# INVESTIGATING THE EFFECTS OF MAGNITUDE-SPACE BASED NUMERICAL WORKING MEMORY LOADS ON THE SNARC EFFECT UNDER DIFFERENT NUMBER JUDGMENT TASKS

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# ETHICAL DECLARATION

I hereby declare that I am the sole author of this thesis and that I have conducted my work in accordance with academic rules and ethical behaviour at every stage from the planning of the thesis to its defence. I confirm that I have cited all ideas, information and findings that are not specific to my study, as required by the code of ethical behaviour, and that all statements not cited are my own.

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# ABSTRACT

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The Spatial-Numerical Association of Response Codes (SNARC) effect refers to the phenomenon where smaller numbers are associated with faster left-side responses and larger numbers with faster right-side responses. Previous working memory (WM) research on the SNARC effect has examined cognitive load using visuo-spatial and phonological tasks, highlighting the effect's flexibility. This dissertation investigated the effects of mental number line (MNL) compatibility (small-left/large-right vs. small-right/large-left) and magnitude-space-based cognitive loads (space, magnitude, and magnitude-space) on number judgments. Participants completed a numerical 1-back task involving three types of WM loads presented in either MNL compatible or incompatible formats. Responses to targets were made based on whether a number matched the spatial position (space load), magnitude category (magnitude load), or both (magnitude-space load) of the preceding number. After each 1-back evaluation, participants performed either a single parity judgment (odd/even) or magnitude comparison (smaller/larger than 5). The results showed that MNL compatible conditions produced a regular SNARC effect, while incompatible conditions led to a reverse SNARC. The effect was more pronounced under the space load than under the magnitude load. In parity judgment, compatible loads produced a regular SNARC effect, whereas incompatible loads showed no reverse SNARC. In contrast, the magnitude comparison task revealed a more pronounced reverse SNARC under incompatible loads. These results challenge the SNARC effect as purely automatic, emphasizing the coactivation of long-term numerical representations and WM in shaping spatial-numerical associations. Furthermore, the findings highlight the effect's sensitivity to task-specific demands, demonstrating that spatial-numerical associations can dynamically adapt to varying cognitive strategies.

Keywords: the SNARC effect, magnitude-space association, the Mental Number Line compatibility, working memory.

# ÖZET

## BÜYÜKLÜK-UZAM TEMELLİ SAYI İLİŞKİLİ ÇALIŞMA BELLEĞİ YÜKLERİNİN SNARC ETKİSİ ÜZERİNDEKİ ETKİSİNİN FARKLI SAYI DEĞERLENDİRME GÖREVLERİNDE İNCELENMESİ

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Tepki Kodlarına İlişkin Uzamsal-Sayısal Bağıntı (SNARC) etkisi, küçük sayıların daha hızlı sol tepki uzamı, büyük sayıların ise daha hızlı sağ tepki uzamıyla ilişkilendirilmesi olgusunu ifade eder. SNARC etkisi üzerine yapılan önceki çalışma belleği (ÇB) araştırmaları, görsel-uzamsal ve fonolojik görevler kullanarak bilişsel yükü incelemiş ve bu etkinin esnekliğini vurgulamıştır. Bu tezde, zihinsel sayı dizisi (the Mental Number Line, MNL) uyumluluğu (küçük-sol/büyük-sağ ve küçük-sağ/büyük-sol) ile büyüklük-uzam temelli bilişsel yüklerin (uzam, büyüklük ve büyüklük-uzam) sayı değerlendirme görevleri üzerindeki etkileri araştırılmıştır. Katılımcılar, üç tür ÇB yükü içeren sayısal 1-geri görevini, MNL uyumlu veya uyumsuz formatlarda tamamlamışlardır. Hedeflere tepkiler, bir sayının önceki sayının uzamsal konumuna (uzam yükü), büyüklük kategorisine (büyüklük yükü) veya her ikisine birden (büyüklük-uzam yükü) uyup uymamasına göre verilmiştir. Her bir 1-geri değerlendirmesinden sonra, katılımcılar her bir sayı için ya tek-çift sınıflandırması ya da büyüklük değerlendirmesi (5'ten küçük/büyük) yapmışlardır. Bulgular, MNL uyumlu yüklerin tipik bir SNARC etkisine, uyumsuz yüklerin ise ters SNARC etkisine yol açtığını göstermiştir. Bu etki, uzam yükü altında, büyüklük yüküne kıyasla daha belirgin olmuştur. Tek-çift görevinde, uyumlu yükler tipik bir SNARC etkisi oluşturmuş, ancak uyumsuz yükler altında güçlü bir ters SNARC etkisi ortaya çıkmamıştır. Buna karşılık, büyüklük değerlendirme görevinde, uyumsuz yükler sunulduğunda daha belirgin bir ters SNARC etkisi gözlenmiştir. Bu bulgular, SNARC etkisini tamamen otomatik bir süreç olduğu anlayışını sorgulamakta ve sayılara ilişkin uzun-süreli temsiller ile ÇB etkilerinin bir arada var olabileceğini öne sürmektedir. Ayrıca, bu sonuçlar, sayı-uzam ilişkilerinin görev taleplerine ve bilişsel stratejilere göre dinamik olarak şekillendirilebileceğini vurgulamaktadır.

Anahtar Kelimeler: SNARC etkisi, büyüklük-uzam ilişkisi, zihinsel sayı dizisi uyumluluğu, çalışma belleği.

Dedicated to all the women who are not believed to be capable of accomplishment.

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# CHAPTER 1: INTRODUCTION-NUMERICAL MAGNITUDE-SPACE ASSOCIATIONS

The Spatial-Numerical Association of Response Codes (SNARC) effect describes the phenomenon where smaller numbers are linked with quicker left-side responses, while larger numbers correspond to quicker right-side responses. Prior research on working memory (WM) and the SNARC effect has investigated the role of cognitive load through visuo-spatial and verbal tasks, emphasizing the flexibility of this effect.

To further understand this flexibility of the SNARC effect under various cognitive loads, this dissertation examines how different types of magnitude-space-based numerical WM loads influence the SNARC effect in different number judgment tasks. Previous research on the SNARC effect has examined its flexibility by altering the Mental Number Line (MNL) compatibility across various task contexts, including response mappings, spatial layouts, and memory tasks. Additionally, the flexibility of the SNARC effect has been studied by focusing on WM specifically through WM loads in different tasks, employing both visuo-spatial and verbal components to explore how cognitive load impacts spatial-numerical associations. However, these studies have not yet addressed MNL compatibility as a cognitive load, a perspective that integrates MNL and WM to deepen our understanding of number-space associations. This dissertation suggests that MNL compatible or incompatible representations of numbers, when activated as space, magnitude, and magnitude-space WM loads, may enhance or interfere with WM functioning, thereby affecting number judgment performance.

The introduction provides a comprehensive foundation for the study, beginning with an overview of spatial-numerical mapping and its theoretical basis, specifically the concept of the MNL. Next, it examines the automaticity of space-number associations across various factors, such as response directions, modalities, numerical and non-numerical domains, populations, as well as how these associations are represented in the brain. This is followed by an exploration of the flexibility of spatial-numerical associations, emphasizing research on their flexibility across different reading/writing habits, diverse executive functions, and task-contexts, particularly in relation to MNL compatibility. Finally, the role of WM is discussed, with an emphasis on how different types of WM loads influence the SNARC effect.

The question of how humans visualize numbers in their minds was first posed by Francis Galton in 1880. Through the use of introspection, Galton asked participants to describe and draw how they visualize numerals. The majority reported visualizing numbers in a line from left-to-right. Based on these observations, Galton concluded that individuals conceptualize numbers on a line in their minds, suggesting a close relationship between numbers and spatial representations. The concept of numbers being mentally organized along a spatial continuum gained empirical support from Moyer and Landauer's (1967) work, which demonstrated that numbers are represented spatially, much like physical space. This was evidenced by the numerical (or symbolic) distance effect, where reaction times for comparing two digits decreased as the numerical distance between them increased (Dehaene, Dupoux, and Mehler, 1990; Moyer and Bayer, 1976). A related finding, known as, the size effect, showed that reaction times increased when comparing larger digits as opposed to smaller ones. Together, these distance and size effects provided crucial evidence for the existence of spatial-numerical associations, serving as demonstrations of how numbers are mentally represented along the mental number line (Restle, 1970; Moyer and Bayer, 1976; Dehaene et al., 1990). Hence, magnitude-space associations where small numbers are positioned on the left and large numbers on the right are termed compatible with the long-term representation of numbers, while associations with small numbers on the right and large numbers on the left are considered incompatible.

Building on these findings, Dehaene, Bossini, and Giraux (1993) conducted an in-depth exploration of how individuals mentally represent and process numbers. They focused on how parity (odd or even) and magnitude information (smaller or larger than a reference number) are accessed from both Arabic numerals and verbal representations. Their study revealed that numerical information, including parity, is stored in long-term memory (LTM), rather than calculated in real-time. Most importantly, they found an interaction between number magnitude and response side: smaller numbers were associated with faster left-hand responses, while larger numbers with faster right-hand responses. This association, named the SNARC effect, became the most prominent manifestation of the MNL. The presence of the SNARC effect even when magnitude information is irrelevant to the task –such as in parity judgment, where numerical magnitude is not consciously processed– suggests that the SNARC effect may serve as an indicator of automatic access to the spatial representation of numerical magnitudes.

To elucidate the underlying mechanisms of the SNARC effect, two cognitive mechanisms have been debated. A major controversy in this debate is whether the numbers' association with space is accessed automatically through long-term representations, the MNL, or whether it is constructed temporally in WM during task execution. This ongoing debate regarding the role of long-term versus WM mechanisms highlights the need for a deeper exploration of the automaticity and foundational aspects of the SNARC effect.

### *1.1. SNARC as a Well-established Phenomenon: Foundations in Spatial-Numerical Processing*

The SNARC effect has been consistently replicated across a variety of experimental tasks, including phoneme monitoring with number words (Fias et al., 1996), orientation detection (Fias et al., 2001), and pointing responses (Fischer, 2003). Typically observed in bimanual responses along the horizontal dimension (left-right keys), the SNARC effect has also been found when participants performed parity judgments across various response directions and modalities. These include the vertical (top-bottom) and diagonal (combination of left-right and top-bottom) axes (Gevers et al., 2006a; Holmes and Lourenco, 2011; Ito and Hatta, 2004) and three-dimensional response setups, including vertical and sagittal (near-far) dimensions using an ad hoc response box (Aleotti et al., 2020). Further evidence comes from studies using unimanual responses (Riello and Rusconi, 2011), foot responses with a pedal (Schwarz and Müller, 2006), and saccadic eye movements (Schwarz and Keus, 2004). These studies suggested that the SNARC effect occurs independently of numerical judgment task and response modality (cf. Hesse, Fiehler, and Bremmer., 2015).

To build on the diversity of contexts in which the SNARC effect has been observed, evidence suggests it also extends beyond classical numerals. The SNARC effect has been observed with number words, auditory number words, dice patterns, and even sign language numbers, demonstrating its pervasiveness across different numerical modalities (Fias et al., 1996; Nuerk, Wood, and Willmes, 2005; Chinello et al., 2012). Associations of small with left and large with the right have also been observed in non-numerical domains, such as days of the week, letters of the alphabet, months of the year, luminance, and object size (Gevers, Reynvoet, and Fias, 2004; Shaki and Gevers, 2011; Gevers, Reynvoet, and Fias, 2003; Fumarola et al., 2014; Ren et al., 2011), as well as in non-numerical magnitudes, such as dot arrays, pitch height, duration, semantic and physical size of animal names (Nemeh et al., 2018; Rusconi et al., 2006; Vicario et al., 2008; Rubinstein and Henik, 2002; Dural et al., 2017; but see also Fias, van Dijck, and Gevers, 2011 for serial position in WM explanation for non-numerical magnitudes).

Findings from various experimental tasks and across different response and stimulus modalities, both numerical and non-numerical, highlight the robustness of spatial-numerical associations. These results suggest that the SNARC effect extends beyond numerical representations and may reflect a broader spatial association embedded within cognitive processing. To reveal the neural basis underpinning these associations, brain imaging studies have provided valuable insights into the specific regions activated during number processing.

Researchers have long sought to identify specific brain areas involved in number processing, using various imaging techniques that reveal how numerical information is processed and localized. Findings consistently indicate bilateral inferior parietal activation, particularly in the intraparietal sulcus (IPS), during numerical calculation and comparison, observed across studies using functional magnetic resonance imaging, *f*MRI (Roland and Friberg, 1985; Dehaene et al., 1999; Cohen Kadosh et al., 2005; Klein et al., 2010), positron emission tomography, PET (Dehaene et al., 1996), ERP (Dehaene, 1996; Keus and Schwarz, 2005; Libertus, Woldorff, and Brannon, 2007), and functional near-infrared spectroscopy, *f*NIRS (Cutini et al., 2012). Thus, imaging studies converge in pointing to the parietal cortex as the primary region for number processing, with additional involvement of the prefrontal cortex in complex tasks (Pinel et al., 2001; Dehaene et al., 2003; Hubbard et al., 2005; Nieder, 2005; Menon et al., 2000).

Expanding on the evidence that the parietal cortex, particularly the IPS, plays a central role in numerical processing, some studies have examined how this region and others differentially activated during number judgment tasks, such as parity and magnitude comparison. Distinct activation patterns have been observed when participants engage in parity judgment in contrast to magnitude comparison.

An *f*MRI study conducted by Klein et al. (2010) aimed to investigate how the brain processes numbers presented through auditory stimuli and how this differs across parity judgment and magnitude comparison. The findings revealed that both tasks activated the IPS. However, they elicited different patterns of activation. Parity judgment resulted in more bilateral parietal activity, while magnitude comparison led to stronger activation in the left IPS. This distinction reflects the different cognitive demands of implicit (parity judgment) and explicit (magnitude comparison) processing of numbers. The results also indicated that auditory number processing involves neural mechanisms similar to those used in number judgment tasks, suggesting that numerical cognition relies on modality-independent brain regions. Cutini et al. (2012) used *f*NIRS to explore the neuronal correlates of the SNARC effect. They observed increased hemodynamic activity in the bilateral intraparietal sulcus (associated with numerical magnitude representation) and the left angular gyrus (involved in verbal number processing) during magnitude comparison, suggesting that numerical semantics form the cognitive foundation for number–space interactions. These studies provide insights into the shared and task-specific neural substrates of number processing.

Based on brain imaging findings related to number processing, Walsh (2003) introduced A Theory of Magnitude (ATOM), proposing a generalized magnitude system. ATOM emphasizes the interconnected nature of magnitude, space, and time, suggesting that these dimensions share overlapping neural resources to facilitate coordinated actions. The parietal cortex plays a central role in integrating spatial, magnitude, and time processing, providing a neural basis for behavioral associations between these dimensions. While ATOM has been supported in several studies (Bueti and Walsh, 2009; Wühr and Seegelke, 2018; Dural et al., 2018), its potential to explain magnitude-space interactions within WM remains underexplored.

Studies on different populations also provide insights into the foundations of the SNARC effect. Research with brain-damaged patients underscores a critical link between number and spatial processing in the brain. Patients with right hemisphere lesions and hemispatial neglect show impaired spatial-number associations, highlighting spatial processing as essential to number representation (Zorzi, Priftis, and Umiltà, 2002; Umiltà, Priftis, and Zorzi, 2009). Studies with healthy participants also reveal spatial biases in number-space tasks, often referred to as pseudo-neglect. In number bisection tasks, spatial shifts suggest that number processing induces spatial biases in both clinical and healthy populations (Hubbard et al., 2005; Zorzi et al., 2012; Fischer, 2001). Potential differences in implicit (parity judgment) and explicit (magnitude comparison) number processing have also been investigated in patients with neglect. For example, in Zorzi et al.'s study (2012), right-brain-damaged patients and healthy participants exhibited a SNARC effect during parity judgments. However, in magnitude comparison tasks, the SNARC effect persisted only for larger numbers among patients with neglect, suggesting that neglect selectively modulates SNARC effect during magnitude comparison but not in parity judgment. They explained this dissociation by suggesting that magnitude comparison is predominantly influenced by the visuo-spatial coding, while the SNARC effect in parity judgment is guided by verbal-spatial coding of numbers, the account proposed by Gevers et al. (2006b).

The SNARC effect has been studied in both preschool children (without literacy skills) and school-aged children to understand whether spatial-numerical associations emerge early in development and whether they depend on visuo-spatial or verbal processing. For example, van Galen and Reitsma (2008) observed the SNARC effect in 7- to 9-year-olds during magnitude comparison. However, in a detection task, only 9-year-olds and adults demonstrated a SNARC-like effect, even though magnitude information was irrelevant to the task. This finding suggests that automatic spatial-numerical associations may strengthen with age (but see Patro et al., 2015 for interchangeability of the SNARC effect in 3- and 4-years olds with training and Imbo et al., 2012 and Hoffman et al., 2013 for opposing views). Bachot et al. (2005) indicated that the SNARC effect may also depend on children's visuo-spatial abilities; while typically developing children showed a SNARC effect in magnitude comparison, those with visuo-spatial impairments did not, suggesting that visuo-spatial processing plays a role in establishing number-space representations. This foundational evidence supports the idea that spatial-numerical associations, although developing with age, are linked to fundamental cognitive abilities.

While these findings highlight the automatic and embedded nature of spatial-numerical associations, emerging research points to the flexibility of the SNARC effect, suggesting that these associations are not entirely fixed but can adjust to various contextual and task-specific demands.

### *1.2. Insights into SNARC Flexibility: The Role of Task Context, Cultural, and Individual Factors*

Research on the SNARC effect highlights its flexibility, revealing its dependency on various contextual factors. Recent studies have demonstrated that this effect can be influenced by number range, cultural background, individual differences, task context, and task-specific instructions. One notable aspect of this flexibility is the emergence of the reverse SNARC effect, in which the typical left-to-right association of small and large numbers can be reversed under specific conditions. This phenomenon suggests that space-number associations may dynamically respond to situational demands.

Dehaene et al. (1993) first demonstrated the range-dependency of the SNARC effect in Experiment 3, showing that the magnitude of numbers within a specific range can influence the strength and direction of the SNARC effect. This highlights how participants may exhibit different spatial-numerical mappings depending on the numerical range of numbers (see also Fias et al., 1996).

A striking example of the flexibility of the SNARC effect is its susceptibility to cultural influences, particularly the role of reading and writing orientations. In Experiment 7 of Dehaene et al. (1993), it was shown that French-Persian monoliterates and biliterates displayed different SNARC effects based on their reading and writing orientations. Similarly, Zebian (2005) found a reverse SNARC effect for Arabic monoliterates and a weak regular (hereafter regular SNARC effect will be used to differentiate the SNARC and reverse SNARC effect) SNARC for Arabic-English biliterates due to their bidirectional literacy. Shaki, Petrusic, and Leth-Steensen (2012) extended these findings by comparing groups from different cultural backgrounds, including English, Palestinian, and Israeli participants, as well as illiterates. These studies together demonstrated that cultures with right-to-left reading habits tend to show a reverse SNARC effect. However, the influence on spatial-numerical associations is not limited to cultural factors alone.

Beyond cultural influences, task context and instructions can also change the direction of the SNARC effect. Several studies have demonstrated this by considering

MNL compatible and incompatible representations in number judgment tasks, allowing to test the long-term spatial representation of numbers and its interaction with task demands.

In Fischer, Mills, and Shaki's study (2010), participants completed a parity judgment task, but instead of the typical setup, numbers were embedded within short cooking recipes. The spatial positioning of the numbers in the recipes was manipulated to be either compatible or incompatible with directional reading habits of English and Hebrew participants. English readers showed a stable SNARC effect both before and after reading a compatible text. However, the SNARC effect disappeared after reading an incompatible text. Hebrew readers, who showed no SNARC effect, exhibited a reverse SNARC effect after reading an incompatible text, but no SNARC effect was observed either before or after reading a compatible text.

While Fischer et al. (2010) demonstrated that the spatial-numerical associations can be rapidly altered by manipulating the location of numbers in text, other studies have shown this flexibility through different task contexts. For example, Bächtold, Baumüller, and Brugger (1998) tested two spatial conditions: in the 'ruler' condition, where numbers were arranged left-to-right (MNL compatible), participants exhibited the regular SNARC effect. Conversely, in the 'clock face' condition, where numbers were visualized with small numbers on the right and large numbers on the left (MNL incompatible), a reverse SNARC effect was observed. These findings demonstrate that spatial-numerical associations are flexible, and that the direction of the SNARC effect can be shifted by altering the spatial representation context.

The flexibility of the SNARC effect in response to task context was further explored by alternating response and spatial mapping rules (Notebaert et al., 2006). In Experiment 1, participants first completed a magnitude comparison task, with half assigned to an MNL compatible response mapping and the other half to an MNL incompatible mapping. Then, they performed an orientation judgment task, pressing the left button if the number was tilted and the right if it was upright. The results showed a regular SNARC effect for the MNL compatible group and a reversed SNARC effect for the MNL incompatible group. In Experiment 2, the orientation task was combined with a spatial compatibility task, where half of the participants pressed corresponding left/right if the stimulus was displayed on the left/right, while the other half pressed left/right if the stimulus was displayed on the opposite right/left-side. Again, a regular SNARC effect was observed for MNL compatible spatial arrangements, whereas a reverse SNARC effect was found for MNL incompatible spatial arrangements. These findings underscore the flexibility of the SNARC effect, demonstrating that spatial-numerical mappings are not fixed but can be dynamically changed by task demands and instructions.

Lindemann et al. (2008) explored how number-space associations vary based on the order of digit sequences with a memory task. Participants memorized digits arranged in ascending (MNL compatible), descending (MNL incompatible), or disordered sequences and then completed a parity judgment task. The results showed a regular SNARC effect for ascending and disordered sequences, but no effect for descending sequences. These findings suggest that spatial-numerical associations are not solely the result of automatic cognitive processes but are shaped by the cognitive coding strategies used to meet task demands.

