Working Memory Relationships with Cognitive Flexibility and Planning: A Neurocognitive Perspective

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Safae Sedjari
safae.sedjari@usmba.ac.ma

Mohammed El-Mir
mohammed.elmir1@usmba.ac.ma

Department of psychology, Faculty of Letters and Human Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fes, Morocco.

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Abstract

The relationship between working memory and executive functions is widely recognized. Some authors describe working memory as the basis of cognitive functioning, suggesting that its capacity is a strong predictor of higher-level cognition. This relationship has also been explored at the neurological level in several studies using imaging techniques. However, this article will particularly focus on the neurocognitive relationship between working memory and two key executive functions: cognitive flexibility and planning. The aim is to highlight how working memory capacity influences cognitive flexibility and planning, and to emphasize that these three functions share common neural networks.

Keywords: working memory, cognitive flexibility, planning, neurocognitive perspective

Introduction

The relationship between performance in working memory (WM) tasks and high-level cognitive processes has been highlighted in a significant amount of research (e.g., Conway et al., 2005; Ger & Roebers, 2023; Redick et al., 2012; Unsworth et al., 2005). There is a close link between executive functions (EFs) and WM. The unitary model that emerged at the beginning of research on EFs proposed grouping all executive processes into a single component. This is evident in Baddeley's (1986) model, where the functions of the central executive play the same role as EFs. Similarly, in Cowan’s (1995) model, attentional focus performed an executive role in managing attentional resources. Furthermore, the unitary model of Norman and Shallice (1986) proposed that the Supervisory Attentional System governs the entire executive operation. Miyake et al. (2000), with their integrative approach, also proposed three distinct but interconnected EFs, operating through the active maintenance of goals and relevant information during executive control. Some authors describe WM as the basis of cognitive control (Kimberg et al., 1997). It has been shown that WM capacity is correlated with performance on cognitive control tasks (e.g., Conway et al., 2001; McCabe et al., 2010; Redick et al., 2011; Schelble et al., 2012; Unsworth et al., 2012; Wilhelm et al., 2013). Ackerman et al. (2005) suggest that WM capacity is a strong predictor of high-level cognition, despite the lack of consensus about the nature of the link between these two constructs. Studies have also shown that high WM capacity is correlated with effective cognitive control, including the ability to maintain and execute goals for task completion (e.g., McVay & Kane, 2012a). In the same context, a series of studies examining the relationship between WM capacity and stimulus response time found that low WM capacity is associated with very slow responses (McVay & Kane, 2012b; Unsworth et al., 2010; Unsworth et al., 2012), indicating that individuals with low WM capacity frequently fail to maintain the task goal. In their study, McCabe et al. (2010) examined the relationship between WM capacity and executive functioning using a factor-based analytical approach. They administered several tests to measure WM capacity and executive functioning to more than 200 participants aged between 18 and 90 years. The results indicated a very strong correlation between WM capacity and executive function constructs, demonstrating that they are closely related. These researchers suggest that there is an underlying common component between WM capacity and executive functioning, which they referred to as “executive attention,” following the model of Kane and colleagues (Engle & Kane, 2004; Kane & Engle, 2002; McVay & Kane, 2009). This component is essential for maintaining objectives and resolving interference during complex cognitive tasks. On the other hand, Hester and Garavan (2005) conducted a series of three experiments in which they demonstrated that an increase in WM load affects the ability to apply executive control over the elements maintained in WM. In other words, WM load makes executive control over its contents increasingly difficult, particularly with task switching and inhibitory control.

To explain the link between WM and EFs at the neuronal level, many studies using Positron Emission Tomography (PET) and Functional Magnetic Resonance Imaging (fMRI) have been conducted. The results revealed an interaction between executive processes and WM (e.g., Carpenter et al., 2000). Cognitive control and WM share a common neural substrate (Kane & Engle, 2002); the dorsolateral prefrontal cortex (dlPFC), which is known to be central in cognitive control, is also central in WM tasks. In another study of 525 cognitively normal subjects, Bailey et al. (2016) evaluated the *N-back* task of WM using fMRI to determine whether WM activation was associated with performance on executive tasks. The results revealed that activation during the *N-back* task of WM occurs in regions involved in executive functioning.

