially when task-irrelevant emotions were involved (Dolcos & McCarthy, 2006; Hart et al., 2012; Dolcos et al., 2013; Iordan et al., 2013). Pessoa (2009, 2015, 2017) provided evidence that emotion can have both enhancing and interfering effects on executive functions, depending on whether emotion is task-relevant or not. According to the dual competition model proposed by the author (Pessoa, 2009), when emotion is task-relevant, executive functions are improved through the recruitment of specific resources devoted to processing social information, but if the emotion is task-irrelevant, these additional resources are just subtracted from the current task. In line with this model, Berger and colleagues (2017) found that, when emotions are task-relevant, emotional faces are updated faster than neutral ones under low cognitive load conditions.

Other contrasting evidence of the effect of emotional information on working memory come from the positivity bias (Carstensen et al., 1999), a bias that leads older adults to focus on positive information rather than on negative one if limited time is available, and the results reported by Allard and Isaacowitz (2008) on how processing positive emotional material does not require full attention, suggest that faces with positive expressions are processed faster and more accurately. On the other hand, Mather and Knight (2005) provided evidence that older adults tend to remember more negative than positive images in the presence of a distractor task. In addition, they show an attentional preference for negative images compared to positive ones (Knight et al., 2007). Kensinger and Corkin (2003) demonstrated that negative emotional expressions (e.g., an angry face) are more effectively retained in memory than positive ones (e.g., a happy face).

Emotional faces, in contrast to neutral ones, have been shown to produce significant effects on visual working memory and cognitive processes costs (Curby et al., 2019). An example of the interference of emotional information on the encoding and maintenance of visual information is given by emotional attentional blink, a phenomenon that occurs when a task-irrelevant, emotionally arousing stimulus temporarily captures attention, impairing detection of following stimuli for several hundred milliseconds (Most et al., 2005; McHugo et al., 2013). Angry and fearful facial expressions are particularly salient social cues from an evolutionary standpoint due to their strong association with potential threats (Fox et al., 2000). Such a greater sensitivity toward threat-related social cues can produce a narrowing in attentional focus, impairing other cognitive functions such as spatial awareness and working memory processes (Ishikawa et al., 2021). In fact, empirical evidence suggests that emotional stimuli, in particular fearful facial expressions, can impair working memory performance, especially when the emotional content is irrelevant to the task (Dolcos & McCarthy, 2006). Neurocognitive models propose that the perception of fearful expressions engages neural mechanisms involved in threat detection and arousal regulation, resulting in an increased state of vigilance. This high-arousal state may divert cognitive resources from task-relevant processes, thereby interfering with the encoding and retrieval of visuospatial information (Pessoa et al., 2002).

Also angry facial expressions can interact with visuospatial working memory and many related cognitive processes (Fox et al., 2000; Pessoa et al., 2002). Evidence from visual search paradigms demonstrates that angry faces are detected more rapidly and accurately compared to other emotional expressions (Hansen & Hansen, 1988). Given their salience, angry faces may interrupt ongoing visuospatial processing by reallocating cognitive resources toward the evaluation of potential threats (Fox et al., 2000). This interference reflects the cognitive load imposed by processing angry expressions, which decreases the resources available for maintaining visuospatial representations (Dolcos & McCarthy, 2006). Moreover, the negative affective state elicited by angry faces may lead to an additional interference effect in visuospatial working memory tasks, further impairing the manipulation and retention of information (Vuilleumier et al., 2001). Notably, Jackson and colleagues (2009) reported that a greater number of angry face identities can be maintained in visual

working memory compared to happy or neutral faces, a finding replicated by Thoma et al. (2014). This suggests a preferential allocation of cognitive resources for threatening stimuli.

Sex differences and emotions

There is plenty of evidence in the literature reporting a wide range of sex differences between men and women in processing skills. For example, it has been observed that women recall better than men the appearance of other individuals (Mast & Hall, 2006); they perform better in phonological and semantic information manipulation tasks, and they have higher scores in tasks involving episodic and semantic memory, verbal analytical working memory, verbal learning, object location memory, fine motor skills, and perceptual speed. On the other hand, men have better performance in visuospatial working memory tasks, positional reconstruction, fluid reasoning, and spatiotemporal analysis (Duff & Hampson, 2001; Halpern, 1997; Kramer, Delis, Kaplan, O'Donnell, & Prifitera, 1997; Lejbak, Vrbancic, & Crossley, 2009; Maitland, Herlitz, Nyberg, Bäckman, & Nilsson, 2004; Postma, Winkel, Tuiten, & van Honk, 1999; Ramos-Loyo & Sánchez-Loyo, 2011; Voyer, Postma, Brake, & Imperato-McGinley, 2007). As already said, there is evidence supporting the idea that some combinations of facial expression-gaze direction (i.e., a scared face with a diverted gaze) may enhance attention toward the stimulus due to its salience (Pecchinenda, Pes, Ferlazzo, & Zoccolotti, 2008). Weirich and colleagues (2011) suggested that, in such cases, women are generally better than men at recognizing faces if the stimuli are presented for longer periods. In a self-report questionnaire, Baggini and colleagues (2025) observed a significant difference between men and women in the reported intensity of emotions expressed by faces, with women reporting higher levels of intensity compared to men.