While task context and cultural influences highlight the flexibility of the SNARC effect, exploring individual differences also offers insights into how cognitive abilities and characteristics shape these spatial-numerical associations. To examine the individual variability characterizing the SNARC effect, researchers have examined the role of executive functions, including inhibition, WM, general processing speed (reaction time), and visuo-spatial abilities. Stronger SNARC effects were observed in participants with poor inhibition ability on the Stroop task, poor mental rotation ability in 2D mental rotation task, and slower processing speeds (Hoffmann, Pigat, and Schiltz 2014; Viarouge, Hubbard, and McCandliss, 2014; Wood et al., 2008). Conversely, no significant relationship was found between SNARC and performance on the Simon, Corsi block, digit span forward (DSF) and backward (DSB) tasks, or the consonant-vowel-consonant letter tasks (Hoffmann et al., 2014; Herrera, Macizo, and Semenza 2008). Studies that measured WM capacity with a DSB task found a significant relationship between WM capacity and RT in the parity judgment task, where participants with higher WM capacity responded faster (Hoffmann et al., 2014). However, no significant relationship was found between WM capacity and SNARC slope and size (Herrera et al., 2008; Hoffmann et al., 2014). These findings suggest that individual differences in WM capacity may play a role in influencing the SNARC effect, warranting consideration when examining spatial-numerical associations.

These findings show that the SNARC effect is highly flexible, and the reverse SNARC effect emerges under specific cultural, task-related, and instructional conditions. The dynamic nature of the MNL highlights that spatial-numerical mappings are not fixed but are influenced by cultural context, individual differences, and task demands. Moreover, the role of WM appears pivotal in shaping these associations, as it enables adaptive engagement with task demands and cognitive load. Investigating how WM impacts spatial-numerical associations offers valuable insights into the mechanisms underlying the SNARC effect.

### *1.3. The Role of Working Memory in Number-Space Associations*

Many researchers considered that when individuals engaged in a numerical task, spatial properties associated with numerical information are temporarily constructed and represented in memory. This temporary representation depends on task demands and is built-up during task execution, suggesting a critical role of WM in number-space associations (van Dijck and Fias, 2011; van Dijck, Gevers, and Fias, 2014). WM is an important cognitive system essential for a wide range of cognitive functions such as language, learning, reading ability, fluid intelligence, comprehension, reasoning, problem-solving, and mathematical performance (Baddeley, 1992; Attout et al., 2014). It enables individuals to encode, represent, retrieve, and actively manipulate information in mind over a short period, providing the foundation for information processing in complex and novel situations (Baddeley, 2012; Cowan, 1999; Oberauer, 2002).

In recent years, a great deal of research has investigated WM in relation to spatial representation of numbers. Researchers tested the SNARC effect with magnitude comparison and/or parity judgment, after applying various tasks such as phonological span, visuo-spatial WM, verbal WM, and serial order. Findings of those studies suggested that numbers are not intrinsically related to space, rather the association between numbers and space is constructed during the task execution. This construction is affected by the task difficulty, the emergence and the strength of the SNARC effect are modulated by different cognitive loads (Herrera et al., 2008; van Dijck, Gevers, and Fias, 2009; van Dijck and Fias, 2011; Fias et al., 2011; Fias and van Dijck, 2016; Abrahamse, van Dijck, and Fias, 2016; Deng et al., 2017; Wang et al., 2018).

To investigate the role of WM load type and task difficulty on the SNARC effect, researchers increased the difficulty level through different experimental paradigms. Herrera et al. (2008) suggested that the association between number and space can be altered by the task goal, which points to the involvement of WM. Specifically, they investigated the effects of visuo-spatial and phonological WM loads on magnitude comparison. Participants first performed a baseline (without a WM load) magnitude comparison task, followed by a visuo-spatial span test (Corsi Block task), and phonological span test (using consonant-vowel-consonant letter triplets of non-words). In both visuo-spatial and phonological span tasks, they were required to reproduce the presented sequences correctly. The difficulty level of the visuo-spatial task was manipulated by increasing the number of colored squares from 2 to 9; while in the phonological task the consonant-vowel-consonant letter triplets were increased by 2 to 6. Then, they performed a magnitude comparison task right after each WM task. Results of the study indicated the SNARC effect after phonological WM load, but the absence of the SNARC effect after visuo-spatial WM load. Based on these findings, researchers suggested that the type of WM load modulates the SNARC effect.

van Dijck and Fias (2009) examined the number-space associations underlying the SNARC effect by placing a verbal and visuo-spatial WM load during a parity judgment and a magnitude comparison task, following the same procedure with Herrera et al. (2008). They replicated Herrera et al.'s findings, showing that spatial, but not the verbal load abolished the SNARC effect in a magnitude comparison task. However, in parity judgment, the SNARC effect was abolished under verbal WM load, but not under visuo-spatial WM load. van Dijck and Fias concluded that the SNARC effect changes depending on both the WM load type and the number judgment task.

The involvement of WM in number-space relations was investigated by van Dijck and Fias (2011) and they argued that the mechanism underlying the association between numbers and space is the ordinal position of numbers in WM. Specifically, if an item's position in a sequence is at the beginning or end it is associated with the left or right, respectively. To examine this, they asked the participants to memorize a sequence of numbers (Experiment 1) and fruit and vegetable words (Experiment 2) in the correct order then they performed a parity judgment. However, in the parity judgment, researchers instructed them to respond only to the numbers that were in the memorized sequence to ensure WM access. After they completed the parity judgment task, participants were asked to select the memorized sequence from the four different sequences, which were displayed vertically (Experiment 1) and one by one (Experiment 2). Their findings indicated an association of the first stimuli with the left response-side, and between the last stimuli with the right response-side, for both numerical and non-numerical verbal stimuli. Although they did not find a SNARC effect in Experiment 1, they demonstrated the effect in Experiment 2 in a separate parity judgment task. These findings suggest that number-space associations have their roots in the ordinal positional coding in WM during task execution, offering a WM account for the SNARC effect as an alternative to the long-term representation of numbers.

In addition to WM load type, Deng et al. (2017) studied the effect of load amount on the SNARC effect by employing a *n*-back task paradigm. Initially, participants performed a baseline parity judgment or magnitude comparison, without WM load. Then, *n*-back tasks with varying load types (verbal load: letters or spatial load: black squares) with varying load amounts (1-, 2-, and 3-back) and a number judgment task (parity judgment or magnitude comparison) were consecutively presented. With this procedure, unlike previous studies, each number judgment was verbally or spatially loaded. In the *n*-back tasks, participants were required to respond if the displayed item was the same as presented 1, 2, or 3 item(s) before. The results showed that in parity judgment, irrespective of the type or amount of load, SNARC effect disappeared. Contrarily, in magnitude comparison, the SNARC effect became stronger, as the spatial load increased, whereas it weakened as the verbal load increased. Deng et al. (2017) pointed out that for both parity judgment and magnitude comparison, WM is crucial, but the type and amount of WM resources are differentially needed.

Several research suggested that long-term representations of numbers and temporary position-space representations of numbers in WM coexist. These representations can either interfere with or cancel each other out depending on the task, supporting the coexistence of MNL and WM (Lindemann et al., 2008; van Dijck et al., 2014; Pinto et al., 2019; Ginsburg and Gevers, 2015; Huber et al., 2016; Hepdarcan, Çetinkaya, and Dural, 2024).

Ginsburg and Gevers (2015) provided evidence for the coexistence of long-term numerical representations and temporary number-space associations in WM. They structured their study in three phases: In the encoding phase, participants memorized a number sequence in order. Then, in the classification phase (inducer blocks/go condition), all numbers were displayed, and participants performed a magnitude comparison task. Following this, in the diagnostic blocks (go-nogo condition), they compared only the numbers in the memorized sequence. Finally, in the control phase, participants judged whether a presented sequence matched the one held in memory. Results showed that during the inducer blocks/go condition, a regular SNARC effect appeared, but no ordinal position effect was found. In contrast, the diagnostic blocks/go-nogo condition produced an ordinal position effect without a regular SNARC effect. In a second experiment, a task-switching paradigm was used to present inducer and diagnostic blocks randomly within the classification phase. Results mirrored Experiment 1, revealing a regular SNARC effect during inducer blocks/go condition and both SNARC and ordinal position effects in the diagnostic blocks/go-nogo condition. Overall, these findings suggested that while ordinal position and SNARC effects do not interfere, number-space associations are influenced by both long-term and short-term representations.

Unlike previous studies, Gut and Staniszewski (2016) took a direct approach by using recall rates of numbers to assess the SNARC effect. They explored the interaction between short-term memory (STM) and LTM representations on the SNARC effect during digit recall without requiring an additional task (e.g., parity judgment). They hypothesized that small numbers displayed on the left would be retrieved more quickly than those on the right, due to MNL compatibility. In the experiment, four digits (laterally left, medially left, medially right, and laterally right) appeared around a fixation point (e.g., congruent: 1 4 + 5 9; incongruent: 8 4 + 5 2) and participants memorized these positions. A single digit then appeared at the center of the screen, and participants indicated its position. Results showed that retrieval efficiency was influenced by the congruency between a number’s position in STM and its LTM representation on the MNL, suggesting that LTM modulates digit retrieval within a spatial context.

In a recent study, Hepdarcan et al. (2024) investigated how congruent, incongruent, and negatively congruent magnitude-space associations –both numerical and non-numerical– affect 1- and 2-back task performance. Instead of focusing directly on the SNARC effect, the study investigated how magnitude-space relations impact WM tasks, with emphasis on the role of LTM representations. The study investigated MNL compatibility, where congruent (e.g., the *n*-back item 2 on the left- and the test item 4 on the left-side of the screen), incongruent (e.g., the *n*-back item 2 on the left- and the test item 4 on the right-side), and negatively congruent (e.g., the *n*-back item 2 on the right- and the test item 4 on the right-side), *n*-back and test items reflect varying degrees of compatibility. Both congruent and incongruent representations elicited faster and more accurate responses than negative congruent representations, suggesting the activation of LTM representations during the WM task. The study pointed towards the coactivation of LTM and WM in magnitude-space associations.

### *1.4. The Rationale of the Present Dissertation*

Studies testing the predictions of automaticity and irrepressibility in the MNL explanation of the SNARC effect have highlighted the importance of WM, revealing that the SNARC effect is flexible and context-dependent. It emerges or diminishes based on temporary representations activated during WM tasks (Herrera et al., 2008; van Dijck et al., 2009; van Dijck and Fias, 2011; Deng et al., 2017). This underscores the need to explore theoretical frameworks of WM to better understand how it contributes to number-space associations.

The most commonly known WM model is Baddeley and Hitch’s three-component framework (1974), which is built around the central executive, a limited-capacity system for attentional control. This central component is supported by two subsidiary systems: the phonological loop, which maintains and rehearses acoustic or speech-based information, and the visuo-spatial sketchpad, which performs similar functions for visual and spatial information. In response to growing evidence highlighting interactions between WM and LTM, Baddeley (2000) revised the original model by introducing a fourth component, the episodic buffer, which integrates information from WM subsystems and LTM to create new episodic memories. As demonstrated in the literature on the role of WM in number-space relations, cognitive load is typically imposed on WM through distinct verbal and visuo-spatial tasks, separately activating the phonological loop and visuo-spatial sketchpad in Baddeley’s WM model.

While Baddeley's WM model emphasizes distinct components within WM, Oberauer's (2009) framework offers a more unified explanation of WM by emphasizing the role of activated LTM and temporary bindings. According to Oberauer, WM arises from a dynamic interaction between three regions: (1) activated LTM, which keeps background information accessible and allows for easy retrieval when needed (e.g., activating numerical representations); (2) the direct access region, which has a limited capacity and forms temporary bindings between contents and contexts (e.g., associating numbers with spatial locations during task execution); and (3) the focus of attention, which selects relevant information from the direct access region for cognitive action (e.g., identifying task-relevant numbers in memory). To clarify the previously abstract concept of "activated LTM" Oberauer proposes a detailed account of how LTM contributes to WM processes.

Recent studies emphasizing the critical role of WM in explaining the SNARC effect suggest that Oberauer's WM model provides a valuable framework for such investigations (Ginsburg et al., 2015; Abrahamse et al., 2014, 2016; Guida and Campitelli, 2019). Unlike Baddeley's modular model, which separates verbal and visuo-spatial tasks into distinct subsystems, Oberauer's model conceptualizes WM as a unified system that interacts dynamically with activated LTM, offering a refined perspective on how cognitive loads influence spatial-numerical associations. It explains number-space associations as emerging from dynamically organized representations within WM, with LTM integration playing a central role in task execution.

While previous research has primarily relied on Baddeley's WM model, this dissertation adopts Oberauer's framework to examine cognitive loads on WM. In this context, Oberauer's model was operationalized by constructing cognitive loads based on long-term representations of numbers and their compatibility or incompatibility with the MNL. These loads –implemented as space, magnitude, and magnitude-space WM tasks– allow for a dynamic exploration of how activated LTM and WM interact to shape number-space associations, making Oberauer's model particularly suited for investigating the SNARC effect in relation to the MNL.

Specifically, the cognitive loads were constructed by incorporating long-term representations of numbers through MNL compatible and incompatible loads, based on their numerical magnitude and spatial positioning. As pointed out earlier, the effect of MNL compatibility has been examined in various formats in studies exploring the flexibility of the SNARC effect, such as in task contexts, response and spatial mapping, and memory tasks (Fias et al., 2010; Bächtold et al., 1998; Notebaert et al., 2006; Lindemann et al., 2008). However, none of the studies that addressed the SNARC effect considered MNL compatibility as a cognitive load, which would integrate MNL and WM accounts in number-space associations. Building on this idea, it is proposed that the compatible/incompatible representations of numbers with LTM which are activated as cognitive loads might contribute or disrupt WM to function, hence impact number judgments.

To attain a deeper understanding of the spatial representations of numbers, Walsh's (2003) ATOM model is particularly relevant. ATOM posits that overlapping cortical regions in the brain establish a common metric system, allowing for the common processing of magnitude, space, and time. Building on this concept, this dissertation focused on the number-space relationship by examining the numerical magnitude and space components. These components were implemented as cognitive load types in WM, constructed as space, magnitude, and magnitude-space.

### *1.5. The Aim and Hypotheses of the Present Dissertation*

This dissertation aimed to investigate the effects of magnitude-space-based numerical WM loads on the SNARC effect across different number judgment tasks. To achieve this, participants completed a numerical 1-back task with three types of WM loads as space, magnitude, and magnitude-space, where small or large numbers were presented on the left- or right-side of the screen. These presentations were either MNL compatible (small-left, large-right) or MNL incompatible (small-right, large-left). Following each number presentation, participants performed one of two number judgment tasks: parity judgment or magnitude comparison.

In the *n*-back task, participants were instructed to respond as a target if the presented number was in the same spatial position (space load), the same magnitude category (magnitude load), or both in the same spatial position and magnitude category (magnitude-space load), as the number presented one trial earlier. No response was required for non-targets. In the SNARC tasks, participants were either asked to determine whether the presented number was even or odd (parity judgment), or smaller or larger than 5 (magnitude comparison) with counterbalanced left/right response sides. To examine the effects of MNL compatibility of the WM load and WM load types on number judgments, unstandardized SNARC slopes, difference reaction time (dRT), and the interaction between magnitude (small, large) and response-side (left, right) on reaction time measures were evaluated.

### Hypothesis 1: Magnitude-Space-Based WM Loads are Expected to Impact the Emergence of the SNARC Effect

Based on the findings of van Dijck et al. (2009), Herrera et al. (2008), and Deng et al. (2017), which show that WM loads influence spatial-numerical associations, it is hypothesized that WM load will affect both the emergence and strength of the regular (small-left/large-right) SNARC effect compared to the baseline condition. Differential cognitive demands imposed by different types of WM load are expected to modulate the SNARC effect.

Specifically, under spatial and magnitude WM loads, regular SNARC effects are expected to occur, as neither load type imposes heavy cognitive demand on WM, making interference with number judgments unlikely. However, there are differences in the cognitive demands between the two loads. The spatial WM load is considered less demanding because it primarily activates the visuo-spatial system, which places lower cognitive demands on WM. This reduced demand may allow for a stronger regular SNARC effect. In contrast, the magnitude WM load requires participants to engage with numerical magnitude-related resources, thereby increasing cognitive demand. Although the regular SNARC effect is still expected to emerge, under the magnitude WM load, it may be slightly weaker compared to the spatial WM load due to the higher cognitive demands associated with processing numerical information.

In the case of the magnitude-space load, where participants simultaneously process both magnitude and spatial information, a higher cognitive load is imposed compared to the other two loads. Despite this added cognitive demand, simultaneous processing of magnitude information and space is expected to activate the spatial representations of numbers due to the close relationship between magnitude and space as proposed by ATOM (Walsh, 2003). Therefore, the magnitude-space load is expected to reinforce the emergence of a regular SNARC effect, rather than weaken or abolish it.

### Hypothesis 2: MNL Compatibility of the WM load is Expected to Impact the Direction of the SNARC Effect

Based on the results of Fischer et al. (2010), Bächtold et al. (1998), and Lindemann et al. (2008), which demonstrated the influence of task context and demands on spatial-numerical associations through MNL compatible and incompatible representations, it is hypothesized that the compatibility of WM loads with the MNL will affect the direction of the SNARC effect. Specifically, when WM loads are compatible with the MNL, a regular SNARC effect (small-left/large-right) is expected. Conversely, when WM loads are incompatible with the MNL, a reverse (small-right/large-left) SNARC may be observed. Under MNL incompatible WM loads, small numbers will be associated with faster right-sided responses, and large numbers with faster left-sided responses, contrary to the regular SNARC effect. This reversal is hypothesized to occur because MNL incompatible WM loads disrupt long-term spatial representation of numbers, causing interference in accessing the cognitive resources required for typical numerical processing. This interference is likely to reverse the regular spatial-numerical mapping.

### Hypothesis 3: MNL Compatibility of the WM load and WM load Type are Expected to Modulate the Direction of the SNARC Effect

It is hypothesized that the direction of the SNARC effect will be influenced by an interaction between MNL compatibility and WM load type (space, magnitude, and magnitude-space). Specifically, MNL compatible WM loads are expected to reinforce the emergence of a regular SNARC effect across all WM load types. While MNL incompatible WM loads may reverse the SNARC effect, particularly under magnitude and magnitude-space WM loads, where cognitive demand is higher compared to baseline and space WM load.

### Hypothesis 4: MNL Compatibility of the WM load, WM load Type, and The Number Judgment Task are Expected to Modulate the Direction of the SNARC Effect

van Dijck and Fias (2009) and Deng et al. (2017) showed that the SNARC effect varied depending on both the type of WM load and the number judgment task. In parity judgment, magnitude information is activated implicitly and task-driven, however, in magnitude comparison, magnitude information is activated automatically and task-dependently. Previous research, such as Deng et al. (2017), showed that the SNARC effect disappeared after both verbal and visuo-spatial WM loads in parity judgment. However, in magnitude comparison, the SNARC effect was reduced after verbal load but became stronger after visuo-spatial load. Building on these findings, it is hypothesized that MNL compatible WM loads, particularly under magnitude and magnitude-space WM loads, will strengthen the SNARC effect during magnitude comparison. Since spatial and magnitude information are being processed explicitly during task execution, these WM loads are expected to reinforce spatial-numerical associations and lead to a stronger SNARC effect. In parity judgment task, however, MNL incompatible WM loads, particularly under magnitude and magnitude-space WM loads, may interfere with the activation of spatial-numerical mappings. This interference is hypothesized to lead to a weaker or abolished SNARC effect, as the MNL incompatible cognitive load involved in processing magnitude and both magnitude and spatial information may overwhelm the implicit processes underlying the SNARC effect.

# CHAPTER 2: PILOT STUDIES

Before conducting the main study, two pilot studies were carried out. Previous research has provided evidence of spatial-number associations in Turkish participants (Dural et al., 2018; Hepdarcan et al., 2021). However, these studies did not directly investigate the SNARC effect; instead, they examined related phenomena, such as MNL alignment within a false memory paradigm and the distance effect using a go/no-go procedure, respectively. Similarly, attentional SNARC studies employed methodologies distinct from traditional SNARC paradigms, such as using eye movements and a spacebar for responding (Atalar et al., 2022) or directional keys on a keyboard (Salman, 2021). This highlights the need for Pilot Study 1 to explore the distribution and characteristics of the SNARC effect in a Turkish sample. Furthermore, Pilot Study 2 was conducted to assess the dissertation's design, ensure the experimental program ran smoothly, and confirm that the instructions were clearly understood and accurately followed.

## *2.1. Pilot Study 1*

The aim of Pilot Study 1 was to examine the distribution of the SNARC effect in a Turkish sample and investigate its potential variation based on gender, hand preference, and starting finger used for counting. Additionally, the study explored participants' pre-existing spatial biases through number bisection and line bisection tasks, as well as their relationship with number judgment tasks. Finger counting habit was examined in the pilot study as it has been proposed as a potential modulator of space-number associations (Fischer, 2008; Fischer and Brugger, 2011; Prete and Tommasi, 2020). Similarly, bisection tasks were included as alternative measures to assess spatial-numerical associations, providing additional insights into participants' spatial biases (Fischer, 2001; Fischer and Shaki, 2014).

### *2.1.1. Method*

#### *2.1.1.1. Participants*

Pilot Study 1 included 64 voluntary university students (43 females; mean of age ($M_{\text{age}}$) = 20.47 years, age range = 18-30 years, standard deviation of age ($SD_{\text{age}}$) = 2.66). Among them, 34 participated in the parity judgment task, and 30 in the magnitude comparison task. A total of 59 participants were right-handed, and 46 were observed starting with their right hand in finger counting. Regarding finger counting preferences, 38 began with their thumbs, 15 with their index fingers, and 11 with their little fingers. None of the participants had previously taken part in a study investigating number-space relations. All participants provided written informed consent and self-reported as generally healthy.

#### *2.1.1.2. Stimuli and Apparatus*

In the number judgment tasks, stimuli consisted of numbers from 1 to 9 (excluding 5) displayed individually in black against a white background (Courier New, 55-point font). The stimuli were presented using SuperLab software (Version 4.0, Cedrus, Inc.) on a 20-inch LCD monitor with a resolution of 1600 × 900 and a refresh rate of 60 Hz. Participants responded using the "A" (leftmost) and "İ" (rightmost) keys on a Turkish QWERTY keyboard. Finger counting habits were verbally obtained from the participants, and their responses were recorded. Bisection tasks were administered in a paper-pencil format.