1. Concepts of Working Memory, Cognitive Flexibility, and Planning

1.1. Definition

1.1.1. Working Memory

Baddeley and Hitch (1974) defined WM as a cognitive mechanism that allows for the temporary storage and manipulation of information. In 1986, Baddeley argued that this system is specifically designed for holding and manipulating information needed to perform complex cognitive tasks, like comprehension, reasoning, and learning. However, in 2003, he redefined it as a limited cognitive structure that links perception, long-term memory, and action. Later, in 2007, Seron offered a definition that was seen as the result of decades of research, emphasizing that WM includes all the mental processes involved in retaining and manipulating information to achieve a goal.

The definitions above suggest that WM is a system that carries out two closely connected activities, enabling it to serve as an executive function:

- Active maintenance: it refers to the activity that controls the content of the information held in mind and blocks access to irrelevant information related to the task in progress. Thus, working memory is considered to have a role in resisting distraction.
- Information processing: it allows the simultaneous manipulation of information during the performance of different cognitive activities.

WM is the most widely used concept to explain the development of children in complex cognitive tasks. The capacity of this system increases both quantitatively and qualitatively during childhood (Molliere, 2013). In other words, as children grow older, their memory span expands, and they develop new strategies. Additionally, WM impacts cognitive functioning, in this sense consistent findings linked it to reading performance (El-Mir, 2017, 2020, 2022; Naciri & El-Mir, 2019), reading comprehension (Bouayad & El-Mir, 2022), and academic achievement (El-Mir, 2019). Its functioning has also been shown to decline in some neurodevelopmental disorders, such as autism (Guennach & El-Mir, 2019) and specific developmental language disorders (Kriblou & El-Mir, 2021, 2024). Research has shown that WM is one of the memory structures most affected by depression (Dahbi & El-Mir, 2020) and aging (El-Mir, 2021). It has also been proved that WM functioning is affected by emotional state (Bousbaiat & El-Mir, 2021; El-Mir, 2018). Furthermore, cognitive training improves WM capacity in children with autism spectrum disorder (Sedjari & El-Mir, 2021; Sedjari, El-Mir & Souirti, 2023), children with attention-deficit/hyperactivity disorder (Alaoui Belghiti & El-Mir, 2023), and children with dyslexia (Ammour & El-Mir, 2023). The effect of cognitive training on working memory has also been confirmed (El-Mir & Sedjari, 2022). Cognitive training is also related to improvement in working memory performance in people with schizophrenia (El-Haddadi & El-Mir, 2022).

Along these lines, Siegler (2005) suggests that the development of WM with age reflects the acquisition of new strategies and the refinement of existing ones. Furthermore, the different components of this function do not develop at the same pace, and their capacity increases linearly between the ages of 4 and 14 (Gathercole, 1999; Gathercole et al., 2004; Nevo & Breznitz, 2013).

1.1.2. Cognitive flexibility

It is a key component in executive functioning. Known as mental flexibility, task switching, or set switching, this ability allows switching between distinct actions or thoughts depending on the situation and the environment (Armbruster et al., 2012, Geurts et al., 2009; Monsell, 2003) and it is essential for adaptive behavior (Badre & Wagner, 2006). It helps to update contingencies and alternate between responses that guide behavior (Buss & Lowery, 2020; Van der Linden et al., 2000). This function involves changing tasks, focus, or rules (Monsell, 2003) and allows an individual to effectively shift focus from a prior task, adapt by establishing a new set of responses, and apply this updated approach to the current task (Dajani & Lucina, 2015). Enhanced cognitive flexibility is linked to positive outcomes across all stages of life, including improved reading skills in childhood (de Abreu et al., 2014), greater resilience to stress and adverse life events in adulthood (Genet & Siemer, 2011), increased creativity in adults (Chen et al., 2014), and a better quality of life in older age (Davis et al., 2010).

Eslinger and Grattan (1993) distinguish between two types of flexibility: reactive flexibility and spontaneous flexibility. The first refers to adjusting cognition or behavior based on situational demands. According to Slamecka (1968), there are two forms of reactive flexibility: intradimensional flexibility occurs when relevant aspects of a task remain constant, and extradimensional flexibility is involved when a conceptual change in how a task is approached. While spontaneous flexibility consists of generating diverse and new ideas in response to a single question (Zmigrode et al., 2019), it is used when the context is stable and doesn't require modulation, and it is closely tied to the concept of fluency. As indicated by Getzels and Jackson (1962), it can be categorized into two types: ideational fluency (the ability to produce many ideas) and semantic spontaneous flexibility (the ability to generate diverse and varied ideas). Semantic spontaneous flexibility is often associated with divergent thinking, which focuses on producing numerous, relevant, and varied ideas (Chapey, 1994). Cognitive flexibility abilities start emerging in early childhood and show significant increase between the ages of 7 and 9. By the age of 10, this function is mostly developed (Dick, 2014), but it continues to refine and improve during adolescence and adulthood (Anderson, 2002; Hunter & Sparrow, 2012), reaching its highest level between 21 and 30 years of age (Cepeda et al., 2001).