Men and women also differ at a neurophysiological level. Literature provides much evidence of sex related brain anatomical differences. For example, men have a significantly larger left planum temporale area compared to the right one, while in women, such a difference is not significant (Kulynych, Vladar, Jones, & Weinberger, 1994). Another sex related difference in brain physiology is the dimensions of the corpus callosum, in which men present a bigger genu, while women present a larger splenium (Dubb, Gur, Avants, & Gee, 2003). Hippocampal dimensions also vary between men and women (Maller, Réglade-Meslin, Anstey, & Sachdev, 2006). Many studies also reported functional sex-based differences in brain activation patterns during cognitive tasks (Bell, Willson, Wilman, Dave, & Silverstone, 2006; Grabner, Fink, Stipacek, Neuper, & Neubauer, 2004), even though these differences are not directly related to performance. An exception is represented by visuospatial working memory tasks, where sex related differences seem to be present in both behavioral performances, usually better in males, and brain activation patterns (Schöning et al., 2007). In an fMRI study on the effect of stereotypes on spatial reasoning tasks, Wraga and colleagues (2007) found that women are sensitive to stereotyped messages, which can affect cognitive strategies, with positive messages inducing different brain activation patterns and more efficient strategies than negative ones. Koch and colleagues (2007) studied the effect of negative emotions induced through olfactory stimulation on neural activation patterns in men and women during a working memory task. The results revealed a substantial sex-based difference in activated brain areas. While in men an extended activation was observed in the prefrontal and superior parietal regions, in women the strongest activations were observed in the amygdala and the orbitofrontal cortex. All this evidence suggests that different sex-specific neural mechanisms are engaged when combining emotional and cognitive processes.

González-Garrido and colleagues (2013) investigated the sex related differences in visuospatial working memory tasks involving happy, fearful, and neutral faces. The authors observed that cognitive load negatively affected performance for both, but men's performance was significantly better than women's, especially in high cognitive load conditions. This result supports the idea that sex related differences in visuospatial working memory tasks involve a difference in cognitive strategies and neural processes. On the other hand, Mohamed Aly and colleagues (not submitted yet) reported an advantage for men in spatial navigation tasks, but they observed that this advantage disappeared when participants were exposed to fearful faces,

producing a decrease in men's performance and an increase in women's, suggesting that emotive context, especially a negative one, interacts with sex, affecting working memory and spatial navigation.

The present study

This exploratory study had two main objectives. The first was to investigate the role of sex in maintaining and updating emotional information in working memory, in order to find whether there is a difference in performance between men and women. Based on the literature, we likely expect a difference in performance between men and women, although we cannot predict the direction of the effect. The second objective was to investigate whether different types of emotions expressed by emotional stimuli affect the ability to maintain and update emotional information. To observe the effect of our independent variables on the maintenance and updating of emotional information, we used an n-back task, a widely used paradigm to study working memory processes, especially updating. In this study, we considered only three emotions: happiness, fear, and anger. This allowed us to compare emotions with different valences (positive for happiness, and negative for fear and anger). To further explore these effects, cognitive load was also manipulated to explore the response patterns at different levels of the task's cognitive demands.

Methods

In this study, we used an n-back task, a widely used paradigm in working memory studies, to test our participants, who had to maintain and update information held in working memory. The n-back task consists of a series of stimuli presented one at a time, and participants must decide whether the currently presented stimulus is the same as or different from the one presented n positions before. In a 1-back task, participants must compare the current stimulus with the previous one, in a 2-back task with the stimulus presented two positions before, and so on. The stimuli used can be of various natures (words, numbers, tones…). In our study, stimuli were pictures of human faces expressing different emotions.

Participants

An a priori power analysis was conducted with the software More Power 6.0.4 to determine the minimum sample size required in order to achieve a power of .8, with an $\alpha = .05$; the minimum sample size required was 56.

Unfortunately, due to time restrictions, data collection has not been completed yet. A total of 35 participants (20 men, 15 women) voluntarily took part in this study. All participants had normal or corrected-to-normal vision, and none of them had neurological or learning diseases. All participants consented to data treatment and received university credits as a reward for their participation.

The study was considered minimal risk (as defined by the National Research Council of the Academies of Science and, as such, was approved by the Committee for Research Evaluation of the Psychology Department of the University of Milano-Bicocca (protocol number N. RM-2025-954) and was conducted in accordance with the Helsinki treaty.