#### *2.1.1.3. The SNARC effect (The Number Judgment Tasks: Parity Judgment and Magnitude Comparison)*

In the number judgment tasks (parity judgment and magnitude comparison), each trial began with a 300 ms white fixation rectangle outlined in black (22 mm × 32 mm), followed by a single number from the set "1, 2, 3, 4, 6, 7, 8, and 9", displayed at the center of the screen. The number remained on the screen until the participant responded using either "A" or "İ" key or for a maximum of 1300 ms if no response occurred. A 1500 ms blank screen followed each trial, resulting in a 2800 ms response window per number. Both the parity judgment and magnitude comparison tasks consisted of two blocks with reversed response key assignments, separated by a 30-second rest period.

#### *2.1.1.4. Finger counting habits*

Participants were verbally instructed to imagine counting from 1 to 10 and to show how they count using their fingers. Their responses, including the starting hand and the specific starting finger, were recorded on the participants' forms.

### *2.1.1.5. Bisection tasks (Line Bisection and Number Bisection)*

Following Fischer's (2001) methodology, the bisection task involved presenting participants with two A4 sheets placed along a midsagittal plane. Each sheet contained either 16 lines or 16 digit strings, with the order of presentation counterbalanced. The lines were either 59 mm or 63 mm in length and 1 mm in width. The digit strings consisted of 17 or 18 repeated digits, formatted in 18-point Monaco font, using "1" or "2" for the small numbers and "8" or "9" for the large numbers. To avoid reliance on previous judgments, the stimuli were intentionally misaligned. Participants were instructed to bisect the lines and digit strings by placing a vertical mark with a pencil. They were explicitly asked not to count the digits and instead to base their judgments on visual estimation. The task was supervised to ensure compliance with the instruction to avoid counting.

### *2.1.1.6. Procedure*

Participants were asked to fill out the Participant Information Form, Informed Consent Form, Demographic Information Form, and Edinburgh Handedness Inventory. Each participant was either assigned to the parity judgment or the magnitude comparison task, and tested individually in a sound-isolated, dimly lit experimental chamber at the Neuroscience of Mind and Behavioral Research Laboratory, Izmir University of Economics. In the parity judgment task, participants identified whether a centrally displayed number was odd or even, while in the magnitude comparison task, they determined whether the number was smaller or larger than the reference number 5. Responses were made by pressing either the "A" or the "İ" keys on a keyboard, using their left or right index fingers, respectively. Each task began with a practice session, where participants judged each number once to familiarize themselves with the procedure. The experimental session consisted of two blocks, with the block order counterbalanced across participants. Each number appeared 11 times per block, resulting in a total of 176 trials. Participants were instructed to respond both quickly and accurately.

After completing the number judgment task, participants in both number judgment groups were required to perform the bisection tasks. To control for potential order effects, half of the participants completed the bisection tasks first, followed by the number judgment task, while the other half began with the number judgment task first and completed bisection tasks afterward. In addition, the administration order of the bisection tasks was also counterbalanced across participants. Finger counting habits were assessed verbally by asking participants to imagine counting from 1 to 10 and they were required to show with their fingers how they count. Finger counting habits were obtained either before or after the experimental sessions, with this order counterbalanced among participants.

### *2.1.2. Results*

The SNARC effect was assessed using the linear regression approach (Fias et al., 1996). Individual slopes were calculated by regressing dRTs (mean RT for the right hand - mean RT for the left hand) on number magnitude. All analyses related to the SNARC effect were based on these calculated individual slope values. When the distribution of SNARC slopes was examined to explore participants' general tendencies regarding numbers and space, the SNARC effect was found to follow a normal distribution in both the parity judgment task ($D(34) = 0.09$, $p > .05$; Skewness = -0.58, Kurtosis = 0.30) and the magnitude comparison task ($D(30) = 0.13$, $p > .05$; Skewness = 0.15, Kurtosis = 0.17). Additionally, no significant differences were found between the SNARC scores ($t(41) = -0.27$, $p > 0.05$) of participants in the parity judgment and magnitude comparison tasks, nor in their performance on the number bisection ($t(62) = -0.41$, $p > 0.05$) and line bisection tasks ($t(62) = -0.36$, $p > 0.05$). Furthermore, participants' performance on SNARC tasks did not significantly differ based on gender, dominant hand (right or left), or whether they initiated finger counting with their right or left hand ($t(62) = -1.27$, $p > 0.05$; $t(62) = -1.22$, $p > 0.05$; $t(62) = -0.43$, $p > 0.05$, respectively). Correlation analyses also revealed no significant relationships between the slope and hand preference scores ($r = -0.08$), number bisection ($r = -0.18$), and line bisection performance ($r = -0.25$), with all $p_s > 0.05$.

### *2.1.3. Conclusion*

Overall, the findings of Pilot Study 1 demonstrated that the SNARC effect followed a normal distribution in this sample. No significant differences were observed between parity judgment and magnitude comparison tasks. Furthermore, gender, handedness, finger counting habits, and bisection tasks neither correlated with nor influenced the SNARC effect. Consequently, the main study of this dissertation did not account for gender or handedness, nor did it include additional space-number-related tasks.

## *2.2. Pilot Study 2*

The aim of Pilot Study 2 was to investigate how magnitude-space-based numerical WM loads influence the SNARC effect across different number judgment tasks. This pilot study served as a preliminary evaluation to ensure that the experimental framework was well-designed to address the primary objectives of the dissertation. Specifically, Pilot Study 2 assessed the feasibility of the study's design, ensured the experimental program functioned as intended, and verified that the instructions were clear, and the task requirements were accurately completed. Additionally, it aimed to identify potential issues related to task implementation, data collection, or participant compliance, allowing for necessary adjustments to be made prior to the main study.

### *2.2.1. Method*

#### *2.2.1.1. Participants*

Pilot Study 2 was conducted with 60 voluntary university students who were randomly assigned to one of the number judgment tasks. Upon reviewing the data, it was identified that three participants in the magnitude comparison task and one participant in the parity judgment task did not correctly follow the response-mapping rules in the second block of the number judgment tasks. Additionally, the data of two participants in the magnitude comparison task and one participant in the parity judgment task were incomplete due to their withdrawal from the experiment, stating its extended duration. Consequently, a total of 53 participants (41 females; $M_{\text{age}}$ = 21.68 years, range = 18-30 years, $SD_{age}$ = 1.65) completed Pilot Study 2, with 28 participants assigned to the parity judgment task and 25 to the magnitude comparison task. Among them, 50 participants were right-handed. None had prior experience with studies exploring number-space relationships. All participants provided written informed consent and reported being in good health.

#### *2.2.1.2. Stimuli and Apparatus*

The stimuli consisted of single-digit numbers from 1 to 9, excluding 5. In the number judgment tasks, each number was presented in black Courier font (48-point) at the center of the screen. For the WM loads, numbers were presented in black Times New Roman font (48-point) on either the left- or right-side of the screen. All stimuli were displayed on a white background to enhance visibility. Different font types were used for each task to create a clear contrast, signaling the upcoming task. Stimuli presented using SuperLab software (Version 4.0, Cedrus, Inc.) and responses were recorded via a Turkish QWERTY keyboard. For the number judgment tasks, participants used the “A” and “İ” keys to respond to the numbers. For the WM loads, half of the participants responded to the target numbers using the “B” key and to the non-targets using the “N”. The other half responded with the reverse key assignments.

#### *2.2.1.3. The SNARC Effect (The Number Judgment Tasks: Parity Judgment and Magnitude Comparison)*

In the baseline (no load) number judgment tasks (parity judgment and magnitude comparison), each number “1, 2, 3, 4, 6, 7, 8, and 9” was displayed at the center of the screen following a fixation cross (300 ms). Each number remained for 1500 ms or until a response was made, followed by an inter-stimulus interval (ISI) of 1000 ms (van Dijck and Fias, 2011). Each number was presented 9 times (once for practice), resulting in a total of 64 trials per block. Two blocks, with response-mapping rule reversed between blocks, allowed participants to evaluate a total of 144 numbers, including practice trials. The order of the SNARC response mappings was counterbalanced: some participants began with a compatible response-mapping rule (e.g., for parity judgment: odd-left/even-right; for magnitude comparison: small-left/large-right), while others started with an incompatible rule (e.g., for parity judgment: odd-right/even-left; for magnitude comparison: small-right/large-left).

For the number judgment tasks under WM loads, the same procedure was followed; however, each number was presented following the completion of an *n*-back judgment.

#### *2.2.1.4. Working Memory Loads (The n-back Task)*

The 1-back procedure was employed for the WM task, which consisted of three load types: space load, magnitude load, and magnitude-space load. In each WM load type, following a fixation cross (500 ms), the numbers (1, 2, 3, 4, 6, 7, 8, and 9) were presented on either the left or right side of the screen for 2000 ms or until a response was made (Deng et al., 2017). Each number was displayed 8 times, resulting in a total of 64 $n$-back judgments per block, comprising 12 target and 52 non-target trials. The occurrence of targets and non-targets was determined pseudorandomly to maintain a consistent rate for each number as both target and non-target. MNL compatible and MNL incompatible loads were administered in separate blocks within each WM load type. Participants completed the tasks across two blocks: in one block, numbers were presented in an MNL compatible arrangement (e.g., ‘1’ on the left and ‘9’ on the right), and in the other, numbers were presented in an MNL incompatible arrangement (e.g., ‘1’ on the right and ‘9’ on the left). Each block included all three WM load types, with participants completing six trials in total, ensuring a balanced and unbiased sequence of tasks. Within each number judgment task, some participants completed the MNL compatible loads first, followed by the MNL incompatible loads, whereas others followed the reverse order. The order of MNL compatibility was counterbalanced across participants, and the presentation order of the WM load types within each block was randomized.

#### ***2.2.1.5. Design***

Pilot Study 2 employed a mixed-design with a 2 X 2 X 4 X 2 X 2 structure. The first factor was the number judgment task (parity judgment, magnitude comparison), which was a between-subject factor. The second factor was the MNL compatibility (compatible, incompatible). The third factor was the WM load type (baseline, space load, magnitude load, magnitude-space load). The fourth factor was the magnitude (small, large) and the fifth factor was the response-side (left, right), which were within-subjects factors, repeated across participants.

#### ***2.2.1.6. Procedure***

Participants were asked to fill out the Participant Information Form, Informed Consent Form, Demographic Information Form, and Edinburgh Handedness Inventory. Participants were assigned to either the parity judgment or magnitude comparison task. Seated approximately 65 cm from the monitor, they performed the tasks in a soundproof and dimly lit experimental chamber at the Neuroscience of Mind and Behavioral Research Laboratory of Izmir University of Economics, maintaining this position throughout the session. Experimental sessions started with practice trials of the baseline (no load) SNARC task. The experimental procedure for both the parity judgment and magnitude comparison tasks in the baseline (no load) condition followed the same structure as described in Pilot Study 1. However, stimuli numbers and stimulus durations differed from those used in Pilot Study 1. For the parity judgment task, numbers were presented one by one at the center of the screen between left- and right-sided *n*-back stimuli. If the number was odd, participants were instructed to press the “A” key with their left index finger, and if it was even, they pressed the “İ” key with their right index finger. For the magnitude comparison task, participants pressed the “A” key with their left index finger if the number was smaller than 5, and the “İ” key with their right index finger if it was larger than 5.

Before starting the next experimental program, participants were shown an instructional screen explaining the small (1-2-3-4) and large number categories (6-7-8-9). Following this, participants completed a practice session for the upcoming task, where each number was evaluated once, with verbal feedback provided by the researcher. If a participant indicated any misunderstanding or confusion regarding the task, the researcher repeated the practice trial until both the participant and the researcher confirmed that the task was fully understood.

In the space load condition, participants pressed the “B” key with their thumb if the number appearing on the left or right side of the screen were in the same spatial position as the previously presented number (target) and pressed the “N” key if it differed (non-target). For example, if the number 1 appeared on the left and the previously presented number 2 had also appeared on the left, the number 1 was a target, prompting a “B” key press. Conversely, if the number 6 appeared on the right and the previously presented number 4 had appeared on the left, the number 6 was a non-target, requiring a “N” key press.

In the magnitude load condition, participants pressed the “B” key with their thumb if the number appearing on the left or right side of the screen belonged to the same magnitude category as the previously presented number (target) and pressed the “N” key if it differed (non-target). For example, if the number 1 was smaller than 5, and the previously presented number 2 was also smaller than 5, the number 1 was a target, prompting a “B” key press. Conversely, if the number 6 appeared on the right and was larger than 5, while the previously presented number 4 was smaller than 5, the number 6 was a non-target, requiring an “N” key press.

In the magnitude-space load condition, participants pressed the “B” key with their thumb if the number appearing on the left or right side of the screen was in the same spatial position and belonged to the same magnitude category as the previously presented number (target) and pressed the “N” key if it differed (non-target). For example, if the number 1 (smaller than 5), presented on the left, and the previously presented number 2 was also smaller than 5 and shown on the left the number 1 was considered a target, prompting a “B” key press. Conversely, if the number 6 appeared on the right and was larger than 5, while the previously presented number 4 was displayed on the left and was smaller than 5, the number 6 was a non-target, requiring an “N” key press.

For the number judgment tasks under WM loads, numbers were presented one by one at the center of the screen between the left- and right-sided *n*-back stimuli. In the parity judgment task, participants were instructed to press the “A” key with their left index finger if the number was odd, and the “İ” key with their right index finger if it was even. In the magnitude comparison task, participants pressed the “A” key with their left index finger if the number was smaller than 5, and the “İ” key with their right index finger if it was larger than 5.

### *2.2.2. Results*

The main effect of the MNL compatibility order, a variable that must be controlled, was statistically significant, $F_{(1,47)} = 11.90$, $p < .05$, $\eta_p^2 = .20$. Bonferroni corrected pairwise comparisons indicated that participants who completed MNL compatible loads first responded faster than those who completed it later ($M = 1067.24$, $SD = 187.18$; $M = 1258.27$, $SD = 222.82$). Also, MNL compatibility order interacted with MNL compatibility, $F_{(1,47)} = 34.72$, $p < .05$, $\eta_p^2 = .43$. Simple effect analysis revealed that participants who started with the MNL compatible loads responded slower to MNL compatible loads compared to those who started with the MNL incompatible loads, $F_{(1,47)} = 19.31$, $p < .05$, $\eta_p^2 = .29$. Conversely, participants who took MNL incompatible loads first responded slower to MNL incompatible loads than the ones who took MNL compatible loads first, $F_{(1,47)} = 15.48$, $p < .05$, $\eta_p^2 = .25$. The three-way interaction between MNL compatibility, MNL compatibility order, and the number judgment task was found to be statistically significant, $F_{(1,47)} = 34.72$, $p < .05$, $\eta_p^2 = .43$. Simple effect analysis revealed that participants who took parity judgment task and started with MNL compatible loads, responded faster to MNL incompatible loads compared to compatible loads, $F_{(1,47)} = 12.58$, $p < .05$, $\eta_p^2 = .21$, $MD = -116.39$, $SE = 32.81$, whereas participants started with MNL incompatible loads, responded faster to MNL compatible loads compared to incompatible loads, $F_{(1,47)} = 35.42$, $p <$

.05, $\eta_p^2$ = .43, $MD$ = -195.29, $SE$ =32.81. Participants who took magnitude comparison task and started with MNL compatible loads, responded faster to MNL incompatible loads compared to compatible loads, $F_{(1,47)}$ = 7.44, $p$ < .05, $\eta_p^2$ = .14, $MD$ = -100.97, $SE$ = 37.02.

The five-way interaction between MNL compatibility, WM load type, number judgment task, magnitude and response-side was not found statistically significant. However, with the involvement of the MNL compatibility load order, the six-way interaction became statistically significant, $F_{(2,94)}$ = 3.13, $p$ < .05, $\eta_p^2$ = .06. For example, compared to participants who started with MNL incompatible loads, those who started with MNL compatible loads and took parity judgment task responded faster to MNL incompatible loads for small numbers on both the left- and right-sides under space load, left: $F_{(1,47)}$ = 3.78, $p$ < .05, $\eta_p^2$ = .07, $MD$ = -186.32, $SE$ = 95.87, right: $F_{(1,47)}$ = 8.36, $p$ < .05, $\eta_p^2$ = .15, $MD$ = -313.18, $SE$ = 108.31; magnitude load, left: $F_{(1,47)}$ = 5.48, $p$ < .05, $\eta_p^2$ = 10, $MD$ = -254.75, $SE$ = 108.80, right: $F_{(1,47)}$ = 7.40, $p$ < .05, $\eta_p^2$ = .14, $MD$ = -288.82, $SE$ = 106.20; and magnitude-space load, left: $F_{(2,94)}$ = 6.70, $p$ < .05, $\eta_p^2$ = .13, $MD$ = -276.48, $SE$ = 106.81, right: $F_{(1,47)}$ = 10.64, $p$ < .05, $\eta_p^2$ = .19, $MD$ = -304.64, $SE$ = 93.40.

This interaction highlights a potential limitation in the study, where initial exposure to MNL incompatible loads may have influenced the subsequent response strategy or cognitive processing in later blocks. These findings imply that the order of MNL load presentation could act as a confounding variable, potentially biasing the results.

### *2.2.3. Conclusion*

The results of Pilot Study 2 revealed that the order of MNL compatibility acted as a confounding variable. Although participants completed a practice session – apparently insufficient, as later increased in the main study– they often struggled with the initial trials, resulting in failures and incorrect responses. As participants required time to familiarize themselves with the task, their performance improved in subsequent trials. To avoid overwhelming participants, all task conditions in Pilot Study 2 were presented only once. However, this limitation made it difficult to calculate the SNARC effect, particularly when a high number of errors occurred during a single trial. Based on these findings, in the main study, MNL compatibility was treated as a between-subject variable, which also allowed for an increased number of stimuli presentations.

Regarding the *n*-back task, participants reported that managing four response keys ("A" and "İ" for the number judgment task and "B" and "N" for WM loads) and keeping track of the response rules was cognitively demanding. Furthermore, it was observed that participants frequently shifted their finger positions to respond to both target and non-target numbers in the *n*-back task, potentially affecting their reaction times in the number judgment tasks. Maintaining steady finger positioning is critical in SNARC tasks, as disruptions can interfere with the activation of response codes. To address this issue, participants in the main study were required to respond only to targets using their thumbs and the spacebar during the *n*-back tasks. This approach has been documented in previous *n*-back studies (e.g., Jaeggi et al., 2008a, 2008b; Deng et al., 2017).

Additionally, participant feedback revealed that in the magnitude-space load condition, individuals often unintentionally prioritized one task over the other, potentially affecting task interactions. To mitigate this, the main study included an instruction-based approach: half of the participants in each MNL load condition were instructed to prioritize spatial position, while the other half were instructed to prioritize magnitude category during the magnitude-space task. While task prioritization is often uncontrolled in many WM studies (e.g., Jaeggi et al., 2008a, 2008b; Deng et al., 2017), this study followed a controlled approach by manipulating task instructions, as seen in few studies (e.g., Beurskens et al., 2020; Bherer et al., 2008). No significant differences were anticipated between the instruction groups.

Based on the findings and observations from Pilot Study 2, several adjustments were made in the main study to address identified issues and enhance its design. These adjustments included incorporating the MNL compatibility of the load as a between-subject variable, doubling the total number of trials in both practice and the main experiment, reducing the number of response keys in the WM load types, and introducing additional instructions in the magnitude-space load condition to control task prioritization.

# CHAPTER 3: THE MAIN STUDY

## *3.1. Method*

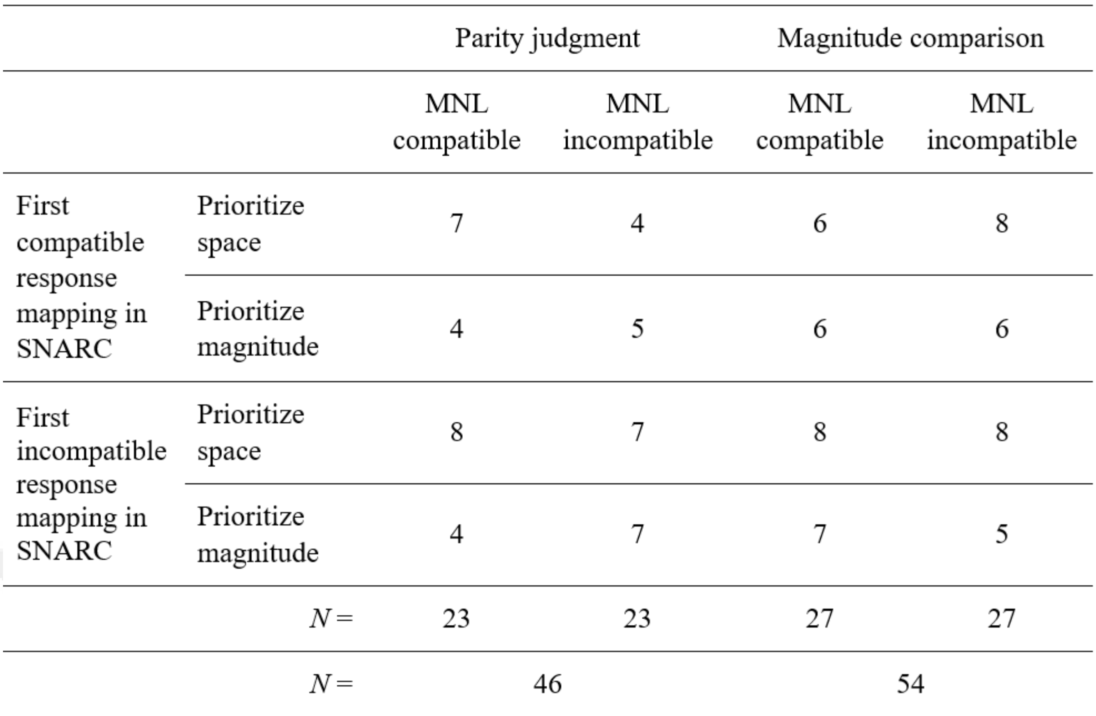
### *3.1.1. Participants*

Data was collected from 110 university students who met the following criteria: right-handed, normal or corrected-to-normal vision, self-reported as healthy, and did not participate in any number judgment studies before. This study was approved by the Ethics Committee of the Izmir University of Economics (approval number: B.30.2.İEÜ.0.05.05-020-156, see Appendix E for Ethical Board Approval). Written informed consent was obtained from all participants, who were then randomly assigned to one of the number judgment tasks. The adequacy of the sample size was calculated using an a priori power analysis in the pwr package of RStudio, based on the two main between-subjects variables: number judgment task (parity vs. magnitude comparison) and MNL compatibility of the WM load (compatible vs. incompatible). With Cohen's $f^2$ as the measure of effect size of .45 for ANOVA, a significance level of .05, and 20 participants per condition (parity judgment and MNL compatible load, parity judgment MNL incompatible load, magnitude comparison and MNL compatible load, and magnitude comparison MNL incompatible load), the calculated power was .95. After reviewing participants' responses, 7 participants were excluded due to inappropriate responses (e.g., pressing the incorrect response key, such as pressing "İ" instead of the instructed "A", for even responses in the SNARC tasks, or failing to respond during the *n*-back task) leaving a sample of 103 participants. Following data processing (see Results Section), 3 additional participants were excluded, resulting in a final sample of 100 participants (67 female, 95 right-handed, $M_{\text{age}}$ = 21.27 years, range = 18-30 years, $SD_{\text{age}}$ = 2.05). At the end of the study, all were given a grocery coupon for their participation. For further details on participant distribution across experimental conditions, see Table 1.