1.1.3. Planning

Planning is one aspect of executive functioning. It is a complex and dynamic cognitive process that involves the evaluation, formulation, and selection of a sequence of actions and thoughts aimed at achieving a goal (Hill, 2004). It requires the ability to organize and plan a series of steps to reach a specific objective (Anderson et al., 2001; Dennis, 2006), conceptualizing changes from the current situation and viewing the environment objectively, managing oneself in relation to the environment, and developing alternative strategies when necessary (Lezak et al., 2004). In other words, it is the skill that helps break down tasks into manageable steps, understand potential challenges, and predict obstacles that could affect task completion (Downing, 2015). As a form of problem-solving, planning also involves mentally executing goal-directed actions to anticipate and assess their potential outcomes (Kaller et al., 2004). Prior to action, the mental representation of the current situation must be transformed into a desired goal state by generating multiple hypothetical scenarios. In addition to these mechanisms, planning requires cognitive abilities such as recognizing goal attainment, anticipating future events related to execution, and storing representations to guide movement from the initial state to the goal (Carlin et al., 2000). Various studies have shown that planning performance increases between the ages of 3 and 14, eventually reaching adult-level efficiency (e.g., Mahone et al., 2002; Malloy-Diniz et al., 2008; Vuelta et al., 2004).

1.2. Neurobiological Bases

1.2.1. Working Memory

Due to a lack of consensus regarding the brain organization of WM, which, according to Rottschy et al. (2012), is attributed to the diversity of tasks and paradigms designed to measure the different aspects of WM, several meta-analyses have been conducted, highlighting the complex and distributed neural networks underlying working memory. Studies show that spatial information activates the superior posterior cortex, while object-related information engages the inferior temporal cortex. Verbal information, however, activates the left lateral inferior frontal cortex and premotor cortex. The superior frontal cortex is involved in tasks requiring information updating or sequence memorization, whereas the inferior prefrontal gyrus is activated during information manipulation tasks (Wager & Smith, 2003). The meta-analysis by Owen et al. (2005) identified activations in frontal and parietal regions, including the median posterior parietal cortex, the bilateral and median premotor cortex, the bilateral rostral PFC, the bilateral dorsolateral prefrontal, and the bilateral mid-ventrolateral prefrontal (vlPFC). Rottschy et al. (2012) found widespread activations in both hemispheres, particularly in the anterior insula, inferior frontal gyrus, and posterior regions like the supplementary motor cortex, intra-parietal sulcus, parietal lobule, ventral visual cortex, and cerebellar V1 lobule. Subcortical activations were also noted in the basal ganglia and thalamus, which connect to the prefrontal and temporal regions. Finally, Yaple and Arsalidou (2018) observed that WM tasks activate posterior brain regions and the right insular cortex.

1.2.2. Cognitive Flexibility

Recent neuroimaging meta-analyses on cognitive flexibility in typically developing adults have reported that task switching probably emerges from the interaction of a network involving specific regions in the frontal and parietal cortices (e.g., Kim et al., 2012; Leber et al., 2008; Niendam et al., 2012; Schmitz et al., 2006; Zühlsdorff et al., 2023). This network includes complex cortical regions such as the vlPFC, dlPFC, anterior cingulate cortex, right anterior insula, as well as the premotor cortex, inferior and superior parietal cortices, inferior temporal cortex, occipital cortex, and subcortical structures like the caudate and thalamus. Additionally, these changes are accompanied by reduced connectivity between the anterior insula, orbitofrontal cortex, and occipital cortex (Zühlsdorff et al., 2023).