Materials and stimuli

The stimuli used in the experiment were images taken from the Radboud Faces Database (Langner et al., 2010) of different people expressing three different emotions (happiness, anger, and fear). In a previous study (Baggini et al., 2025), the same set of stimuli was tested to confirm that all the emotions expressed were perceived correctly and with sufficient intensity. All the stimuli were presented one at a time on a light grey background. The task was presented on a 17-inch Hewlett-Packard monitor operated by an MSI laptop mounting an Intel i7 processor. The screen was adjusted to approximately 60cm from the participants, and it was administered in a quiet room with controlled artificial light. The stimuli occupied a visual angle of approximately 8 degrees. To avoid any potential distraction, participants were asked to turn off or silence all their electronic devices. The whole task was programmed and presented in MATLAB (2023) using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997; Kleiner et al, 2007).

Procedure

In our experimental paradigm, the independent variables considered were the feature of the face (identity, emotion, or both) requested to match in the n-back task, the cognitive load (high, medium, or low), and the participant's sex. In the "identity" condition, participants were asked to consider only the identity of the faces, regardless of the emotion expressed. In the "emotion" condition, they were asked to focus only on the emotion expressed, regardless of the identity. Finally, in the "both" condition, information about identity and emotion expressed had to be taken into consideration. The experiment was conceived as a 3x3 within-subjects design, with an additional between-subjects factor given by the sex of the participant.

The cognitive load was manipulated by changing the n of the task (i.e., the number of previous stimuli in the sequence to be maintained in memory to perform the task). In the low cognitive load, each stimulus was compared to the previous presented stimulus (n = 1). In the medium cognitive load, the stimulus was compared to the stimulus presented two steps before (n = 2). Finally, in the high cognitive load condition, the stimulus was compared to the stimulus presented three steps before (n = 3). For each face presented, participants gave their response by pressing one of two keys on a keyboard as soon as the stimulus appeared on the screen. Upon response, the next stimulus was presented (Figure 4.4).

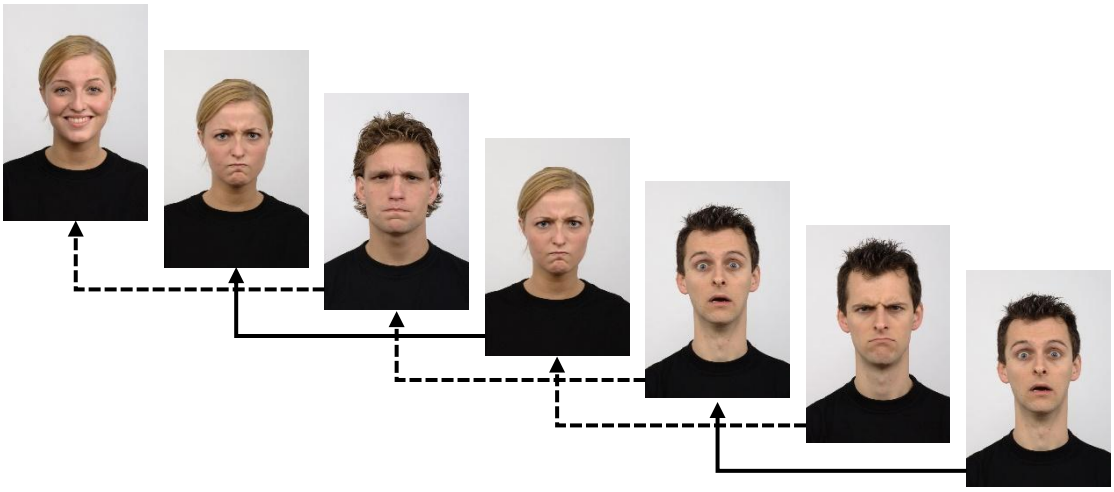

Figure 4.4. Example of the sequence of stimuli presented during the task. Stimuli were presented one at a time, and as soon as a stimulus appeared, participants had to press a key to give a response and trigger the presentation of the next stimulus. In this example, a 2-back task in the "both" condition is depicted. Arrows represent what each stimulus had to

be compared to. Plain arrows represent a match, while dashed arrows represent a mismatch. Note that the figure depicts only a section of the task, which included a sequence of 50 stimuli.

The experimental session began with a brief introduction to the participants about the general context of the study and the task they were going to perform. After that, the task instructions were presented on the computer screen, and participants familiarized themselves with the task through a brief practice phase of a few trials in different conditions. Once the practice was completed, participants began the task. The entire experiment took approximately 15 minutes.