### *3.1.2. Stimuli and Apparatus*

The stimulus characteristics were the same as in Pilot Study 2, with the exception that for the WM loads, responses to target numbers were made using the spacebar, and no response was required for non-targets.

Table 1. Number of Valid Data in Each Experimental Condition



| | | Parity judgment | | Magnitude comparison | |
|---|---|---|---|---|---|
| | | MNL compatible | MNL incompatible | MNL compatible | MNL incompatible |
| First compatible response mapping in SNARC | Prioritize space | 7 | 4 | 6 | 8 |
| | Prioritize magnitude | 4 | 5 | 6 | 6 |
| First incompatible response mapping in SNARC | Prioritize space | 8 | 7 | 8 | 8 |
| | Prioritize magnitude | 4 | 7 | 7 | 5 |
| | *N* = | 23 | 23 | 27 | 27 |
| | *N* = | 46 | | 54 | |

### *3.1.3. The SNARC Effect (The Number Judgment Tasks: Parity Judgment and Magnitude Comparison)*

In the baseline number judgment tasks (parity judgment and magnitude comparison), each number “1, 2, 3, 4, 6, 7, 8, and 9” was displayed at the center of the screen following a fixation cross (300 ms). Each number appeared for 1500 ms or until a response, followed by an ISI of 1000 ms (van Dijck and Fias, 2011). Each number was presented nine times (one for practice), resulting in a total of 64 trials per block. Two blocks, with response codes reversed between blocks and their presentation order was counterbalanced across participants. Some participants started number judgment tasks with compatible response-mapping rule, whereas others with incompatible. Participants evaluated a total of 144 numbers, including practice trials.

For SNARC tasks under WM load types, the same procedure was followed; but each number was presented after completing an *n*-back judgment.

### *3.1.4. Working Memory Loads (The n-back Task)*

The WM load was manipulated exactly the same with Pilot Study 2, with space, magnitude, and magnitude-space loads. Following a 500 ms fixation cross, numbers from 1 to 9, excluding 5, were presented 16 times each for 2000 ms or until a response (Deng et al., 2017), in either MNL compatible or MNL incompatible formats.

In the MNL compatible load condition, smaller numbers appeared on the left-side of the screen, and larger numbers appeared on the right-side (e.g., 1 from the left, 9 from the right). In the MNL incompatible load condition, smaller numbers appeared on the right, and larger numbers on the left (e.g., 1 from the right, 9 from the left). Each trial consisted of 128 *n*-back judgments (24 targets, 104 non-targets) with all three WM load types –space, magnitude, magnitude-space– presented within each block. The number of targets and non-targets were determined pseudorandomly, ensuring that the rate of occurrence for each number as a target and non-target remained constant. Each block also included either compatible or incompatible response mapping rules for the number judgment task, resulting in a total of 6 blocks per participant.

### *3.1.5. Working Memory Capacity (The Digit Span Backward Task)*

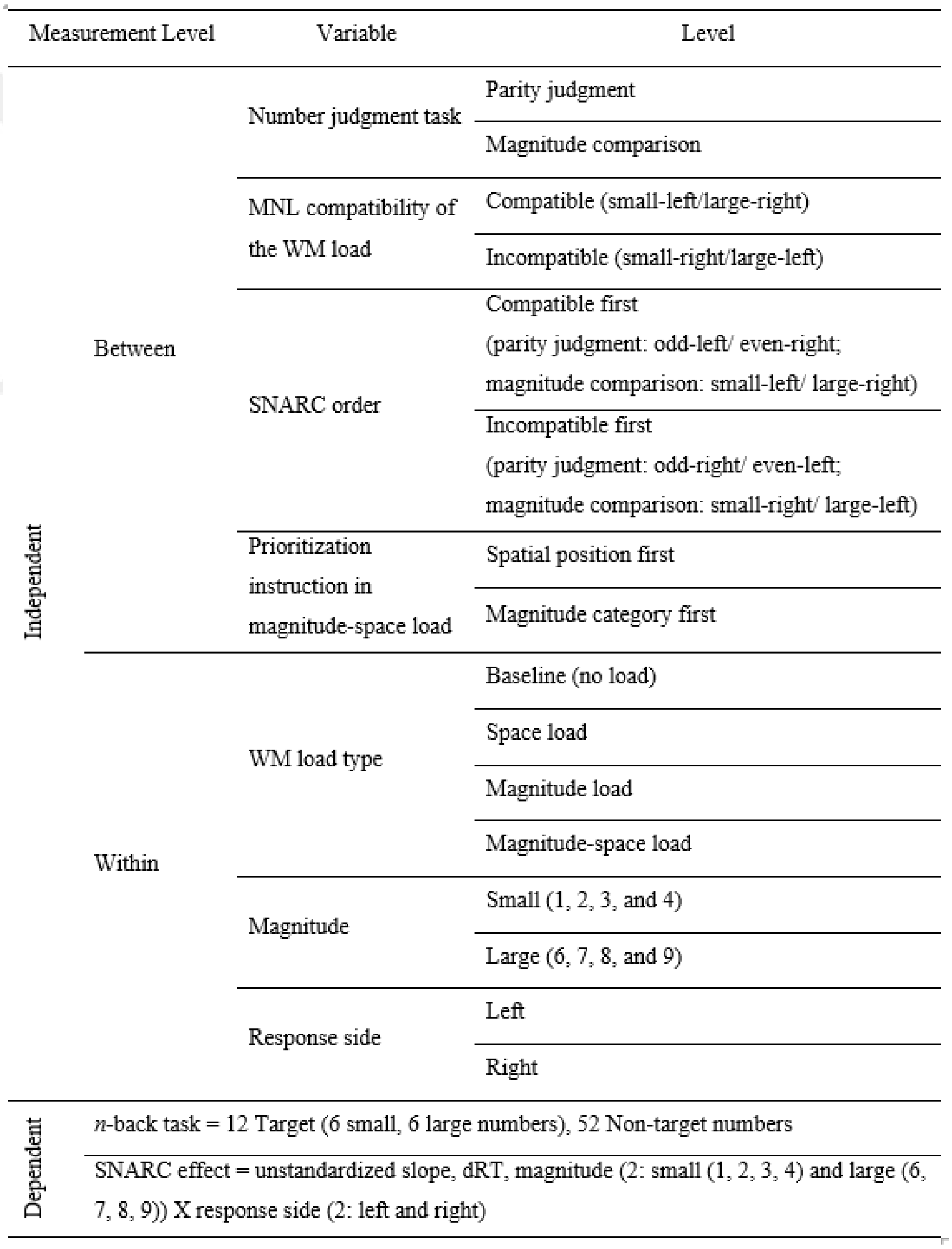
The relationship between the DSB task performance and SNARC measures (e.g., reaction times in number judgment tasks, SNARC slope, and effect size) remains inconclusive. Nevertheless, the DSB task (Wechsler, 1997) was included to assess participants' WM capacity, as WM capacity may influence the SNARC effect. Accounting for individual differences in WM is essential when examining spatial-numerical associations. Therefore, to ensure comparable WM capacities among participants and address these individual differences in relation to the SNARC effect, the DSB task was incorporated.

The DSB task involves recalling digits in reverse order. In this study, digit sequences began with two digits (e.g., 1-5) and increased up to seven digits (e.g., 4-7-3-9-1-2-8). Each sequence was shown twice with unique digits, presented at one per second at the center of the screen. Participants were instructed to repeat each sequence in reverse order as accurately as possible, and responses were recorded manually. The task ended when participants provided incorrect answers for both trials of a sequence. Reproduction of the sequence before completion was not allowed. A sample answer sheet for the DSB task can be found in Appendix D.

### *3.1.6. Design*

The study employed a mixed-design with a 2 X 2 X 4 X 2 X 2 structure. The first factor was the number judgment task (parity judgment, magnitude comparison), and the second factor was the MNL compatibility condition (compatible, incompatible). Both were between-subjects factors. The third factor was the WM load type (baseline, space load, magnitude load, magnitude-space load). The fourth factor was the magnitude (small, large) and the fifth factor was the response-side (left, right) which were within-subjects factors, repeated across participants (see Table 2).

Table 2. Variables of the Dissertation



| Measurement Level | | Variable | Level |
|---|---|---|---|
| Independent | Between | Number judgment task | Parity judgment |
| | | | Magnitude comparison |
| | | MNL compatibility of the WM load | Compatible (small-left/large-right) |
| | | | Incompatible (small-right/large-left) |
| | | SNARC order | Compatible first<br>(parity judgment: odd-left/ even-right;<br>magnitude comparison: small-left/ large-right) |
| | | | Incompatible first<br>(parity judgment: odd-right/ even-left;<br>magnitude comparison: small-right/ large-left) |
| | | Prioritization instruction in magnitude-space load | Spatial position first |
| | | | Magnitude category first |
| | Within | WM load type | Baseline (no load) |
| | | | Space load |
| | | | Magnitude load |
| | | | Magnitude-space load |
| | | Magnitude | Small (1, 2, 3, and 4) |
| | | | Large (6, 7, 8, and 9) |
| | | Response side | Left |
| | | | Right |
| Dependent | *n*-back task = 12 Target (6 small, 6 large numbers), 52 Non-target numbers | | |
| | SNARC effect = unstandardized slope, dRT, magnitude (2: small (1, 2, 3, 4) and large (6, 7, 8, 9)) X response side (2: left and right) | | |

### *3.1.7. Procedure*

Participants were first asked to complete the Participant Information Form (Appendix A), Informed Consent Form (Appendix B), Demographic Information Form, and the Edinburgh Handedness Inventory (Appendix C). Participants were seated approximately 65 centimeters from the monitor in a sound-isolated, dimly lit experimental chamber at the Neuroscience of Mind and Behavioral Research Laboratory of Izmir University of Economics, maintaining this position throughout the experiment. Participants were assigned to either parity judgment or magnitude comparison task.

The experimental session began with practice trials for the baseline number judgment task (no load), followed by the actual baseline task. After completing the baseline SNARC task, participants were randomly assigned to one of two conditions: half were assigned to the MNL compatible load condition and the other half to the MNL incompatible load condition. The WM loads were then introduced, followed by the number judgment task.

Once the practice trials were completed, the experimental blocks commenced. For the first block, the presentation order of the WM load types was kept constant for all participants, starting with the space load, followed by the magnitude load, and then the magnitude-space load. To control for order effects, the sequence of WM load types was randomized across participants for the second and third blocks (see Jaeggi et al., 2008b for a similar procedure).

Prior to beginning the next experimental session, participants viewed an instructional screen outlining the small (1-2-3-4) and large number categories (6-7-8-9). Subsequently, they completed a practice session for the upcoming task, during which each number was presented and evaluated once, with verbal feedback provided by the researcher. If a participant expressed confusion or a lack of understanding regarding the task, the researcher repeated the practice session until both parties confirmed that the task instructions were clear and properly understood.

In the space load condition, participants were instructed to press the spacebar with their thumb if the number appearing on the left- or right-side of the screen matched the spatial position of the previously presented number (target).

In the magnitude load condition, participants were required to press the spacebar with their thumb if the number belonged to the same magnitude category (small or large) as the preceding number (target).

In the magnitude-space load condition, participants were instructed to press the spacebar with their thumb if the number matched both the spatial position and magnitude category of the preceding number (target). To address potential task prioritization in this condition, participants were given explicit instructions before the magnitude-space load. Some participants were instructed to prioritize spatial position first, then magnitude, while others were instructed to prioritize magnitude first, then spatial position. No response was required for non-targets in any of the WM load conditions. The number judgment tasks under WM loads followed the same procedure as in Pilot Study 2.

Finally, participants' WM capacity was assessed using the DSB task, which concluded the experiment. For a visual representation of the study's experimental flow under the MNL compatible condition, see Figure 1, and under the MNL incompatible condition, see Figure 2 (Note that in both figures only compatible SNARC trials were presented in the SNARC tasks).

### *3.2. Data Pre-processing*

For the number judgment tasks, practice trials were not analyzed. First, reaction times (RTs) faster than 200 ms (accounting for less than 1% of all trials) and incorrect responses were not included. Second, RTs that were above or below 2.5 *SD*s from each participant's mean RT were excluded. Overall, 87.94% of the data was valid and analyzed further (see Table 3 for detailed information about percentages).

For the *n*-back tasks, RTs faster than 100 ms (accounting for less than 1% of all trials) were not included (Gajewski et al., 2018, Verhaeghen and Basak, 2005). Then, participants with RTs above or below three *SDs* from their mean within each *n*-back task were identified as outliers resulting in the exclusion of one participant from the analysis (Deng et al., 2017; Miller et al., 2007; Jaeggi et al., 2008b). In addition, two participants with extreme RT values were removed from the analysis.

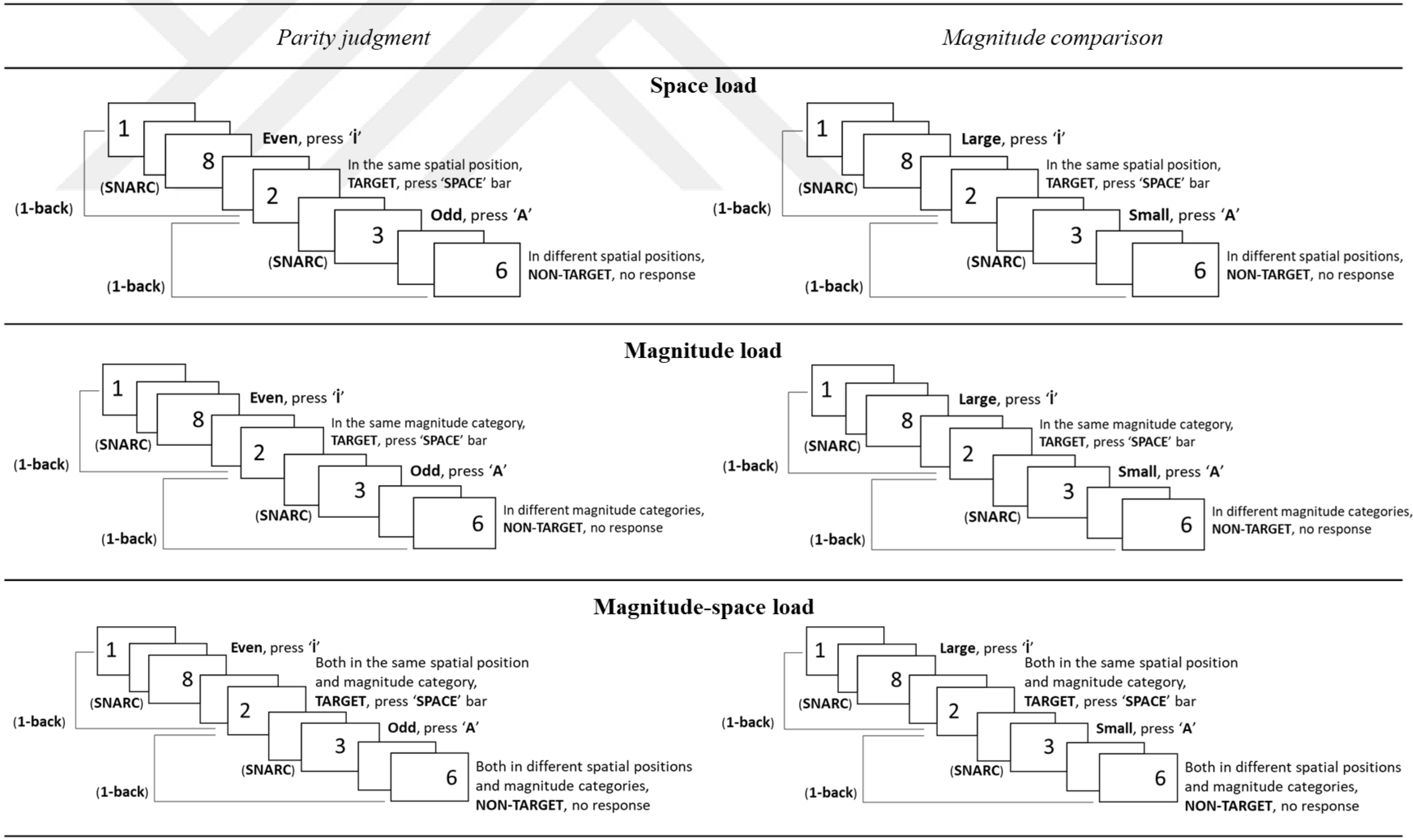


Figure 1. Experimental Flow for the MNL Compatible Condition

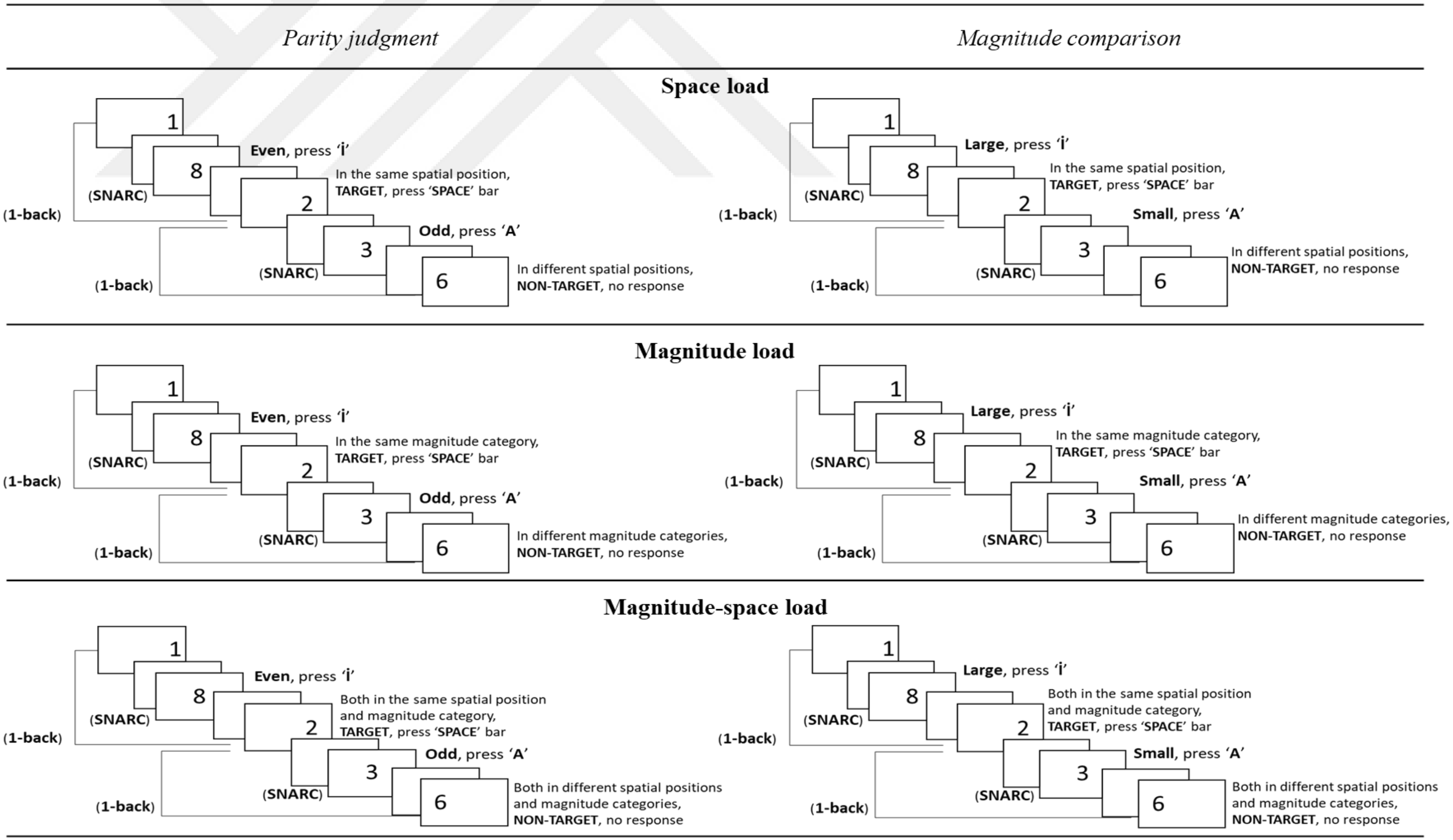
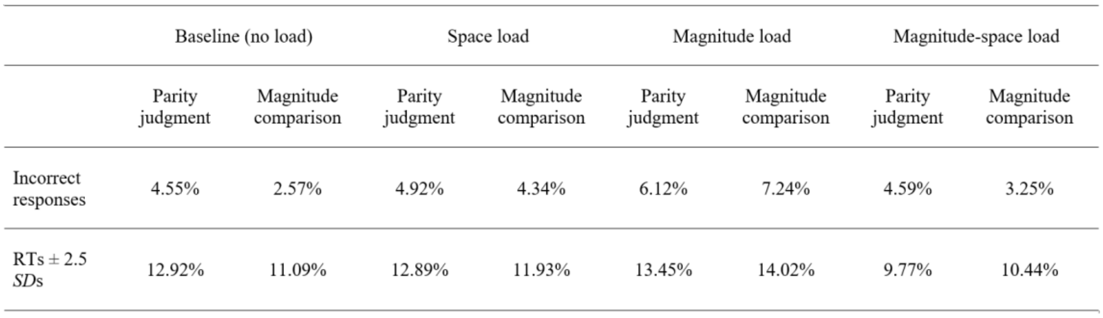


Figure 2. Experimental Flow for the MNL Incompatible Condition

Table 3. Detailed Percentages of Excluded Data in Number Judgment Tasks



| | Baseline (no load) | | Space load | | Magnitude load | | Magnitude-space load | |
|---|---|---|---|---|---|---|---|---|
| | Parity judgment | Magnitude comparison | Parity judgment | Magnitude comparison | Parity judgment | Magnitude comparison | Parity judgment | Magnitude comparison |
| Incorrect responses | 4.55% | 2.57% | 4.92% | 4.34% | 6.12% | 7.24% | 4.59% | 3.25% |
| RTs ± 2.5 *SD*s | 12.92% | 11.09% | 12.89% | 11.93% | 13.45% | 14.02% | 9.77% | 10.44% |

### *3.3. Data Analysis*

To provide a comprehensive analysis of how magnitude-space-based numerical WM loads impact the SNARC effect under different number judgment tasks, the SNARC effect was analyzed using three approaches: 1) linear regression, 2) difference reaction times analysis (dRTs), and 3) interaction between magnitude and response-side on RTs. (1) Linear regression analysis examines the nature of spatial-numerical mappings, indicating whether participants exhibit a regular (left-to-right), reverse (right-to-left) SNARC effect, or whether the effect is strengthened, or weakened under different WM load types. (2) dRTs focus on how numerical magnitude affects reaction times across conditions, specifically how RT varies by magnitude and response-side. A significant linear trend in dRTs indicates the presence of either a regular (negative) or reverse (positive) SNARC. (3) Interaction between magnitude and response-side on RTs assesses the presence of a regular or reverse SNARC effect, supporting the long-term spatial representation of numbers. While RTs reflect spatial-numerical associations (via regular and reverse SNARC effects), they also show how different types of WM loads affect participants’ ability to process and respond to numerical tasks.