1.2.3. Planning

Findings from lesion studies, pathological research, and neuroimaging studies using the *Tower of London* (*TOL*) task strongly highlight the critical role of the prefrontal cortex (PFC), particularly its dorsolateral and rostral regions, in complex problem-solving (Albert & Steinberg, 2011). Using this task, activation was detected across a widespread network of cortical regions, including the prefrontal, cingulate, premotor, parietal, and occipital cortices (Baker et al., 1996). Dagher et al. (1999) indicated that the neural regions involved in planning include the prefrontal cortex, particularly the dlPFC, as well as the anterior cingulate cortex, parietal cortex, and caudate nucleus, which are critical for coordinating complex cognitive processes such as goal setting, strategy formation, and evaluating potential outcomes during planning tasks. As for Van den Heuvel et al. (2003), planning activity was associated with activation in the frontostriatal, visuospatial, and motor systems, specifically involving dlPFC, anterior prefrontal cortex, striatum, precuneus, inferior parietal cortex, premotor cortex, and the Supplementary motor area.

2. Working Memory and Cognitive Flexibility

In Baddeley's (1986) multi-component model, one of the main functions of the central executive is the ability to switch efficiently between tasks (Vandierendonck, 2016). According to Diamond (2013), cognitive flexibility consists of updating information in WM to identify the most appropriate response to the current situation. Several theories have pointed to a strong link between WM and cognitive flexibility (Mayr & Kliegl, 2003; Meiran & Kessler, 2008; Sohn & Anderson, 2001). More specifically, research has shown that this function is closely related to verbal WM, particularly the phonological loop in Baddeley's model. On one hand, it has been shown that verbalizing task goals can improve cognitive flexibility (e.g., Goshke, 2000). On the other hand, depletion of verbal WM can lead to errors and slower processing (Saeki & Saito, 2009; Saeki et al., 2006), affecting the cost of this function (e.g., Baddeley et al., 2001; Miyake et al., 2004; Saeki & Saito, 2004). For example, Baddeley et al. (2001) observed that the cost associated with task switching increased when it was combined with a verbal task. A study by Souza et al. (2012) investigated how WM load impacts task switching. Participants were asked to memorize one to three sets of numbers and complete several tasks, including determining whether the number was greater or less than five, whether it was odd or even, or its position on a number line (inside or outside a range). The results revealed that as the WM load increased, so did the cost of switching tasks, particularly when participants were asked to remember three lists instead of just one or two. This indicates that when WM load is higher, there is a greater need for articulatory rehearsal, which increases the task switching cost, as suggested in earlier studies (Baddeley et al., 2001). Likewise, other studies have shown that increased task switching demands can impair WM performance (Liefooghe et al., 2008). Butler et al. (2011) found a notable link between WM capacity and task switching costs, with higher task-switching costs associated with lower WM capacity. However, some studies have not found a similar relationship, suggesting that WM capacity may not always be closely linked with cognitive flexibility (Draheim et al., 2016; Hambrieck & Altmann, 2015; Kane et al., 2007; Logan, 2004; Pettigrew & Martim, 2016; Unsworth & Engle, 2008). Some researchers even argue that WM should be considered a distinct construct from other executive functions, with no clear connection to task switching (Logan, 2004; Oberauer et al., 2007; Oberauer, 2009; Vandierendonck, 2016).

At the neuronal level, a meta-analysis of 193 neuroimaging studies based on the use of different measures of executive functioning (including WM and task switching) revealed that a network of frontal and parietal regions was constantly active in all areas of the EFs examined. This network included the cingulate cortex anterior, the dlPFC in the frontal lobes, and inferior and superior parietal lobes (Niendam et al., 2012). Despite the differences in modalities, many studies have shown that WM tasks systematically activate the frontoparietal network called the cognitive control network (Kondo et al., 2004; Osaka et al., 2003; Osaka et al., 2004; Owen et al., 2005; Rottschy et al., 2012; Van der Linden et al., 2007; Wager & Smith, 2003), and the performance of task switching is also associated with the activation of this network (Dajani & Uddin, 2015; Richter & Yeung, 2014; Ruge et al., 2013). Other studies on cognitive flexibility reported activation in dlPFC and vlPFC, the additional motor area, lower cingulate cortex, and upper and lower parietal cortex (Karayanidis et al., 2010). These regions are similar to those reported in the WM neuroimaging literature.