Participants performed each of the nine (3x3) experimental conditions. Each condition was composed of 50 trials (each stimulus presented, and the response given was considered as a single trial). Conditions were presented in a random order, but at the beginning of each condition, a message on the screen instructed participants about the change of the condition, and informed them about the new n (1, 2, or 3-back) and the feature (emotion, identity, or both) to be taken into account to perform the task. Participants were instructed to answer as fast and accurately as possible, since both accuracy and response time were recorded. The response was given by pressing a button on the keyboard. The key Z was for "same" and M for "different". The first n trials on each condition did not have any stimulus to compare to. Therefore, they were not included in the analyses.

Results

An analysis of variance was used to assess the effect of participants' sex, the feature of the stimulus to remember (identity, emotion, or both), and the cognitive load (1, 2, or 3-back) on their accuracy. All three factors resulted to have a significant main effect on performance (participants' sex: $F(1, 309) = 4.64, p = .032, \eta^2p = .015;$ feature to maintain: $F(2, 309) = 10, p < .001, \eta^2p = .061;$ cognitive load: $F(2, 309) = 19.14, p < .001, \eta^2p = .11$), but no significant effect resulted from their interactions. A post-hoc Bonferroni correction resulted in a significant difference between the "emotion" and the other two conditions (emotion vs identity: $t(309) = -3.347, p = .003, d = -.46$; emotion vs both: $t(309) = -4.241, p < .001, d = -.58$), but no significant difference emerged between the "identity" and "both" conditions. From a second post-hoc analysis corrected per Bonferroni, it emerged that the difference between the cognitive load conditions is only significant between the lowest (1-back) and the two other conditions (1-back vs 2-back: $t(309) = 3.82, p < .001, d = .52$; 1-back vs 3-back: $t(309) = 6.13, p < .001, d = .84$), but no significant difference emerged between the 2 and 3-back conditions (Figure 4.5).

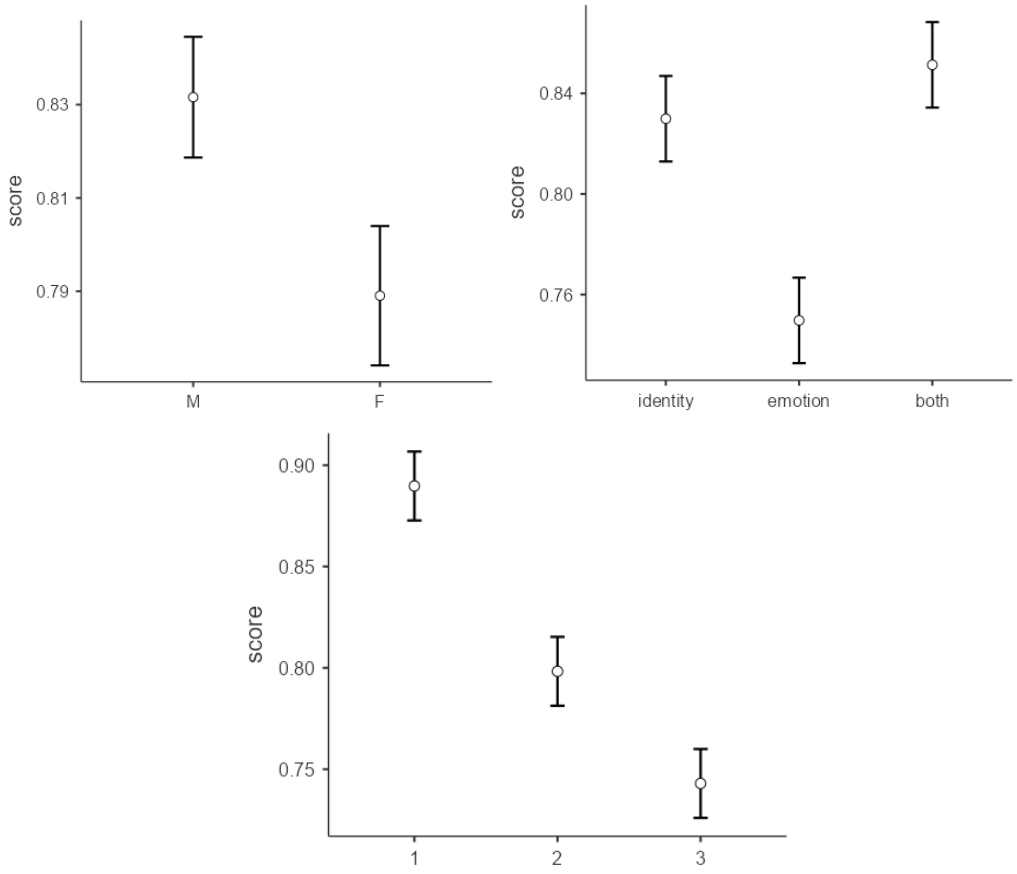

Figure 4.5. The plots report the difference expressed in accuracy in performance between men and women (top left), between the three different emotions (top right), and between the three levels of cognitive load. Bars represent the standard error.