The classical way of analyzing the SNARC is the linear regression approach (Fias et al., 1996). For each participant and each number, dRT score was calculated by subtracting the mean RTs of left-sided responses from the mean RTs of right-sided responses. Each participant’s dRTs were then entered into a regression analysis with magnitude as the predictor variable. Negative regression slopes indicate the SNARC effect, with faster left-sided responses for small numbers and faster right-sided responses for large numbers. The unstandardized SNARC slopes of each participant across experimental conditions were used for further analysis. In addition to the

SNARC effect, linguistic markedness of response codes (MARC) effect (Nuerk et al., 2004) might occur specifically in the parity judgment task, characterized by faster left-sided responses to odd numbers and faster right-sided responses to even numbers. Therefore, the MARC effect was also analyzed for the parity judgment tasks. To determine the presence of a significant SNARC (and MARC) effect at the group level, unstandardized slopes were tested against 0 using a one-sample *t* test. To further examine the differential effects of WM load type and MNL compatibility condition on the SNARC effect across number judgment tasks, a mixed design ANOVA was conducted on the unstandardized slopes (see van Dijck et al., 2009; Deng et al., 2017), with number judgment task (parity judgment, magnitude comparison) and MNL compatibility condition (compatible, incompatible) as between-subject variables and WM load type (baseline, space load, magnitude load, and magnitude-space load) as a within-subjects variable.

Although regression slopes reflect the linear relation between numbers and dRT, the effect size cannot be determined in terms of proportion of individual variance within RTs. Therefore, in addition to linear regression approach, a mixed design ANOVA of dRT with magnitude (very small: 1 and 2, small: 3 and 4, large: 6 and 7, very large: 8 and 9) as a within-subject factor was used to measure the SNARC, as recommended by Pinhas, Tzelgov, and Ganor-Stern (2012). A significant main effect of magnitude associated with a significant linear trend indicates the presence of the SNARC effect.

As initially revealed by Dehaene et al. (1993) and utilized in several studies that examine the role of WM in number-space association (Herrera et al., 2008; van Dijck and Fias, 2011; Wang et al., 2018), the interaction between magnitude (small/large) and response-side (left/right) on average RTs was also explored. A significant interaction effect, identified through mixed design ANOVA, was accepted as an indicator of the SNARC effect (van Dijck and Fias, 2011). Additionally, the potential interactions between magnitude, response-side, and WM load type, as well as between magnitude, response-side, and MNL compatibility of the load, were examined to determine whether the SNARC effect was moderated by either the WM load type, the MNL compatibility condition, or both. Therefore, a mixed design ANOVA was conducted on the RTs in number judgment tasks (see van Dijck et al., 2009; Deng et al., 2017), with number judgment task (parity judgment, magnitude comparison) and MNL compatibility condition (compatible, incompatible) as between-subject variables and WM load type (baseline, space load, magnitude load, and magnitude-space load), magnitude (small, large) and response-side (left, right) as within-subjects variables.

To ensure that WM load types generated cognitive load in participants and to examine their differential effects as WM loads, a mixed design ANOVA was conducted on the mean accuracy percentages and RTs of the *n*-back tasks. The analysis included number judgment task (parity judgment, magnitude comparison) and MNL compatibility condition (compatible, incompatible) as between-subject variables, and WM load type (space load, magnitude load, and magnitude-space load) as a within-subject variable.

Lastly, the WM capacity of participants, as measured by the DSB task, was compared across those assigned to different number judgment tasks using a one-way ANOVA to determine whether participants differed in their WM capacities. Additionally, because in the literature the relationship between WM capacity and different outcome variables of the SNARC effect (slope, size, and RTs) remains inconclusive, a correlational analysis was conducted. This analysis examined the relationship between WM capacity and unstandardized slopes and RTs in baseline and WM load conditions, as well as for each number judgment task.

### *3.4. Results*

The results section begins by presenting findings on how MNL compatibility conditions and WM load types influence the SNARC effect through linear regression, dRT analyses, and ANOVAs on reaction time measures in number judgment tasks, focusing on interactions involving magnitude and response-side. Next, ANOVA results are reported, examining the impact of MNL compatibility conditions and WM load types on accuracy and reaction times in the *n*-back task. Finally, an ANOVA investigating whether participants' WM capacities differed is presented, along with correlational analyses exploring the relationship between WM capacity and SNARC outcomes.

### *3.4.1. The SNARC Effect (The Number Judgment Tasks: Parity Judgment and Magnitude Comparison)*

#### *3.4.1.1. T-test Analysis Results on SNARC Slopes Obtained from the Number Judgment Tasks*

For both the parity judgment (including MARC slopes, specific to this task) and the magnitude comparison, one-sample *t*-tests revealed that unstandardized SNARC slopes did not significantly deviate from zero under any of the loads: baseline (no load), space load, magnitude load, or magnitude-space loads (see Tables 4 and 5, respectively). The non-significant finding of the MARC effect indicates that the parity status of numbers did not interfere with magnitude judgments.

Table 4. SNARC and MARC Effects in the Parity Judgment across WM Load Types

| *Slope* | *M* | *SD* | *t* (45) | *p* |
|---|---|---|---|---|
| Unstandardized SNARC baseline (no load) | 2.03 | 10.35 | 1.33 | .19 |
| Unstandardized SNARC space load | -1.26 | 19.49 | -.44 | .66 |
| Unstandardized SNARC magnitude load | -4.82 | 23.24 | -1.41 | .17 |
| Unstandardized SNARC magnitude-space load | 1.57 | 21.99 | .49 | .63 |
| Unstandardized MARC baseline (no load) | 4.41 | 73.60 | .40 | .69 |
| Unstandardized MARC space load | -48.23 | 232.83 | -1.41 | .17 |
| Unstandardized MARC magnitude load | 15.70 | 304.36 | .35 | .73 |
| Unstandardized MARC magnitude-space load | -58.95 | 268.64 | -1.49 | .14 |

Table 5. SNARC Effects in the Magnitude Comparison Task across WM Load Types

| *Slope* | *M* | *SD* | *t (53)* | *p* |
|---|---|---|---|---|
| Unstandardized SNARC baseline (no load) | -.15 | 12.93 | -.09 | .93 |
| Unstandardized SNARC space load | 4.75 | 47.02 | .74 | .46 |
| Unstandardized SNARC magnitude load | 13.19 | 55.25 | 1.76 | .09 |
| Unstandardized SNARC magnitude-space load | 9.66 | 51.38 | 1.38 | .17 |

#### *3.4.1.2. ANOVA Results on SNARC Slopes in Number Judgment Tasks*

To further investigate the differential effects of WM load type and MNL compatibility on the SNARC effect, a 2(number judgment task: parity judgment, magnitude comparison) X 2(MNL compatibility: compatible, incompatible) X 4(WM load type: baseline, space load, magnitude load, and magnitude-space load) mixed design ANOVA was conducted on unstandardized slopes.

The main effect of MNL compatibility was statistically significant, $F_{(1,96)} = 12.16$, $p < .05$, $\eta_p^2 = .11$. Bonferroni corrected pairwise comparisons indicated that participants assigned to the MNL compatible condition showed a regular SNARC effect (a decreasing linear trend as a function of magnitude) compared to those in the incompatible condition who showed a reverse SNARC effect (an increasing linear trend as a function of magnitude (*MD* = -17.77, $p < .05$) (see Figure 3).

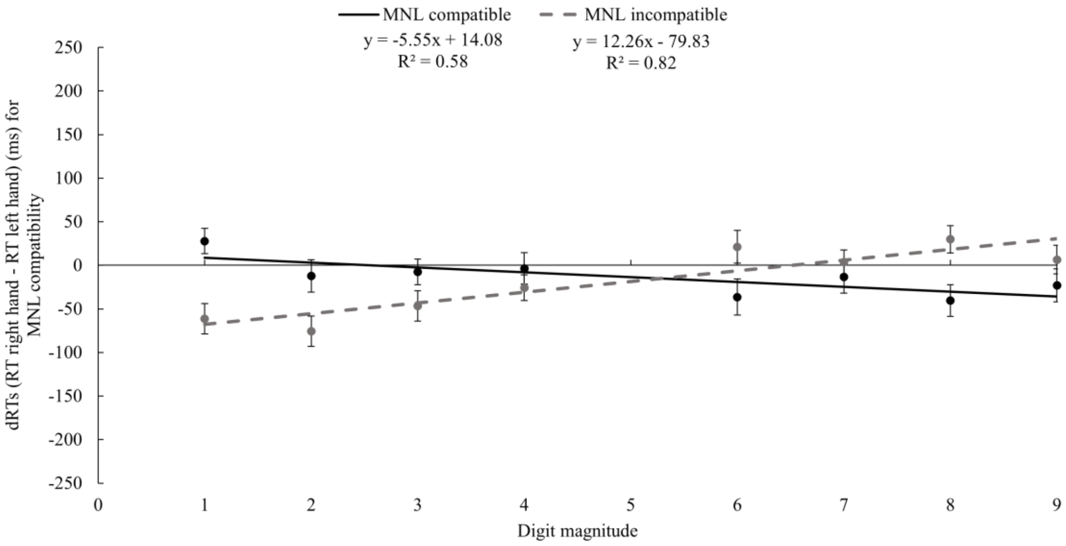


Figure 3. A Regular SNARC Effect in MNL Compatible Condition and a Reverse SNARC Effect in MNL Incompatible. Error Bars Represent 95% CIs, Adjusted for Repeated Measures

The interaction between MNL compatibility and WM load was statistically significant, $F_{(3,288)} = 7.84$, $p < .05$, $\eta_p^2 = .08$. Bonferroni corrected simple effect analysis showed that unstandardized slopes differed significantly among WM load types in the MNL incompatible condition, $F_{(3,94)} = 4.47$, $p < .05$, $\eta_p^2 = .13$. Compared to baseline, participants who took MNL incompatible load showed a reverse SNARC effect in magnitude load (*MD* = -20.00, *SE* = 5.72) and magnitude-space load (*MD* = -16.46, *SE* = 5.40) (see Figure 4).

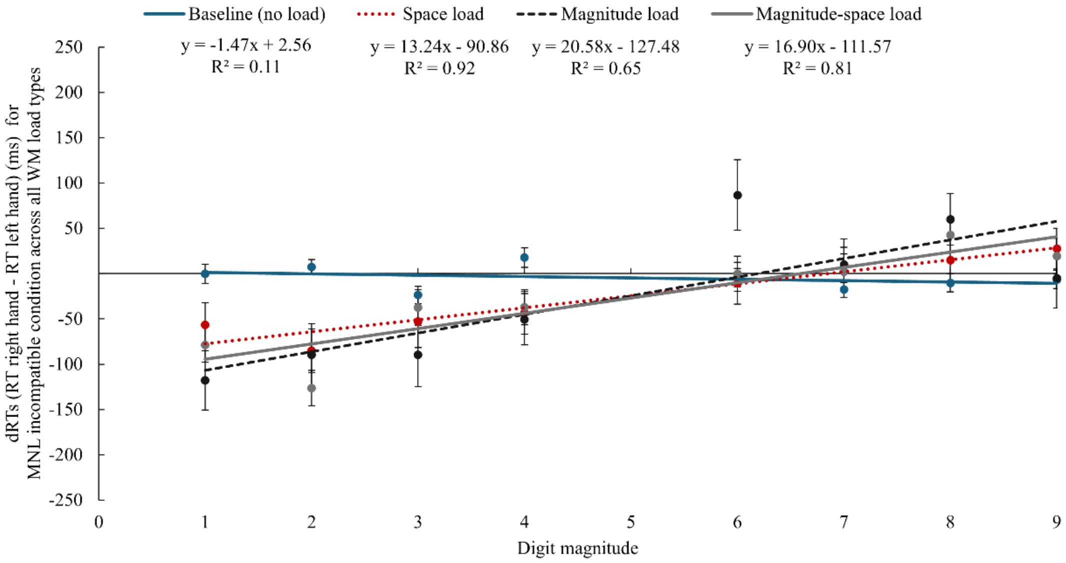


Figure 4. Reverse SNARC Effects in the MNL Incompatible Condition Under Magnitude Load and Magnitude-Space Load Compared to Baseline (no load). Error Bars Represent 95% CIs, Adjusted for Repeated Measures

A significant interaction between WM load type and number judgment task was also observed, $F_{(3,288)} = 2.63$, $p < .05$, $\eta_p^2 = .03$. Bonferroni corrected simple effect analysis revealed that unstandardized slopes significantly differed between the parity judgment and magnitude comparison tasks under the magnitude load, $F_{(1,96)} = 4.91$, $p < .05$, $\eta_p^2 = .05$. Specifically, a stronger regular SNARC effect was observed in the parity judgment task compared to magnitude comparison (*MD* = -18.02, *SE* = 8.13) under the magnitude load.

Moreover, a significant three-way interaction of WM load type, MNL compatibility, and the number judgment task was observed, $F_{(3,288)} = 2.80$, $p < .05$, $\eta_p^2 = .03$. Bonferroni corrected simple effect analysis revealed that unstandardized slopes differed significantly between WM load types for the magnitude comparison task under the MNL incompatible condition, $F_{(3,94)} = 8.79$, $p < .05$, $\eta_p^2 = .22$. Compared to baseline, a diminished SNARC effect was observed under the space load (*MD* = -22.65, *SE* = 6.76), magnitude load (*MD* = -38.32, *SE* = 7.76), and magnitude-space load (*MD* = -31.33, *SE* = 7.32) for the participants who took MNL incompatible condition in the magnitude comparison task, indicating reverse SNARC effects (see Figure 5) Other main effects and interactions did not reach statistical significance (*F*s < 2.63, *p*s > .05).

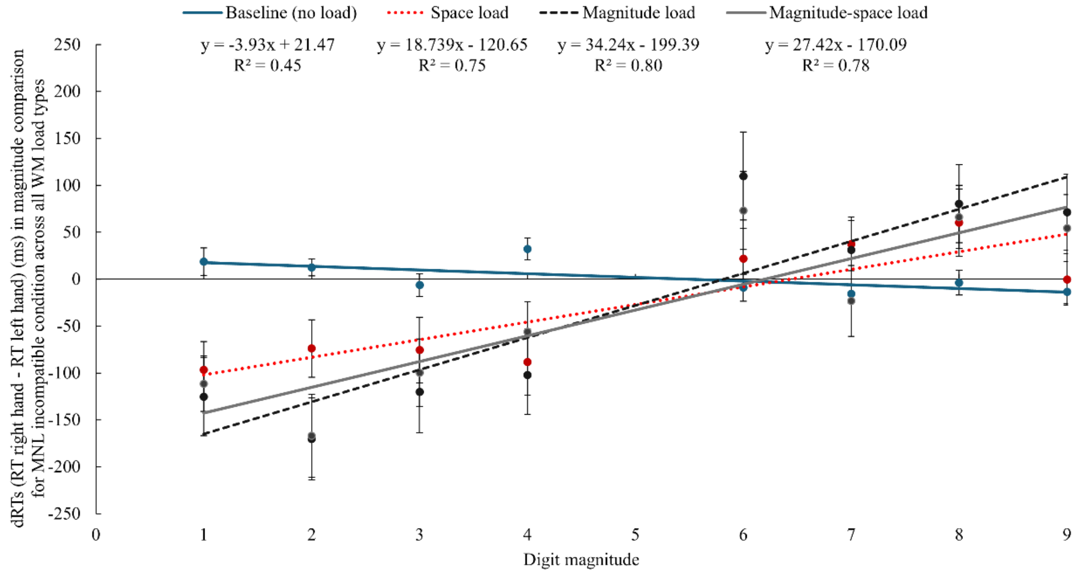


Figure 5. Reverse SNARC Effects in the MNL Incompatible Condition Under Space Load, Magnitude Load, and Magnitude-Space Load Compared to Baseline (no load) in Magnitude Comparison. Error Bars Represent 95% CIs, Adjusted for Repeated Measures

#### *3.4.1.3. ANOVA Results on Difference Reaction Time (dRT) Measures in Number Judgment Tasks*

A 2(number judgment task: parity judgment, magnitude comparison X 2(MNL compatibility of the load: compatible, incompatible) X 2(magnitude: very small = 1 and 2, small = 3 and 4, large = 6 and 7, very large = 8 and 9) X 4(WM load type: baseline, space load, magnitude load, and magnitude-space load) mixed design ANOVA was conducted on dRT measures.

A statistically significant interaction between MNL compatibility and magnitude was found, $F_{(3,285)} = 9.70$, $p < .05$, $\eta_p^2 = .09$, associated with a significant linear trend, $F_{(1,95)} = 13.38$, $p < .05$, $\eta_p^2 = .12$, meaning that the SNARC effect differed between MNL compatible and incompatible conditions. Bonferroni corrected simple effect analysis revealed a significant reverse SNARC in MNL incompatible condition, $F_{(3,93)} = 4.29$, $p < .05$, $\eta_p^2 = .12$. The significant linear trend as a function of magnitude can be seen in Figure 3.

The interaction between MNL compatibility, WM load, and magnitude was found statistically significant, $F_{(9,855)} = 4.29$, $p < .05$, $\eta_p^2 = .04$, associated with a significant linear trend, $F_{(1,95)} = 11.72$, $p < .05$, $\eta_p^2 = .\ 11$. Bonferroni corrected simple effect analysis indicated a significant reverse SNARC effect for MNL incompatible condition under magnitude load, $F_{(3,953)} = 3.85$, $p < .05$, $\eta_p^2 = .11$, and magnitude-space load, $F_{(3,953)} = 4.71$, $p < .05$, $\eta_p^2 = .13$. Figure 4 illustrates the significant linear trend as a function of magnitude.

The interaction between MNL compatibility, WM load, the number judgment task, and magnitude was found statistically significant, $F_{(9,855)} = 1.91$, $p = .047$, $\eta_p^2 = .02$, associated with a significant linear trend, $F_{(1,95)} = 5.74$, $p < .05$, $\eta_p^2 = .\ 06$. Bonferroni corrected simple effect analysis revealed a significant reverse SNARC effect in magnitude comparison task for MNL incompatible condition under space load, $F_{(3,93)} = 2.63$, $p = .05$, $\eta_p^2 = .08$, magnitude load, $F_{(3,93)} = 5.36$, $p < .05$, $\eta_p^2 = .15$, and magnitude-space load, $F_{(3,93)} = 4540$, $p < .05$, $\eta_p^2 = .15$. A significant linear trend as a function of magnitude is displayed in Figure 5.

Lastly, significant interactions were found between MNL compatibility, the number judgment task, and magnitude, $F_{(3,285)} = 3.05$, $p < .05$, $\eta_p^2 = .03$, as well as WM load, the number judgment task, and magnitude were found statistically significant, $F_{(9,855)} = 1.92$, $p < .05$, $\eta_p^2 = .02$. However, the trend analyses for these interactions did not reach statistical significance.

### *3.4.1.4. ANOVA Results on Reaction Time Measures in Number Judgment Tasks*

A 2(number judgment task: parity judgment, magnitude comparison X 2(MNL compatibility of the load: compatible, incompatible X 4(WM load type: baseline, space load, magnitude load, and magnitude-space load) X 2(magnitude: small, large) X 2(response-side: left, right) mixed design ANOVA was conducted on RTs in number judgment tasks.

The main effect of WM load type was statistically significant, $F_{(3,285)} = 310.85$, $p < .05$, $\eta_p^2 = .77$. Bonferroni corrected pairwise comparisons indicated that participants responded significantly faster under space load (*MD* = -365.77, $p < .05$), magnitude load (*MD* = -492.10, $p < .05$), and magnitude-space load (*MD* = -441.61, $p < .05$) compared to the baseline (Figure 6).