3. Working Memory and Planning

In their founding book, Plans and the Structure of Behavior (Miller et al., 1960), WM is used for the execution of plans. Nevertheless, many authors have linked WM and planning. It has been shown that people with high WM ability are significantly better at tasks traditionally used to evaluate planning (e.g. Gihooly et al., 2002; Miyake et al., 2001; Zook et al., 2004). Ohbayashi et al. (2003) reported that during movement planning, WM plays a crucial role in actively maintaining relevant information and then converting it into a movement program to achieve goals. Another study by Spiegel et al. (2012) showed that the planning phase and WM share cognitive resources, and both functions seem fundamental to organizing action. Altagassen et al. (2007) revealed that in healthy people, each of the three components of WM was linked to the task of the *TOL*. Studies have indicated that the phonological loop helps to achieve verbally generated mental plans (Altgassen et al., 2007), the visuospatial sketchpad is important in the construction and reformulation of plans (Phillips, 1999), while the central executive may be involved in monitoring the achievement of objectives and the change of focus. Episodic buffer, and despite the absence of studies on its role in planning tasks (Altagassen et al., 2007), it appears to play an important role as the *ToL* task requires the development of strategic information in long-term memory and its subsequent retrieval.

In 2014, Behmer and Fournier conducted a study of 168 participants to examine whether the ability to plan an action and maintain a plan can be influenced by the WM capacity. Participants were divided into two groups: participants with low WM capacity and others with high WM capacity. All participants were asked to briefly maintain a stimulus action plan in WM that they would execute immediately after responding to another stimulus. First, arrows pointing left or right are shown on the screen with an asterisk above or below the point of the arrow. The arrow points indicate which hand the participant should use (left or right), and the asterisk indicates the direction of movement (upper or lower key). There were four different action plans (left hand moved up, left hand moved down, right hand moved up, and right hand moved down). Participants should use the correct keyboard buttons to indicate the correct answer (the correct plan), but before answering this part of the experiment they should double-press the left key on the keyboard with their left hand if they see a green numeric symbol (#) and double-press the right key with their right hand if the symbol is red. The results of this study indicated that participants with low WM capacity did not remember the action plan from the first part of the experiment, as well as those with high WM capacity.

Anatomically, many researchers have conducted studies using fMRI, PET and mono-photon emission tomography to specify brain areas associated with planning ability (e.g., Baker et al., 1996; Dagher et al., 1999; Morris et al., 1993; Rowe et al., 2001). Although it is difficult to determine the areas involved in each cognitive process (Unterrainer & Owen, 2006), these researchers indicated that the rostrolateral and dlPFC, premotor cortex, parietal cortex, and inferior frontal gyrus are among the active zones associated with the planning task (*ToL*). These areas were also linked to WM tasks (Owen et al., 2005; Rottschy et al., 2012; Wager & Smith, 2003). Again, in a recent study, Pouladi et al. (2021) put 15 subjects under transcranial direct current stimulation to assess whether dlPFC stimulation will lead to improved WM and planning. Using the *N-back* task and the *ToL* task, these researchers showed that both functions improve after stimulation of this region, which proves that WM and planning share a common neural substrate called the dlPFC.

Discussion

The present article specifically focuses on the neurocognitive relationship between WM and two key EFs: cognitive flexibility and planning. Indeed, the relationship between WM and EFs is well-established (McCabe et al., 2010), despite the heterogeneity of results observed in the literature. This variability can be attributed to multiple factors, such as differences in participant characteristics, methodological approaches used to measure these constructs, and the inherent complexity of executive functioning. WM is considered a core component of cognitive control and a strong predictor of high-level cognition. Individuals with high WM capacity tend to achieve higher scores in complex cognitive tasks (e.g., Redick et al., 2012). Also, distinct EFs and WM are closely interrelated, sharing underlying neural substrates and activating overlapping brain regions (e.g., Anderson et al., 2001; Huizinga et al., 2006; Lehto et al., 2003; Miyake et al., 2000).

The findings regarding the close relationship between WM and other EFs can serve as a foundation for improving the efficiency of neurocognitive interventions. For instance, rather than attempting cognitive remediation for multiple impaired EFs simultaneously, it may be more effective to focus on remediating WM alone. Given the central role of its capacity in cognitive functioning, improvement of WM may have an impact on other EFs, enhancing the efficiency of interventions (Sedjari & El-Mir, 2021, Sedjari et al., 2023).

Conclusion

In sum, WM, cognitive flexibility, and planning are distinct but interrelated executive components that share underlying neural substrates, generating activation in overlapping brain regions. This conclusion supports the idea that WM could be a prime target for neurocognitive therapies, allowing an efficient and practical means to enhance not just its capacity but also other EFs that rely on it.

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