Another analysis of variance was used to assess the effect of the same three factors on participants' response time. A significant effect of sex ($F(1, 309) = 8.59$, $p = .004$, $\eta^2p = .027$) and cognitive load ($F(2, 309) = 17.78$, $p < .001$, $\eta^2p = .103$) emerged, but no effect of the feature to remember or any interaction between the factors was observed. A Bonferroni post-hoc correction revealed a significant difference in reaction times between the 1-back and the other two conditions (1-back vs 2-back: $t(309) = -5.267$, $p < .001$, $d = -.72$; 1-back vs 3-back: $t(309) = -5.056$, $p < .001$, $d = -.69$), but no difference was observed between 2 and 3-back conditions (Figure 4.6).

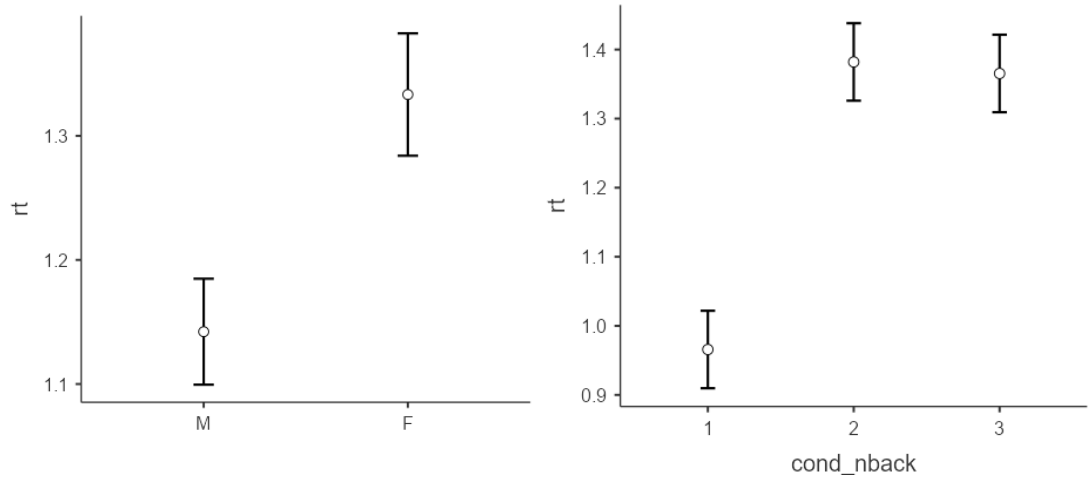

Figure 4.6. Plots represent the average response times expressed in seconds for men and women separately (left), and for the three cognitive load conditions (right).

A generalized linear model was used to explore the effect of age on accuracy and response times, and the effect of response time on accuracy. While no significant effect of age was observed on accuracy or response times, a significant effect of response time on accuracy emerged ($X^2(1) = 17.9$; $p < .001$; $\eta^2 = 1.6$) (Figure 4.7).

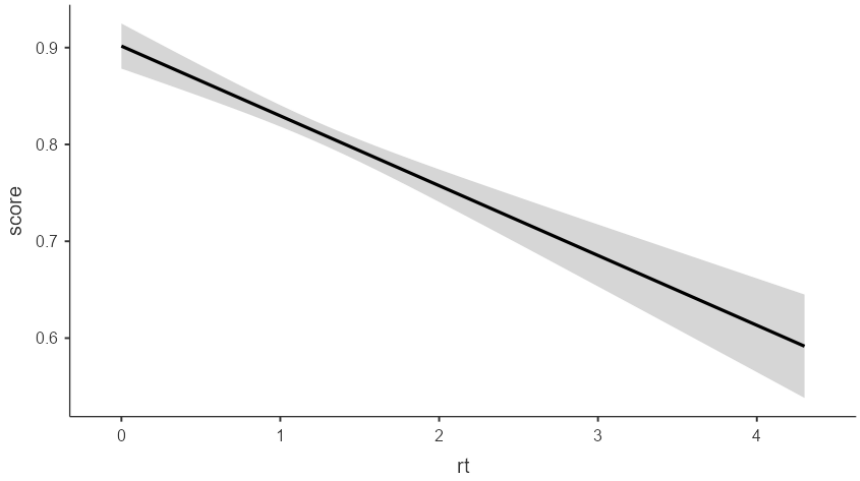

Figure 4.7. Relationship between response time and accuracy. Higher response times are associated with lower accuracy.

Accuracy and response times were then analyzed separately for each emotion expressed by stimuli. To do so, we considered all the trials in which a certain emotion appeared n stimuli before, where n depended on the cognitive load condition, and, therefore, had to be maintained until and recalled in that trial. An analysis of variance resulted in no significant difference in accuracy or response times between the three emotions.