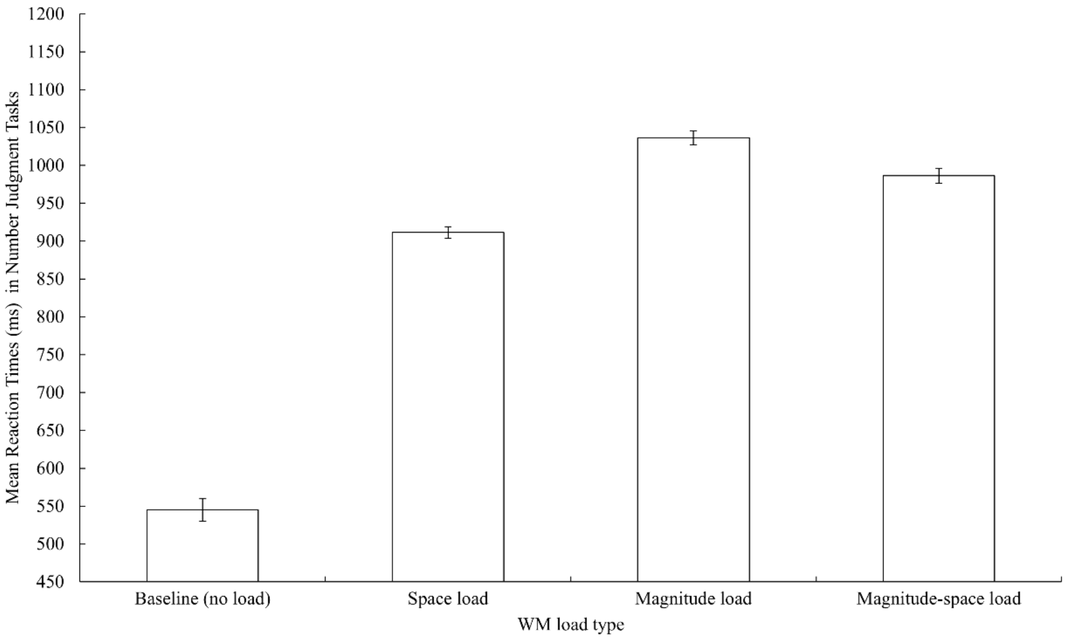


Figure 6. Mean RTs as a Function of WM Load Type. Error Bars Represent 95% CIs, Adjusted for Repeated Measures

The main effect of magnitude was statistically significant, $F_{(1,95)} = 10.33$, $p < .05$, $\eta_p^2 = .10$. Bonferroni corrected pairwise comparisons revealed that participants responded significantly faster to small numbers than to large ones ($MD = -11.23$, $p < .05$). The main effect of response-side was also found significant, $F_{(1,95)} = 24.21$, $p < .05$, $\eta_p^2 = .20$, with Bonferroni corrected pairwise comparisons indicating that right-sided responses were faster than left-sided ones ($MD = -18.53$, $p < .05$). Lastly, the main effect of the number judgment task was significant, $F_{(1,95)} = 5.52$, $p < .05$, $\eta_p^2 = .06$. Bonferroni corrected pairwise comparisons indicating that participants who took magnitude comparison task responded significantly faster than those who performed parity judgment ($MD = -87.24$, $p < .05$).

In terms of interaction effects, the interaction between the number judgment task and magnitude was statistically significant, $F_{(1,95)} = 10.79$, $p < .05$, $\eta_p^2 = .10$. Bonferroni corrected simple effect analysis indicated that the RTs significantly differed between small and large numbers for the parity judgment task, $F_{(1,95)} = 10.79$, $p < .05$, $\eta_p^2 = .10$. Participants who performed parity judgment responded to small numbers faster than to large ones ($MD = -22.71$, $SE = 5.11$). Also, the interaction of WM load type and response-side was statistically significant, $F_{(3,285)} = 2.90$, $p < .05$, $\eta_p^2 = .03$. Bonferroni corrected simple effect analysis indicated that the RTs significantly differed between left-sided and right-sided responses across all WM load types: baseline, $F_{(1,95)} = 5.69$, $p < .05$, $\eta_p^2 = .06$; space, $F_{(1,95)} = 15.64$, $p < .05$, $\eta_p^2 = .14$; magnitude, $F_{(1,95)} = 7.67$, $p < .05$, $\eta_p^2 = .08$; and magnitude-space loads, $F_{(1,95)} = 16.60$, $p < .05$, $\eta_p^2 = .15$. In all WM load types, right-sided responses were significantly faster than left-sided responses, (baseline: $MD = -5.95$, $SE = 2.49$; space load: $MD = -20.57$, $SE = 5.20$; magnitude load: $MD = -21.70$, $SE = 7.83$; magnitude-space load: $MD = -25.91$, $SE = 6.36$).

A significant three-way interaction of MNL compatibility, WM load type, and magnitude was observed, $F_{(3,285)} = 3.25$, $p < .05$, $\eta_p^2 = .03$. Bonferroni corrected simple effect analysis showed that RTs significantly differed between small and large numbers under the magnitude load for MNL compatible condition, $F_{(1,95)} = 7.89$, $p < .05$, $\eta_p^2 = .08$. Participants in the MNL compatible load condition responded significantly faster to small numbers than to large ones when the WM load type was magnitude (*MD* = -27.86, *SE* = 9.92). Furthermore, for MNL incompatible loads, Bonferroni corrected simple effect analysis indicated that RTs significantly differed between small and large numbers under magnitude-space load, $F_{(1,95)} = 6.98$, $p < .05$, $\eta_p^2 = .07$. Participants in MNL incompatible condition responded more rapidly to small numbers than to large ones when the WM load was magnitude-space (*MD* = -22.97, *SE* = 8.70).

One of the most important three-way interactions –MNL compatibility, magnitude, and response-side– was found statistically significant, $F_{(1,95)} = 10.96$, $p < .05$, $\eta_p^2 = .10$. Bonferroni corrected simple effect analysis revealed that RTs differed between small and large numbers under the MNL compatible load for left-sided responses, $F_{(1,95)} = 8.47$, $p < .05$, $\eta_p^2 = .08$, but not for right-sided responses, $F_{(1,95)} = .07$, $p > .05$. Participants in the MNL compatible condition responded significantly faster to small numbers than to large ones with left-sided responses (*MD* = -32.53, *SE* = 11.18), indicating a regular SNARC effect (see the left-side of Figure 7). Additionally, Bonferroni corrected simple effect analysis indicated that RTs differed between small and large numbers in the MNL incompatible condition for both left-sided responses, $F_{(1,95)} = 4.48$, $p < .05$, $\eta_p^2 = .05$, and right-sided responses, $F_{(1,95)} = 10.61$, $p < .05$, $\eta_p^2 = .10$. Participants in the MNL incompatible condition responded significantly faster to large numbers than to small ones with left-sided responses (*MD* = -23.45, *SE* = 11.08), and to small numbers than to large ones with right-sided responses (*MD* = -39.00, *SE* = 11.97). Showing the reverse SNARC effect (see the right-side of Figure 7).

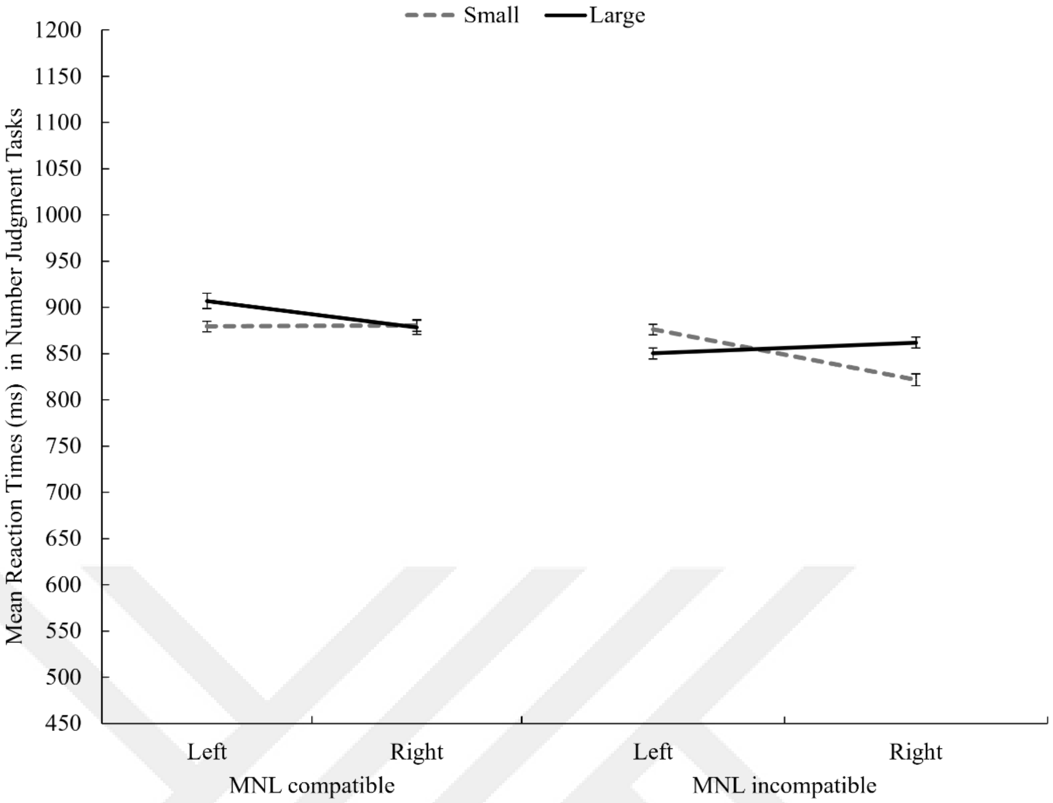


Figure 7. Mean RTs as a Function of MNL Compatibility (Compatible, Incompatible), Magnitude (Small, Large), and Response-Side (Left, Right). Error Bars Represent 95% CIs, Adjusted for Repeated Measures

Furthermore, the four-way interaction between MNL compatibility, WM load type, magnitude, and response-side was found statistically significant, $F_{(3,285)} = 7.09$, $p < .05$, $\eta_p^2 = .07$. Bonferroni corrected simple effect analysis revealed that RTs significantly differed between small and large numbers for left-sided responses in the MNL compatible condition under the space load, $F_{(1,95)} = 5.51$, $p < .05$, $\eta_p^2 = .06$, magnitude load, $F_{(1,95)} = 7.06$, $p < .05$, $\eta_p^2 = .07$, and magnitude-space load, $F_{(1,95)} = 4.76$, $p < .05$, $\eta_p^2 = .05$. Participants who took MNL compatible condition under space load (*MD* = -47.25, *SE* = 17.42), magnitude, and magnitude-space load (*MD* = -46.25, *SE* = 18.49 gave faster left-sided responses to small numbers than to large ones, implying a regular SNARC effect (see Figure 8, the left-side of Panels B, C, and D, respectively). Conversely, Bonferroni corrected simple effect analysis showed that RTs significantly differed between small and large numbers for right-sided responses in the MNL incompatible condition under space load, $F_{(1,95)} = 6.09$, $p < .05$, $\eta_p^2 = .06$, magnitude load, $F_{(1,95)} = 6.14$, $p < .05$, $\eta_p^2 = .06$, and magnitude-space load, $F_{(1,95)} =$

11.61, $p < .05$, $\eta_p^2 = .11$. RTs also differed for left-sided responses between small and large numbers in the MNL incompatible condition under magnitude load, $F_{(1,95)} = 9.71$, $p < .05$, $\eta_p^2 = .09$. Participants in the MNL incompatible condition under space load (*MD* = -42.55, *SE* = 17.25), magnitude load (*MD* = -49.32, *SE* = 19.90), and magnitude-space load (*MD* = -63.12, *SE* = 18.53) gave faster right-sided responses to small numbers than to large numbers (see Figure 8, the right-side of Panels B, C, and D, respectively). Additionally, faster left-sided responses to large numbers than to small numbers under magnitude load (*MD* = -61.36, *SE* = 19.69) revealed the reverse SNARC effect (see Figure 8, the right-side of Panel C).

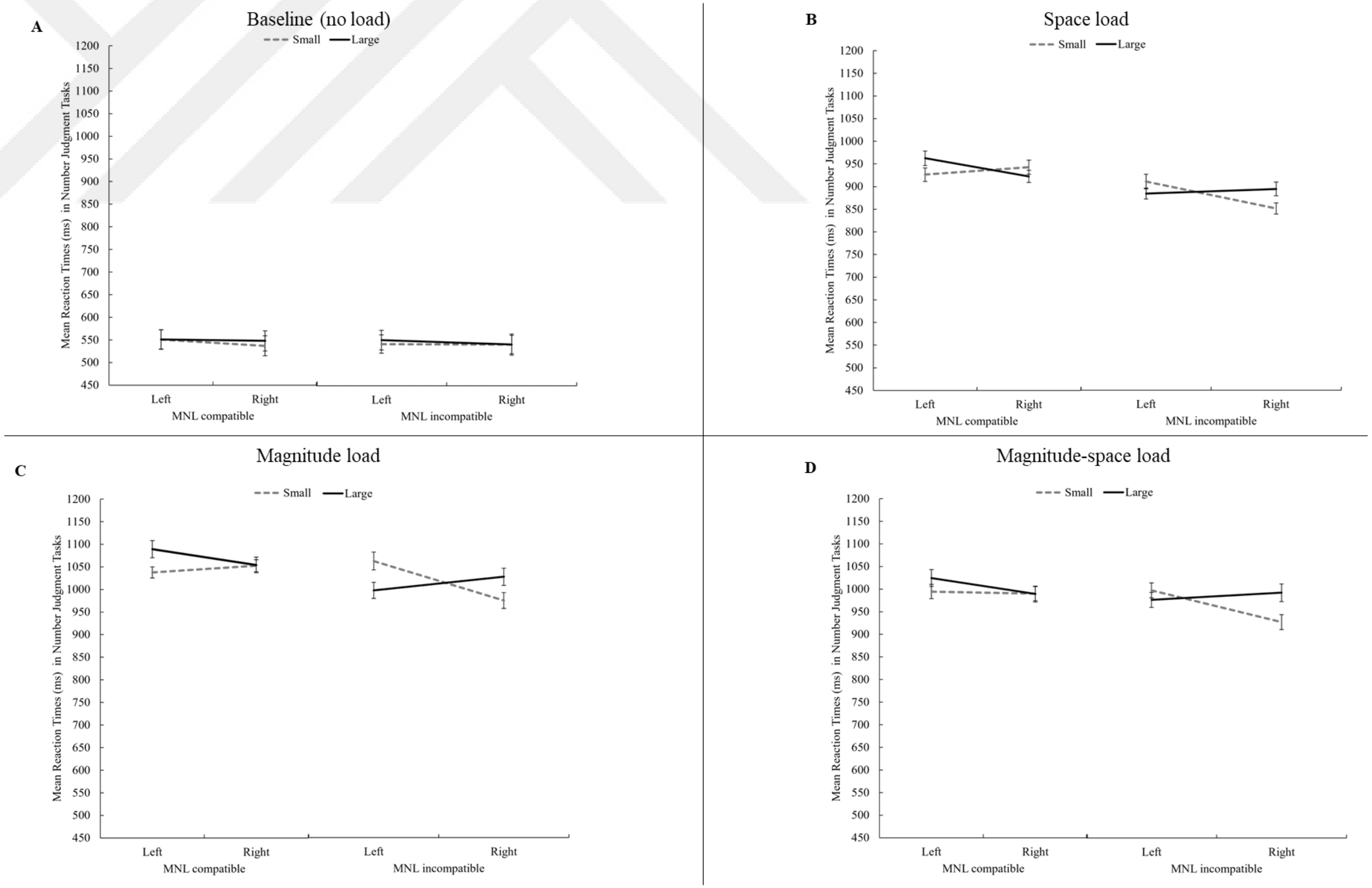


Figure 8. Mean RTs as a Function of MNL Compatibility (Compatible, Incompatible), WM Load Type (Baseline, Space, Magnitude, and Magnitude-Space Load), Magnitude (Small, Large), and Response-Side (Left, Right). Error Bars Represent 95% CIs, Adjusted for Repeated Measures

Lastly, the five-way interaction between MNL compatibility, WM load type, number judgment task, magnitude and response-side was found statistically significant, $F_{(3,285)} = 3.08$, $p < .05$, $\eta_p^2 = .03$. Bonferroni corrected simple effect analysis revealed that RTs significantly differed between small and large numbers for left-sided responses in the MNL compatible condition under space load, $F_{(1,95)} = 4.78$, $p < .05$, $\eta_p^2 = .05$, and magnitude load, $F_{(1,95)} = 6.35$, $p < .05$, $\eta_p^2 = .06$, for the parity judgment task. Participants who performed parity judgment and took MNL compatible condition under space load (*MD* = -53.62, *SE* = 24.52) and magnitude load (*MD* = -72.93, *SE* = 28.94) gave faster left-sided responses to small numbers than to large numbers (see Figure 9, the left-side of Panel C and E, respectively). On the contrary, Bonferroni corrected simple effect analysis revealed that RTs significantly differed between small and large numbers for left-sided responses in the MNL incompatible condition under space load, $F_{(1,95)} = 7.83$, $p < .05$, $\eta_p^2 = .08$, magnitude load, $F_{(1,95)} = 14.62$, $p < .05$, $\eta_p^2 = .13$, and magnitude-space load, $F_{(1,95)} = 8.24$, $p < .05$, $\eta_p^2 = .08$, for the magnitude comparison task. Participants who performed magnitude comparison task and took MNL incompatible condition under space load (*MD* = -63.31, *SE* = 22.63), magnitude load (*MD* = -102.13, *SE* = 26.71), and magnitude-space load (*MD* = -64.39, *SE* = 22.42) gave more rapid left-sided responses to large numbers than to small ones (see Figure 9, the right-side of Panel D, F, and H, respectively). Additionally, participants who took magnitude comparison task gave more rapid right-sided responses to small numbers than large ones under space load as revealed by Bonferroni corrected simple effect analysis, $F_{(1,95)} = 4.59$, $p < .05$, $\eta_p^2 = .05$, magnitude load, $F_{(1,95)} = 9.95$, $p < .05$, $\eta_p^2 = .10$, and magnitude-space load, $F_{(1,95)} = 11.93$, $p < .05$, $\eta_p^2 = .11$. Participants who performed magnitude comparison task and took MNL incompatible condition under space load (*MD* = -50.10, *SE* = 23.40), magnitude load (*MD* = -85.16, *SE* = 27.00), and magnitude-space load (*MD* = -86.81, *SE* = 25.14) gave more rapid right-sided responses to small numbers than to large ones (see Figure 9, the right-side of Panel D, F, and H, respectively).

To review the overall findings of this dissertation in relation to the hypotheses across the three outcome variables, see Table 6.

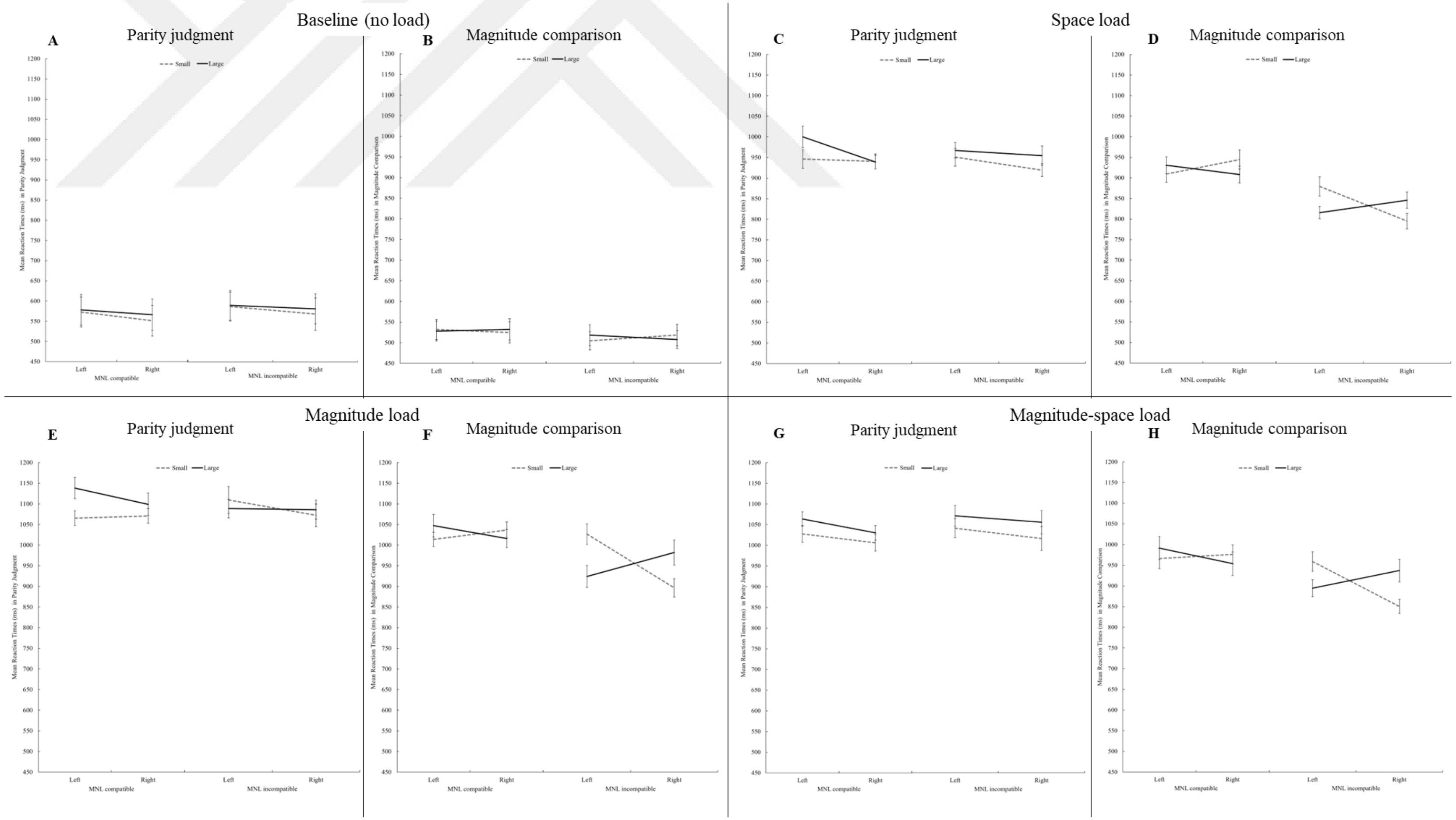
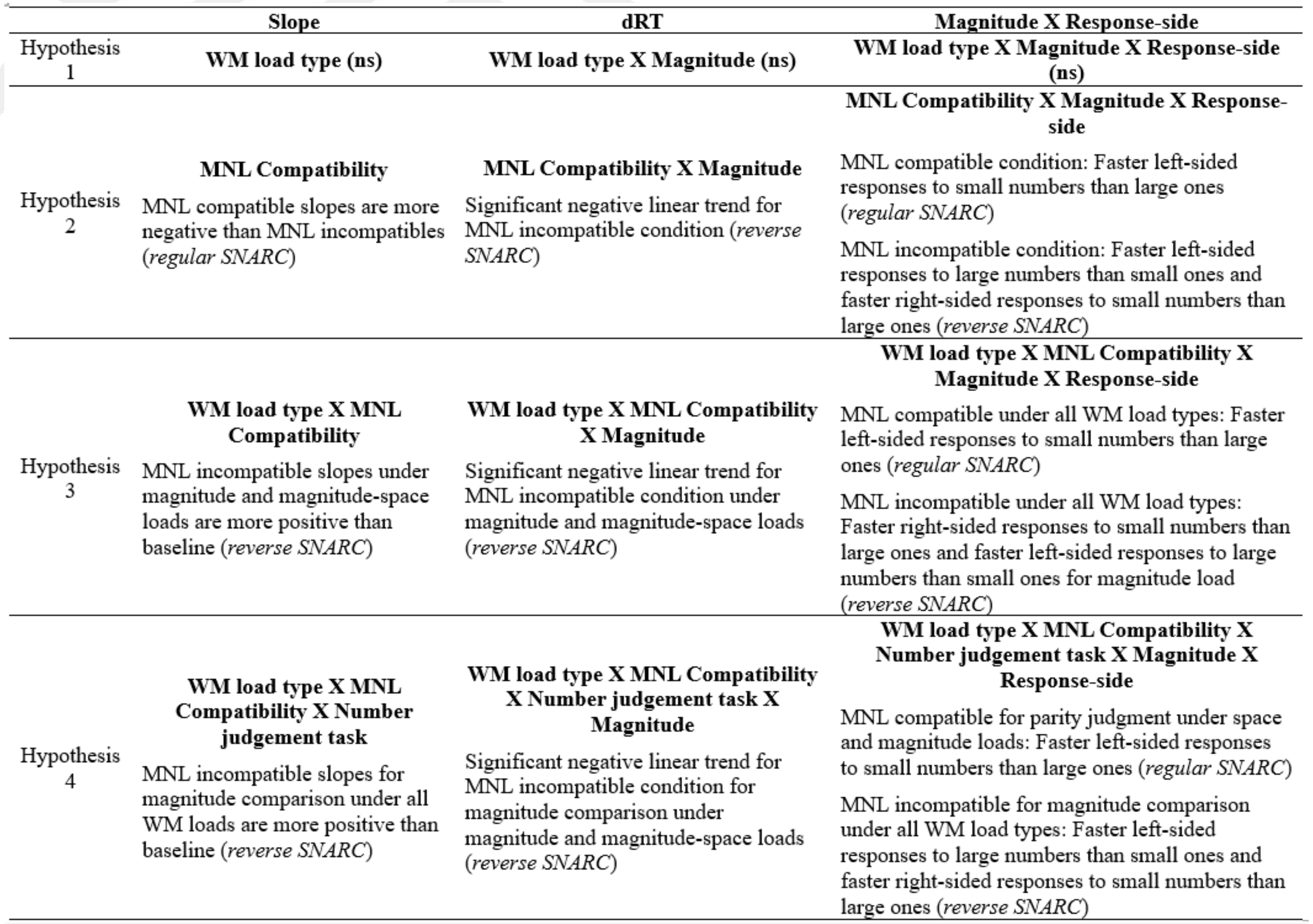