Discussion

In this study, we investigated the processing of faces and emotive expressions in working memory. Our aim was to explore the possible effect of participants' sex on their ability to maintain and update emotional information and to investigate whether different types of emotion perceived influence performance in maintaining and updating such information in working memory. To do so, we tested 35 participants with an n-back task, a task that specifically involves information updating in working memory. The stimuli used in our task were faces of different people displaying three different emotions (happiness, fear, and anger). Participants performed three different conditions for the task, each at a different level of cognitive load. In one condition, they had to remember only the identity of the faces they saw, in another condition, only the emotion expressed, and in the third condition, both these elements. For each of these conditions, a 1, 2, and 3-back task was performed. We decided to include three cognitive load levels in the paradigm in order to gather some additional information on the results trend through different levels of cognitive demands.

From the analyses, a significant difference emerged in performance for both accuracy and response time, given by the sex of the participant, with men performing more accurately than women, and with lower reaction times. These effects do not seem to interact with any other variable taken into consideration in this study.

Concerning the difference in performance for maintaining and updating different emotions, results showed no significant difference between the three emotions considered in this study in both accuracy and response times.

An interesting finding that emerged from the results is the significant difference in accuracy between the three conditions regarding the feature of the face to remember (identity, emotion, or both). Although no difference was observed between the "identity" and the "both" conditions, the accuracy in the "emotion" condition was significantly lower than the others. This result suggests that emotive information is more difficult to maintain in working memory if it's not bound to some other face characteristics. Possibly, the mutable nature of facial expressions makes this kind of information harder to preserve when it lacks some of the immutable features of the face. Expressing an emotion through faces, in fact, is an action, and, by definition, an action requires a subject that performs it in order to exist. A possible interpretation of this result is that an abstract idea of a facial expression, such as the generic concept of smiling, might be maintained less efficiently than an actual face smiling by visuo-spatial cognitive mechanisms. Interestingly, the absence of a significant difference between the "identity" and the "both" conditions suggests that when emotive information is bound to an identity, maintaining such information does not significantly increase the cognitive demands compared to maintaining only the information about identity. From an evolutionary perspective, this evidence can be interpreted as an optimization of a cognitive process necessary during social interactions with other individuals. In fact, during an interaction such as a conversation, it is fundamental to keep track of the other person's intentions and emotions that are communicated through facial expressions, and it is equally important to quickly update our knowledge and behavior based on the other person's reactions. Since in this type of scenario emotional information is often communicated through facial expressions that are depicted on the face of the interlocutor, it is not difficult to imagine that the identity-related features of the face are integrated with the social information of the expression to enhance this process. On the other hand, a situation in which someone must interact with an agent that expresses emotions through facial expressions but lacks a facial identity is not particularly common; hence, this type of update has never needed to be improved or optimized.

Not surprisingly, cognitive load proved to have an effect on performance. In fact, accuracy decreased across conditions as the cognitive load increased. What is more interesting to note is how it affected response times. A significant increase in response times was observed between the 1 and 2-back conditions, but no difference was observed between the 2 and 3-back conditions. This suggests the presence of a ceiling effect in response times under time constraints; in fact, all participants were instructed to perform the task as fast as they could.

Obviously, response times can grow to virtually no limit; hence, in this experiment, the ceiling might have been created artificially by participants by simply having the perception of taking too long to complete the trial after a certain temporal threshold.

Finally, it emerged that response times are negatively correlated with accuracy, meaning that higher response times correspond to lower accuracy. This result finds a place in the ongoing debate about how information in working memory decays. Some authors gathered evidence showing that information in working memory decays as a function of time (for example, Barrouillet et al., 2004; McKeown & Mercer, 2012; Ricker & Cowan, 2010; Zhang & Luck, 2009), while others sustain the hypothesis that information decay is due to interference from other subsequent information (for example, Brown & Lewandowsky, 2010; Lewandowsky et al., 2009). Since this effect did not seem to interact with the cognitive load condition (i.e., the number of faces seen between the presentation and the recall of the target), this result can be interpreted as evidence that the decay of information in working memory occurs because of time rather than interference, and might play an important role in future research on the topic.

Conclusion

In this study, we provided evidence of sex-based differences in performance for maintaining emotive information in working memory. We also observed a significantly lower performance in maintaining information about emotion when such information is not bound to identity, compared to identity and emotion bound together or identity only. In addition, we provided useful evidence in support of the time-related decay of information in working memory that does not support the hypothesis of interference-related decay.

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Chapter 5: Conclusion

In this dissertation, a series of original studies on different working memory processes was presented. The general aim of these studies was to contribute to the literature through the addition of new evidence and observations, and by providing some useful insight for future research on information processing in the human cognitive system. The topic has been widely studied, but the knowledge accumulated so far represents just the tip of an iceberg, and many findings must be made before fully comprehending the subject. The studies presented in this dissertation focused on working memory, a specific component of the cognitive system devoted to many complex cognitive tasks, such as encoding, manipulating, and updating information.

Summary of the studies presented

In Chapter 2, a study on the relationship between working memory and long-term memory was presented. The study aimed to investigate the role that cognitive load has on the process of storing information in the long term. It was based on the assumption that information, in order to be stored in long-term memory, must first be encoded and processed by working memory. The Time-Based Resource Sharing model of working memory was used as a theoretical frame for the study. In this model, information must be actively maintained in working memory using a limited source of attentional resources that must be shared with other ongoing processes. The experimental hypothesis of this study was that the information maintenance process also acts as an information transfer process, during which information is gradually moved to long-term storage. This means that the more a piece of information undergoes the maintenance process loop, the fewer cognitive resources will be needed to actively maintain it. Two experiments were conducted to test this hypothesis. In both experiments, participants were tested with a reading digit span task with a delayed response. The task consisted of a series of characters to be read, but only some of those characters had to be maintained in memory until the end of the trial for recall. The response was delayed by an n-back task, a working memory task that requires participants to constantly maintain and update new information. The overload of the working memory system caused by the n-back task had the purpose of redirecting as many cognitive resources as possible from maintaining the relevant information for the reading digit span task, heavily disrupting the memory traces relevant to the reading digit span task. Two different conditions were presented to participants. In the control condition, the series presented in the reading digit span task were always randomly generated. In the experimental condition, on the other hand, only the targets to remember were randomly created for each trial, while all the other irrelevant stimuli remained the same across trials. Nothing changed in the n-back delay task between the two conditions, where all the stimuli were randomly generated at each trial. Maintaining the same set of irrelevant stimuli in the experimental condition served the purpose of decreasing cognitive load across trials by taking advantage of the Hebb repetition learning effect, according to which already encountered information is better maintained in memory compared to novel information due to its gradual shift toward long-term storage. This means that, in the experimental condition, fewer cognitive resources were needed to perform the reading digit span task, leaving more resources for the maintenance process of relevant information. According to the study hypothesis, this greater number of available resources would have improved the maintenance process and, therefore, the transfer of information to long-term memory. This effect should have been reflected in an increase in performance in the late trials of the experimental condition, where the cognitive load was lower. The n-back task ensured that the reading digit span task-relevant information recalled at the end of the trials was not maintained in working memory, since it was occupied with another demanding task.

The two experiments conducted in the study, involved the same experimental paradigm except for the design (between-subjects in the first experiment and within-subjects in the second), the length of the reading digit span task series to remember in each trial (four for the first experiment and six for the second), and the number of single repeated series in the reading digit span task (four in the first experiment and one in the second), leading to a difference in the overall cognitive load variations.

A clear primacy effect for the order of presentation of characters was found in both experiments, reflecting the transfer of information from working memory to long-term memory. In the first experiment, an improvement in remembering the order of the elements presented was observed with the decrease in cognitive load, consistent with the hypothesis that the transfer of information to long-term memory occurs during the maintenance process and involves cognitive load. However, no improvement in the recall of the total number of elements emerged, suggesting that different mechanisms and factors are at play in the process of information transfer. Although these findings were not completely consistent between the two experiments, the observed difference in performance between maintaining the items of a series and their order led to the design of the experiment presented in Chapter 3.

The study presented in Chapter 3 aimed to better investigate the cognitive mechanisms involved in the maintenance of serial information, with the focus on the processes underlying the retention of item identity, serial position, and the interaction between these two processes. The main objective of the study was to determine whether the retention of item identity and that of their serial position are two distinct processes that involve different mechanisms, or if they are part of the same unique process. The task we used to answer this question was an immediate serial recall. In this task, a series of stimuli is presented to participants one at a time, and they are asked to recall the complete series at the end of the presentation. The aspect of the series to remember (only the items of the series, only their order, or both) and the cognitive load of the task (low or high) were the variables manipulated in the experimental paradigm. Cognitive load was varied by changing the length of the series presented. In the low cognitive load condition, the series had a length of three digits, while in the high cognitive load condition, they had a length of seven. To modulate the aspect of the series that participants had to maintain in memory, three conditions were created. In the “presence” condition, items were digits between 0 and 9 selected randomly at each trial but always presented in ascending order. In the “order” condition, items were digits between 1 and 3 or 7, based on the length of the series, and they were always presented in a random order. In the “both” condition, items were digits between 0 and 9, always selected and presented randomly. These three different conditions allowed us to test the retention performance of participants in maintaining these different types of information, both separately and together. In this study, our hypothesis was that, if the two types of information are encoded or maintained by two different cognitive processes, performance in the “presence” and “order” conditions should have been higher than performance in the “both” condition, since in the “both” condition two processes are performed at the same time, while in the other conditions only one is required.