Figure 9. Mean RTs as a Function of MNL Compatibility (Compatible, Incompatible), WM Load Type (Baseline, Space, Magnitude, and Magnitude-Space Load), Magnitude (Small, Large), Response-Side (Left, Right), and the Number Judgment Task (Parity Judgment, Magnitude Comparison). Error Bars Represent 95% CIs, Adjusted for Repeated Measures

Table 6. Overall Findings in Relation to the Hypotheses across Slope, dRT, and the Interaction of Magnitude and Response-side



| | **Slope** | **dRT** | **Magnitude X Response-side** |
|---|---|---|---|
| Hypothesis 1 | **WM load type (ns)** | **WM load type X Magnitude (ns)** | **WM load type X Magnitude X Response-side (ns)** |
| Hypothesis 2 | **MNL Compatibility**<br>MNL compatible slopes are more negative than MNL incompatibles (*regular SNARC*) | **MNL Compatibility X Magnitude**<br>Significant negative linear trend for MNL incompatible condition (*reverse SNARC*) | **MNL Compatibility X Magnitude X Response-side**<br>MNL compatible condition: Faster left-sided responses to small numbers than large ones (*regular SNARC*)<br>MNL incompatible condition: Faster left-sided responses to large numbers than small ones and faster right-sided responses to small numbers than large ones (*reverse SNARC*) |
| Hypothesis 3 | **WM load type X MNL Compatibility**<br>MNL incompatible slopes under magnitude and magnitude-space loads are more positive than baseline (*reverse SNARC*) | **WM load type X MNL Compatibility X Magnitude**<br>Significant negative linear trend for MNL incompatible condition under magnitude and magnitude-space loads (*reverse SNARC*) | **WM load type X MNL Compatibility X Magnitude X Response-side**<br>MNL compatible under all WM load types: Faster left-sided responses to small numbers than large ones (*regular SNARC*)<br>MNL incompatible under all WM load types: Faster right-sided responses to small numbers than large ones and faster left-sided responses to large numbers than small ones for magnitude load (*reverse SNARC*) |
| Hypothesis 4 | **WM load type X MNL Compatibility X Number judgement task**<br>MNL incompatible slopes for magnitude comparison under all WM loads are more positive than baseline (*reverse SNARC*) | **WM load type X MNL Compatibility X Number judgement task X Magnitude**<br>Significant negative linear trend for MNL incompatible condition for magnitude comparison under magnitude and magnitude-space loads (*reverse SNARC*) | **WM load type X MNL Compatibility X Number judgement task X Magnitude X Response-side**<br>MNL compatible for parity judgment under space and magnitude loads: Faster left-sided responses to small numbers than large ones (*regular SNARC*)<br>MNL incompatible for magnitude comparison under all WM load types: Faster left-sided responses to large numbers than small ones and faster right-sided responses to small numbers than large ones (*reverse SNARC*) |

Note. ns denotes not significant

### *3.4.2. Control Analyses: Validation of Working Memory Loads with n-back Task Performance and Assessment of WM Capacity*

This section presents the results of ANOVAs conducted to examine the effects of MNL compatibility conditions and WM load types on accuracy and RTs in the *n*-back task, ensuring that WM load types generated cognitive load in participants and assessing their differential effects as WM loads. Additionally, ANOVA and correlational analyses are included to explore the relationship between WM capacity and SNARC outcomes, providing insights into the role of individual variability in shaping number-space associations under different cognitive demands.

#### *3.4.2.1. Working Memory Loads (The n-back Task)*

##### *3.4.2.1.1. ANOVA Results on Accuracy for the n-back Task*

To investigate the effects of WM load type and MNL compatibility on the *n*-back task, a 2(number judgment task: parity judgment, magnitude comparison) X 2(MNL compatibility: compatible, incompatible) X 3(WM load type: space load, magnitude load, and magnitude-space load) mixed design ANOVA was conducted on the mean accuracy percentages and RTs of *n*-back task.

The *n*-back task showed a significant main effect of WM load type on mean percentage of accuracy measures, $F_{(2,192)}$ =17.16, $p < .05$, $\eta_p^2 = .15$. Bonferroni corrected pairwise comparisons indicated that participants significantly gave more accurate responses under the space load ($MD = 7.85$, $p < .05$) and magnitude-space load ($MD = 5.07$, $p < .05$) compared to magnitude load. However, accuracy did not significantly differ between space and magnitude-space loads ($MD = 2.78$, $p > .05$) (Figure 10). Other main effects and interactions did not reach statistical significance (*F*s < 1.46, *p*s > .23).

Given the simultaneous processing demands of spatial position and magnitude category in the magnitude-space load, participants might prioritize one task over the other. To control this, participants were divided into two groups: one group was instructed to prioritize spatial position, while the other prioritized magnitude. A mixed design ANOVA was conducted on mean accuracy percentages and RTs, with number judgment task (parity judgment, magnitude comparison), MNL compatibility (compatible, incompatible), and prioritization instruction (prioritize space, prioritize magnitude) as between-subject variables, and WM load type as a within-subjects variable (space load, magnitude load, and magnitude-space load). The analysis revealed that neither the main effect of prioritization instruction nor any interactions involving prioritization instruction were found statistically significant (for accuracy: $F$s < 1.79, $p$s > .17 and for RTs: $F$s < 3.08, $p$s > .08).

#### ***3.4.2.1.2. ANOVA Results on Reaction Time Measures for the n-back Task***

A significant main effect of WM load type was found on RTs, $F_{(2,192)} = 52.73$, $p < .05$, $\eta_p^2 = .36$. Bonferroni corrected pairwise comparisons showed that participants significantly gave faster responses to space ($MD = -154.26$, $p < .05$) and magnitude-space ($MD = -82.79$, $p < .05$) compared to the magnitude load. Also, participants were quicker in responding to the space load than to the magnitude-space load ($MD = -71.47$, $p < .05$). No other main effects or interactions reached statistical significance ($F$s < 1.52, $p$s > .22) (Figure 10).

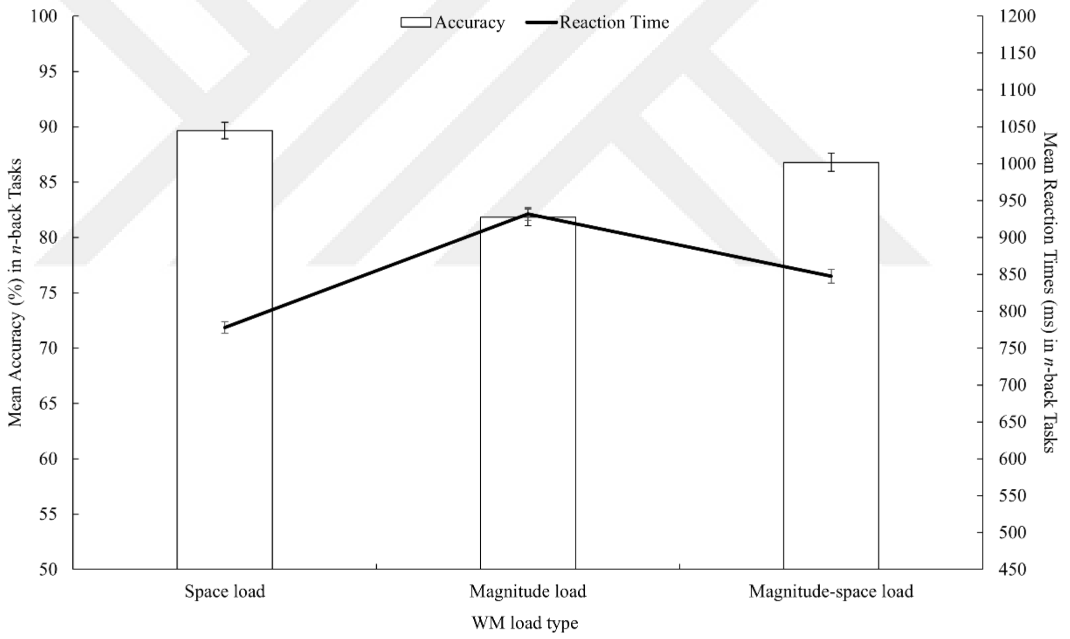


Figure 10. Mean Percentage of Accuracy (Bar Graph) and RTs (Line Graph) for Space, Magnitude, And Magnitude-Space Loads in the *n*-back Task. Error Bars Represent 95% CIs, Adjusted for Repeated Measures

#### *3.4.2.2. Working Memory Capacity (The Digit Span Backward Task)*

##### *3.4.2.2.1. ANOVA Results on Working Memory Capacity*

A one-way ANOVA results showed that the WM capacity of participants did not differ between those who performed the parity judgment and magnitude comparison tasks, $F_{(1,99)} = .16$, $p < .05$.

##### *3.4.2.2.2. Correlational Analyses Results on Working Memory Capacity*

Separate correlation analyses for parity judgment and magnitude comparison tasks were conducted between DSB task performance and unstandardized slopes and RTs across the baseline (no load) and WM loads. For the parity judgment task, significant negative correlations were found between DSB task performance and space load ($r = -.36$, $p < .05$), magnitude load ($r = -.34$, $p < .05$), and magnitude-space load ($r = -.31$, $p < .05$) For the magnitude comparison task, negative correlations were observed between DSB task performance and space load ($r = -.28$, $p < .05$) and magnitude load ($r = -.33$, $p < .05$).

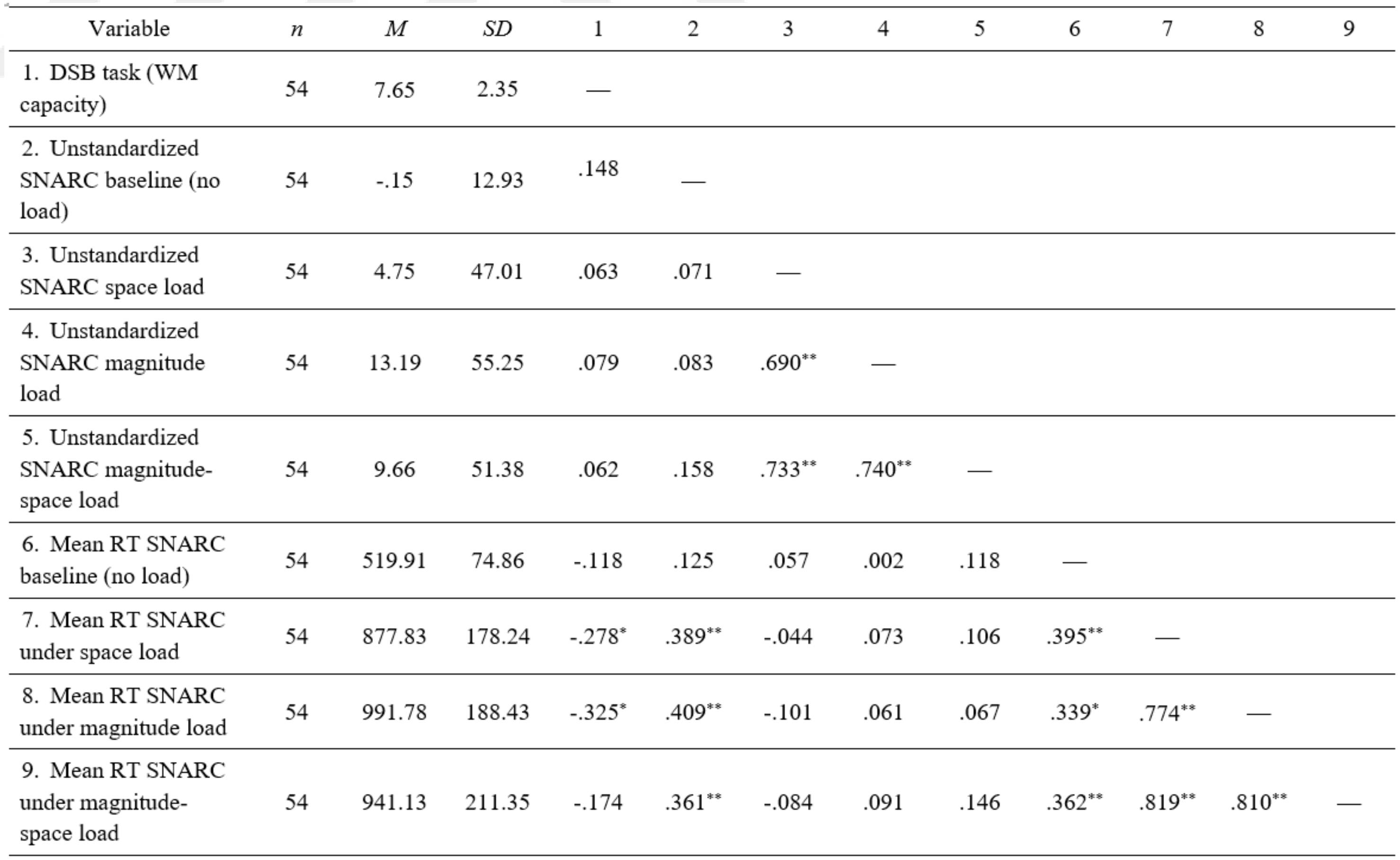
These findings indicate that WM capacity was significantly associated with RTs for space, magnitude, and magnitude-space loads in both tasks. However, no significant relationships were found between WM capacity and either SNARC slopes or baseline SNARC RT, indicating that WM capacity was primarily associated with SNARC RTs only under WM loads. For correlation findings with the parity judgment task, see Table 7, and for the magnitude comparison task, see Table 8.

Table 7. Means, Standard Deviations, and Pearson’s Correlation Coefficients for the DSB Task, Unstandardized SNARC Slopes, and Mean RTs across No Load and WM Load Types in the Parity Judgment Task

| Variable | *n* | *M* | *SD* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. DSB task (WM capacity) | 46 | 7.48 | 1.77 | — | | | | | | | | |
| 2. Unstandardized SNARC baseline (no load) | 46 | 2.03 | 10.35 | -.050 | — | | | | | | | |
| 3. Unstandardized SNARC space load | 46 | -1.26 | 19.49 | .172 | .315$^{*}$ | — | | | | | | |
| 4. Unstandardized SNARC magnitude load | 46 | -4.82 | 23.24 | .103 | .012 | .209 | — | | | | | |
| 5. Unstandardized SNARC magnitude-space load | 46 | 1.57 | 21.99 | .033 | .008 | .088 | .159 | — | | | | |
| 6. Mean RT SNARC baseline (no load) | 46 | 574.05 | 77.06 | -.173 | -.048 | -.160 | -.025 | -.126 | — | | | |
| 7. Mean RT SNARC under space load | 46 | 950.68 | 263.94 | -.359$^{*}$ | .145 | -.111 | -.237 | .037 | .634$^{**}$ | — | | |
| 8. Mean RT SNARC under magnitude load | 46 | 1089.26 | 296.98 | -.340$^{*}$ | .119 | -.202 | -.111 | .020 | .668$^{**}$ | .866$^{**}$ | — | |
| 9. Mean RT SNARC under magnitude-space load | 46 | 1038.85 | 317.29 | -.307$^{*}$ | .204 | -.122 | -.163 | -.005 | .723$^{**}$ | .920$^{**}$ | .938$^{**}$ | — |

$^{*}p < .05$. $^{**}p < .01$.

Table 8. Means, Standard Deviations, and Pearson's Correlation Coefficients for the DSB Task, Unstandardized SNARC Slopes, and Mean RTs across No Load and WM Load Types in the Magnitude Comparison Task



| Variable | *n* | *M* | *SD* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. DSB task (WM capacity) | 54 | 7.65 | 2.35 | — | | | | | | | | |
| 2. Unstandardized SNARC baseline (no load) | 54 | -.15 | 12.93 | .148 | — | | | | | | | |
| 3. Unstandardized SNARC space load | 54 | 4.75 | 47.01 | .063 | .071 | — | | | | | | |
| 4. Unstandardized SNARC magnitude load | 54 | 13.19 | 55.25 | .079 | .083 | $.690^{**}$ | — | | | | | |
| 5. Unstandardized SNARC magnitude-space load | 54 | 9.66 | 51.38 | .062 | .158 | $.733^{**}$ | $.740^{**}$ | — | | | | |
| 6. Mean RT SNARC baseline (no load) | 54 | 519.91 | 74.86 | -.118 | .125 | .057 | .002 | .118 | — | | | |
| 7. Mean RT SNARC under space load | 54 | 877.83 | 178.24 | $-.278^{*}$ | $.389^{**}$ | -.044 | .073 | .106 | $.395^{**}$ | — | | |
| 8. Mean RT SNARC under magnitude load | 54 | 991.78 | 188.43 | $-.325^{*}$ | $.409^{**}$ | -.101 | .061 | .067 | $.339^{*}$ | $.774^{**}$ | — | |
| 9. Mean RT SNARC under magnitude-space load | 54 | 941.13 | 211.35 | -.174 | $.361^{**}$ | -.084 | .091 | .146 | $.362^{**}$ | $.819^{**}$ | $.810^{**}$ | — |

$^{*}p < .05$. $^{**}p < .01$.

### *3.5. Discussion*

This dissertation investigates how different types of magnitude-space-based numerical WM loads affect the SNARC effect across various number judgment tasks. Previous research has explored the SNARC effect’s flexibility by adjusting MNL compatibility within diverse task contexts, such as response mappings, spatial layouts, and memory tasks. Studies have also examined the flexibility of the SNARC effect in the context of WM by imposing WM loads through tasks that incorporate visuo-spatial and verbal components to observe cognitive load effects on spatial-numerical associations. However, no prior work has treated MNL compatibility itself as a cognitive load with different types of magnitude-space-based WM loads, which could connect MNL and WM accounts on number-space associations.

Before testing the main hypotheses of the dissertation, the presence of the SNARC effect without WM load (baseline) and under space, magnitude, and magnitude-space load conditions was examined for both parity judgment and magnitude comparison tasks. Recent research with Turkish participants, who have left-to-right reading and writing habits, reported the absence of a regular SNARC effect in both parity judgment (Bulut et al., 2023) and magnitude comparison tasks (Hepdarcan et al., under review). Our findings on baseline number judgment tasks supported these studies across all measures, including slope, dRT, and the interaction of magnitude and response-side. The SNARC effect, whether explicitly (magnitude comparison) or implicitly measured (parity judgment), did not manifest under baseline conditions. One plausible explanation for this absence of the SNARC effect in our sample is that spatial-numerical associations may require explicit task demands or WM engagement to be activated.