The results of this study only partially confirmed our hypothesis. In fact, we observed a significantly higher performance in the “presence” condition compared to the “both” condition, which is perfectly in line with our hypothesis, but we did not find any differences between the “order” and “both” conditions. The higher performance in remembering the items of a series compared to their order or both the aspects together, supports the idea that the process of remembering the items of a series is independent from the process of remembering the order of items. This result adds to the body of evidence in the literature on the subject, supporting the hypothesis of a separation between the two processes, but further research is required to fully comprehend the dynamics of interaction between these two types of information in working memory.

Chapter 4 presented two studies on face processing. The first was a validation of a dataset of stimuli, and the second was more focused on the processing of social and emotional information in working memory. In the first study, we tested the reliability of the stimuli from a database of face images. These images depicted different individuals with different facial expressions and different gaze directions. The primary aim of the experiment was to ensure that all the emotions expressed by the stimuli (happiness, fear, and anger) were perceived coherently and consistently by different people. We presented to a group of participants an online questionnaire, in which 90 random images from the database were displayed. For each image, participants had to decide what emotion the subject in the picture was displaying and rate its intensity on a Likert scale. Results showed that emotions were correctly perceived with almost perfect accuracy, ensuring the validity of the stimuli. It emerged that fearful faces were generally reported to have a higher intensity compared to the other expressions considered in the experiment. It was also observed that a strong difference in the

reported intensity was given by the sex of the participant, with women reporting higher perceived intensity than men.

In the second study presented in Chapter 4, we investigated the processing of faces and emotive expressions in working memory. The aim of this study was to explore the possible effect of participants' sex on their ability to maintain and update emotional information and to investigate whether different types of emotion expressed by faces influence performance in maintaining and updating such information in working memory. We tested participants with an n-back task, a task in which a series of stimuli is presented in succession and, for each stimulus, participants must decide whether the currently displayed stimulus is the same or not compared to n stimuli before. The stimuli used in this experiment are the same set of faces that have been validated in the previous study, which express happiness, fear, and anger. The feature of the stimulus to remember was varied across three conditions. In one condition, they had to remember only the identity of the faces they saw, in another condition, only the emotion expressed, and in the third condition, both these elements. For each of these conditions, a 1, 2, and 3-back task was performed. We observed a significant difference in performance for both accuracy and response time, given by the sex of the participant, with men performing more accurately than women, and with lower reaction times. However, no significant difference in performance emerged between the three emotions considered in this study for both accuracy and response times. On the other hand, a significant difference was observed in accuracy between the "emotion" condition and the "identity" and "both" conditions, with the performance in the former being significantly lower than the others, suggesting that emotional information is more challenging to maintain and update when it is not bound to facial identity elements. We also observed a negative correlation between the cognitive load of the task (i.e., the length of the series to maintain in memory for the comparison) and performance. This correlation was approximately linear when considering accuracy, but a ceiling effect was reached when response times were taken into consideration. The last observation that emerged from the results was a negative correlation between response times and accuracy. This last finding, although not directly related to the aim of the study, has relevant implications for the debate on the cause of information decay in working memory. In fact, this can be interpreted as evidence in favor of the time-related decay of information, rather than interference-related decay.

The studies presented in this dissertation provided original, useful evidence for already studied topics, which can add to the already existing literature, and delivered new insights on how to face long-standing questions that still remain unanswered. All the results reported clearly highlight the complexity of the processes underlying apparently simple actions performed by our cognitive system, such as remembering a short series of numbers or a face encountered a few seconds earlier. Also, the convoluted nature of the interconnections between cognitive processes and structures was put in the spotlight, stressing the high level of methodological quality of the experiments and the solidity of the theoretical frameworks adopted, which is required to understand and describe the human cognitive system. These studies aimed at collecting evidence on some of the basic processes of working memory and testing their limitations. The cognitive processes addressed in this dissertation involved the information storage in working memory and its transfer to long-term memory, the maintenance of serial and non-serial verbal information, and the updating of social information in working memory. The evidence provided in this dissertation has been added to the scientific literature, enhancing our understanding of working memory. Hopefully, they will prove useful in refining the already existing models of working memory or the design of new ones.

Unfortunately, due to time restrictions, part of the results presented in this dissertation are based on analyses conducted on undersized samples. Data collection will be completed after the submission of this dissertation, and the relative analyses will be repeated in light of the new information acquired, to ensure the publication of all the studies collected here, and make available to other researchers all the data and the results collected. Also, new studies will be designed to explore more deeply the topics touched on here, since these results do represent an endpoint, but rather a starting point for posing many new questions.