### *3.5.1. The Influence of Working Memory Load Types on Number Judgments*

It was proposed that magnitude-space-based WM loads would influence the emergence of the SNARC effect. Space load and magnitude load types were anticipated to produce a regular SNARC effect, as these loads were not expected to impose heavy cognitive demands on WM, thereby minimizing interference with number judgments. In contrast, the magnitude-space load condition was expected to enhance the emergence of a regular SNARC effect due to the close relationship between magnitude and space (ATOM, Walsh, 2003).

Although no significant effect of WM load type on the SNARC effect was detected, a significant main effect of WM load type on reaction time provided valuable insights. Participants responded slower under space, magnitude-space, and magnitude loads compared to the no load condition. Similar patterns were observed for the *n*-back measures, where participants responded slower and less accurately in the magnitude load compared to space and magnitude-space loads, confirming the effective manipulation of WM loads. As the space load is cognitively less demanding, participants responded faster and more accurately under this condition. Despite the additional cognitive load in the magnitude-space condition, participants found it less challenging than the magnitude load. This may be because simultaneous processing of magnitude and spatial information activates spatial representations of numbers, aligning with the close relationship between magnitude and space.

Prior studies have demonstrated that the SNARC effect is influenced by various WM load types (Herrera et al., 2008; van Dijck and Fias, 2009; Deng et al., 2017), yet the current finding of no significant effect of WM load type on the SNARC effect may seem inconsistent with this literature. However, it is important to note that this study employed magnitude-space-based WM loads, which differ from the load types used in previous research, warranting cautious interpretation. Herrera et al. (2008) reported that the SNARC effect in the magnitude comparison task disappeared under visuo-spatial load. Similarly, van Dijck and Fias (2009) found that the SNARC effect was abolished in magnitude comparison under visuo-spatial load but persisted under verbal load, while the opposite was observed for parity judgment. Deng et al. (2017) highlighted the sensitivity of parity judgment to WM load type, with the SNARC effect vanishing under both verbal and visuo-spatial loads, pointing out the need for available WM resources. Conversely, in magnitude comparison, the SNARC effect diminished under increased verbal load but strengthened with visuo-spatial load, suggesting that visuo-spatial resources are less critical for magnitude comparison task. These findings indicate the importance of WM resources in the emergence of the SNARC effect. While this study did not detect a significant effect of WM load type on number-space associations, the results may reflect the distinct cognitive demands imposed by magnitude-space-based WM loads, emphasizing the role of WM resource availability. Cognitive demands imposed by magnitude-space-based WM loads were found to influence task performance, even though no significant main effect of WM load type on the SNARC effect was observed across outcome variables. Specifically, the SNARC effect (unstandardized slopes) was more pronounced in parity judgment under magnitude load, suggesting that magnitude load enhances the emergence of the SNARC effect in this task. Under the magnitude load, participants were required to hold the magnitude information of numbers in their minds and respond accordingly, explicitly processing this information as part of the task. After viewing a number, participants may have verbalized it, represented its magnitude as small or large, and categorized it based on this magnitude. As such, the magnitude load condition relies on verbal WM resources. Under this load, stronger regular SNARC effect was observed in parity judgment than magnitude comparison. The presence of a regular SNARC effect in parity judgment under magnitude load may be attributed to the explicit activation of magnitude information in magnitude load, which could trigger associations between numbers and space, even in an implicit task. Since no SNARC effect was observed in baseline number judgment tasks (without WM load), prior activation through a WM task might facilitate these associations. Interestingly, this pattern was not observed in magnitude comparison. A plausible explanation might be that magnitude comparison inherently involves directly processing and categorizing numbers based on their magnitudes, which closely aligns with the demands of the magnitude load. As participants found this condition the most challenging, additional cognitive demands likely overloaded WM, thereby interfering with the emergence of a regular SNARC effect in magnitude comparison. This finding highlights the distinct interactions between WM load types and their specific processing demands in number-space associations.

Nevertheless, the absence of the expected SNARC effect under space and magnitude-space loads warrants discussion. One possible explanation for the lack of a SNARC effect under the space load is that participants were only required to retain the spatial positions of numbers in their minds. This task primarily engaged visuo-spatial resources and activated spatial representations alone, which may not have been sufficient to trigger the association between numbers and space due to the task’s requirements. For the magnitude-space load, while the close relationship between magnitude and space might have made this load less cognitively demanding, the simultaneous processing of both magnitude and spatial information may have transformed the task into a distinct WM process. Participants may have tried to solve the task in a way that minimized interference with the number judgment tasks. Consequently, it might not have functioned effectively as a WM load, thereby failing to influence number-space associations. Consequently, the load may have failed to influence number-space associations.

### *3.5.2. The Critical Involvement of MNL Compatibility on Number Judgments*

As hypothesized, MNL compatibility significantly modulated the SNARC effect. MNL compatible conditions elicited a regular SNARC effect, while incompatible ones consistently resulted in a reverse SNARC effect across all outcome measures (slope, dRT, the interaction of magnitude and response-side). In MNL compatible conditions, numbers aligned with their left-to-right oriented spatial associations (small-left, large-right), activating long-term spatial representations along the MNL. However, in MNL incompatible conditions, the spatial presentation conflicted with the MNL (small-right, large-left), creating interference between task-related spatial representations and numerical processing. This finding is significant as it demonstrates that spatial-numerical associations, even in a sample where no SNARC effect was observed, can be dynamically shaped by task context. These results suggest that altering cognitive demands through compatible or incompatible representations of numbers with LTM influences WM functioning. Consequently, this modulation facilitates a regular or reverse SNARC effect. These findings align with previous research demonstrating that task demands and representations compatible with the MNL strengthen spatial-numerical associations, while incompatible representations reverse them (Fischer et al., 2010; Bächtold et al., 1998). Moreover, this finding highlights that spatial-numerical associations can be shaped based on MNL compatibility within WM.

The significant effects of MNL compatibility across WM load types further emphasize the dynamic interplay between long-term (MNL) and task-specific (WM load) explanations of the SNARC effect. A regular SNARC effect was observed in the MNL compatible condition, while a reverse SNARC effect emerged in the MNL incompatible condition under all WM loads (except for the space load in slope and dRT measures). Although nuanced differences were observed in study outcomes (with the slope for space load approaching significance, $p$ = .058), the overall findings suggest that WM load types influence space-number relations when compatible or incompatible representations of numbers in LTM are considered. When participants engaged in magnitude-space-based loads, even different WM resources (verbal, visuo-spatial, or both) are needed, MNL compatibility activated the spatial representations of numbers, resulting in regular or reverse SNARC effects. These findings align with Oberauer's WM model, suggesting that activated long-term representations influence number judgments. They also highlight the dynamic interaction between MNL and WM accounts, showing that for a regular SNARC effect to emerge, magnitude-space-based WM loads must jointly activate long-term representations during task execution. While WM load types successfully imposed cognitive demands, their interaction with MNL compatibility was critical in activating spatial-numerical associations, ultimately producing regular or reverse SNARC effects. These results underscore the critical role of MNL compatibility in eliciting regular or reverse SNARC effects.

### ***3.5.3. MNL Compatibility as a Key Factor in Shaping the Effects of WM Loads on Number Judgments***

One of the most notable findings of this dissertation is how MNL compatibility interacts with both WM load types and number judgment tasks, leading to differential effects on spatial-numerical associations. A regular SNARC effect was observed in parity judgment for MNL compatible condition under space and magnitude loads. In contrast, a reverse SNARC effect emerged in magnitude comparison for MNL incompatible condition across all WM load types and outcome variables. These results suggest that MNL compatibility modulates magnitude-space-based loads, leading to distinct outcomes in parity judgment and magnitude comparison. This finding aligns with Deng et al. (2017) and van Dijck and Fias (2009), who reported differences in how these tasks interact with WM load types. The most closely related result, however, is by Lindemann et al. (2008), who found a regular SNARC effect in parity judgment for ascending (MNL compatible) and disordered sequences but no effect or reverse SNARC for descending (MNL incompatible) sequences. They suggested that the MNL's left-to-right orientation is flexible and can be adjusted or suppressed depending on task demands. Specifically, they attributed the absence of a reverse SNARC in MNL incompatible sequences to the higher cognitive demands, which cannot be met unless the task explicitly necessitates such processing. Moreover, they proposed that spatial-numerical reference frames activated during concurrent tasks influence the SNARC effect. These findings align with those of this dissertation. However, Lindemann et al. (2008) focused solely on parity judgment, leaving the influence of MNL compatible and incompatible manipulations on the magnitude comparison task unexplored.

In this dissertation, parity judgment under MNL compatible conditions elicited a regular SNARC effect for space and magnitude loads, but not for magnitude-space load. Conversely, in magnitude comparison, MNL incompatible conditions consistently evoked a reverse SNARC effect across all WM load types, while no regular SNARC effect emerged under MNL compatible conditions. This raises the question of why parity judgment remained unaffected by incompatible representations, whereas magnitude comparison showed no influence from compatible representations.

Building on prior research, the dual-route model (Gevers et al., 2006b) and the verbal-spatial account (Gevers et al., 2010) offer valuable frameworks for understanding the differential effects observed across number judgment tasks. According to the dual-route model, the SNARC effect emerges from a dimensional overlap between numerical magnitude and response-side, as both share a spatial dimension that can either be compatible or incompatible. Within this framework, the SNARC effect reflects the interaction between magnitude information and lateralized responses, processed through a dual-route mechanism.

Specifically, responses are influenced by two distinct routes: the unconditional route, which automatically activates magnitude information and its associated spatial response, and the conditional route, which is guided by task-specific instructions. The unconditional route operates independently of task demands and relies on long-term spatial representations of numbers. For instance, when the number 9 is perceived, its magnitude as “large” and spatial association as “right” are automatically activated through the unconditional route. In contrast, the conditional route adjusts these automatic responses based on task specific instructions. For example, in a parity judgment task where participants are instructed to respond to odd numbers with a left-sided response, the automatic response from the unconditional route must be adjusted to fulfill the task requirement. This makes parity judgment primarily reliant on task-specific instructions and, consequently, the conditional route which is closely associated with verbal-spatial coding. On the other hand, magnitude comparison predominantly engages the unconditional route, as it directly depends on the spatial representation of numerical magnitudes. In this task, visuo-spatial coding drives response patterns. Gevers et al. (2010) suggested that both verbal-spatial and visuo-spatial coding contribute to the emergence of the SNARC effect, with verbal-spatial coding generally taking precedence.

Grounded in Gevers et al.'s (2010) verbal-spatial and visuo-spatial coding framework, the differential effects of MNL compatibility under WM loads on parity judgment and magnitude comparison can be discussed. In this dissertation, the MNL compatible condition aligns with long-term spatial-numerical associations, facilitating the emergence of a regular SNARC effect. Parity judgment, as an implicit task, does not require participants to explicitly engage with magnitude. In MNL compatible conditions, the alignment with the MNL reduces cognitive conflict, allowing the conditional route to operate efficiently without heavily taxing verbal coding, thereby resulting in a regular SNARC effect. Conversely, in MNL incompatible condition, this congruity is disrupted. However, a reverse SNARC may not emerge, as verbal processes dominate in parity judgment and rely less on spatial representations. Consequently, parity judgment's reduced dependence on visuo-spatial representations makes it more resilient to MNL incompatibility, even under WM loads.

On the other hand, the absence of a regular SNARC effect under MNL compatible conditions with WM loads in magnitude comparison suggests interference or competing demands that disrupt the expected alignment. Since magnitude comparison relies on visuo-spatial coding, MNL incompatible representations might hinder the automatic engagement of the visuo-spatial processes necessary for a regular SNARC effect to emerge. Magnitude comparison, as an explicit task, requires participants to directly process and compare numerical magnitudes. This explicit processing may intensify reliance on visuo-spatial resources, particularly under MNL compatible conditions, where participants are expected to align their responses with long-term spatial representations of numbers (the MNL). However, the added WM loads (space, magnitude, and magnitude-space) may impose additional demands on these visuo-spatial resources, reducing their availability for encoding and activating the long-term spatial-numerical associations necessary for a regular SNARC effect. As a result, MNL compatibility might not suffice to counteract the cognitive load introduced by the WM tasks, thereby disrupting visuo-spatial coding. The visuo-spatial resources engaged in magnitude comparison may be reallocated to manage the demands of WM loads, leaving insufficient capacity for the spatial alignment required to produce a regular SNARC effect. Consequently, the magnitude comparison task’s greater dependence on visuo-spatial processing makes it more vulnerable to disruptions caused by MNL incompatible conditions under WM loads.

The differing effects of MNL compatibility under WM loads on number judgment tasks can also be interpreted within the context of their distinct cognitive demands. As revealed by the main effect of the number judgment task, participants performing parity judgment were slower than those engaged in magnitude comparison, indicating that parity judgment posed greater cognitive challenges. In parity judgment, magnitude information is measured implicitly, increasing the task’s cognitive demand compared to magnitude comparison. Due to the need to process multiple attributes – parity (odd/even), magnitude (small/large), and response side (left/right)– parity judgment may be more responsive to MNL compatibility and the facilitative effects of magnitude-space based WM loads. Under MNL incompatible conditions, the conflict with long-term spatial representations of numbers might prompt participants to rely on MNL compatible conditions for smoother task performance. Turning to the specific case of MNL compatible conditions under magnitude-space load, the lack of a regular SNARC effect in parity judgment warrants closer examination. The absence of a regular SNARC effect in parity judgment in MNL compatible condition under magnitude-space load suggests that simultaneously holding magnitude and space information in memory may hinder the emergence of a regular SNARC effect. This could result in the task being less influenced by MNL compatibility. Although participants found magnitude-space load less challenging than magnitude load, this type of load still imposes enhanced cognitive demands, requiring both verbal (magnitude) and visuo-spatial (space) resources. The simultaneous demand on these resources may disrupt number-space relations, preventing the regular SNARC effect from emerging in parity judgment. The high cognitive demands of the magnitude-space load may leave parity judgment particularly susceptible, making even MNL compatibility insufficient to activate spatial-numerical associations and thereby preventing the emergence of a regular SNARC effect.

The observed differences in SNARC effects across number judgment tasks can also be interpreted through broader theoretical and neurobiological frameworks. This interpretation aligns with the discussion presented by Zorzi et al. (2012), who explored space-number associations in neglect patients. They argued that the SNARC effect in magnitude comparison is predominantly influenced by visuo-spatial coding, which is disrupted by neglect, whereas the effect in parity judgment is primarily governed by verbal-spatial coding, remaining unaffected by neglect. This dual-process explanation provides a foundation for understanding how task-specific demands shape spatial-numerical associations. Further support for this interpretation comes from Klein et al. (2010), who demonstrated that implicit (parity judgment) and explicit (magnitude comparison) processing of numbers involve distinct cognitive demands, resulting in differential activation patterns in the parietal cortex. While direct neuroimaging evidence is beyond the scope of this dissertation, these findings suggest that task-specific effects on spatial-numerical associations may reflect the engagement of separate neural circuits within the parietal cortex. Such functional distinctions may offer valuable insights into the cognitive and neurobiological mechanisms underlying the observed differences between number judgment tasks.

### *3.5.4. Individual Differences in Spatial-Numerical Associations: The Role of WM Capacity*

The findings of this dissertation also contribute to the broader understanding of individual differences in spatial-numerical associations, particularly in the context of WM capacity. Before examining the effects of WM loads on number judgment tasks, it is ensured that participants performing parity judgment and magnitude comparison tasks did not differ in their WM capacities. This was crucial in ruling out baseline differences in WM capacity as a potential confounding in interpreting task-specific effects on the SNARC effect. The relationship between WM capacity and task performance aligns with previous research, which highlighted that individual differences in cognitive abilities influence the SNARC effect. Similar to Hoffmann et al. (2014) and Herrera et al. (2008), this study observed that WM capacity was significantly correlated with RTs under WM load conditions, with higher WM capacity associated with faster responses. Consistent with these studies, no significant relationship was found between WM capacity and SNARC slope. This suggests that while WM capacity influences overall task efficiency (e.g., RTs), it does not directly modulate the strength or directionality of spatial-numerical associations. These findings underscore the dynamic and context-sensitive nature of spatial-numerical associations, shaped by individual cognitive capacities and task-specific demands. For example, previous studies have observed stronger SNARC effects in participants with slower processing speeds or poorer visuo-spatial abilities (e.g., in mental rotation tasks), suggesting that weaker executive functions may increase reliance on long-term space-number associations (Hoffmann et al., 2014; Viarouge et al., 2014; Wood et al., 2008). In contrast, tasks that demand higher cognitive control may introduce competing demands, potentially modulating the reliance on these associations. Although this study did not intend to directly assess executive functions or their interaction with task-specific demands, the observed relationship between WM capacity and reaction times under magnitude-space-based WM loads suggests that cognitive resources might play a role in mitigating the effects of additional cognitive demands.

### *3.5.5. Integrating ATOM and Oberauer's WM Model: Insights into LTM-WM Interactions in Spatial-Numerical Associations*

This dissertation contributes to the literature on space-number relations by providing empirical support for the integration of magnitude and space as proposed in ATOM (Walsh, 2003). ATOM emphasizes a shared neural and cognitive system for processing magnitude, space, and time, positing that these dimensions interact to guide action and cognition. The findings of this study align with ATOM, particularly regarding the influence of magnitude-space-based WM loads on spatial-numerical associations. The cognitive load types implemented in this dissertation –space, magnitude, and magnitude-space– reflect the interconnectedness of these dimensions. Even when introduced as cognitive demands in WM, these components activated spatial-numerical associations, as evidenced by the emergence of the SNARC effect. Importantly, the findings highlight that without magnitude-space-based cognitive demands, as in the baseline tasks, these spatial-numerical associations may remain dormant. These findings extend ATOM by demonstrating how magnitude-space relations manifest in the context of cognitive demands. They also underscore the importance of considering both task-specific and long-term representations when examining spatial-numerical associations. This dynamic interaction aligns with ATOM's core assertion that magnitude and space are intertwined, influencing cognitive performance. This dissertation not only provides support for ATOM but also highlights its applicability to WM research. The findings suggest that magnitude-space-based WM loads can effectively engage spatial-numerical associations, shedding light on the conditions under which these associations are activated or suppressed.

In terms of WM loads, this dissertation extends the exploration of cognitive load in WM by utilizing Oberauer's WM model (2009), moving beyond the conventional reliance on Baddeley's framework. Cognitive loads were specifically designed to integrate long-term numerical representations, structured around MNL compatibility. While prior research has examined the flexibility of the SNARC effect across various contexts –such as task demands, response mappings, and spatial arrangements (Fias et al., 2010; Bächtold et al., 1998; Notebaert et al., 2006; Lindemann et al., 2008)– it has not conceptualized MNL compatibility as a cognitive load. This dissertation addresses that gap by demonstrating that MNL compatibility plays a critical role in modulating spatial-numerical associations. MNL compatible loads consistently elicited a regular SNARC effect, reflecting alignment with long-term spatial-numerical representations. Conversely, MNL incompatible loads induced reverse SNARC effects, emphasizing the disruptive impact of conflicting representations. These patterns persisted across various WM load conditions (space, magnitude, and magnitude-space), highlighting the central role of MNL compatibility in influencing WM functioning and task performance. By investigating MNL compatibility as a form of cognitive load, this dissertation provides new insights into how long-term spatial-numerical representations interact with WM processes. These findings enhance our understanding of the SNARC effect's flexibility by illustrating the interaction between LTM and WM in shaping spatial-numerical associations.

Building on these insights, the findings of this dissertation also align with prior research emphasizing the coactivation of LTM and WM in shaping magnitude-space associations. Studies have suggested that both long-term and temporary representations can coexist, with their influence varying based on task demands. This coexistence, as discussed in previous studies (Lindemann et al., 2008; van Dijck et al., 2014; Pinto et al., 2019; Ginsburg and Gevers, 2015; Huber et al., 2016; Hepdarcan et al., 2024) illustrates that spatial-numerical associations are dynamic and influenced by both LTM and WM. In Ginsburg and Gevers' (2015) study, for example, they demonstrated that while regular SNARC effects emerge when long-term spatial representations are activated (inducer blocks), task demands that emphasize short-term positional sequences (diagnostic blocks) reveal the dominance of WM representations, highlighting the coexistence of these two systems. Similarly, Hepdarcan et al. (2024) found that congruent (similar to MNL compatible representations in this study) facilitated faster and more accurate responses in *n*-back tasks, whereas negatively congruent (similar to MNL incompatible representations) representations disrupted performance, underscoring the influence of LTM representations on WM task execution. The present findings expand on these studies by showing that the manipulation of MNL compatibility in WM loads provides evidence for the flexible nature of the SNARC effect, which can be shaped by both LTM-activated spatial representations of numbers and the situational cognitive demands of magnitude-space based WM loads. Specifically, the emergence of a regular SNARC effect under MNL compatible conditions in parity judgment underscores the facilitative role of compatible long-term representations in activating spatial-numerical associations. Conversely, the reverse SNARC effects observed in magnitude comparison under MNL incompatible conditions highlight how conflicting spatial representations can override LTM-based associations when visuo-spatial processing is more heavily relied upon. Together, these findings highlight the idea that spatial-numerical associations are not robust, but can adapt dynamically to task context, cognitive load, and compatibility with long-term representations.

# CHAPTER 4: CONCLUSION

This dissertation explored how different types of magnitude-space-based numerical WM loads affect the SNARC effect across parity judgment and magnitude comparison tasks. The findings reveal that spatial-numerical associations are highly flexible, shaped dynamically by task context, cognitive load, and compatibility with long-term representations (MNL). By incorporating MNL compatibility as a form of cognitive load, this study advances our understanding of the interplay between LTM and WM in numerical representations.

In line with prior research, the absence of a regular SNARC effect under baseline conditions suggests that spatial-numerical associations may remain dormant unless explicitly engaged by task or cognitive demands. Under WM loads, MNL compatibility elicited a regular SNARC effect, while MNL incompatibility consistently reversed this effect, highlighting the modulatory role of long-term representations in activating or disrupting spatial-numerical associations.

Key differences emerged between parity judgment and magnitude comparison tasks. Parity judgment, an implicit task primarily reliant on verbal-spatial coding, demonstrated resilience to MNL incompatibility but required compatible activations to elicit a regular SNARC effect. Conversely, magnitude comparison, driven by visuo-spatial coding, was highly sensitive to MNL incompatibility, producing reverse SNARC effects, but failed to elicit a regular SNARC effect under compatible conditions, likely due to cognitive interference from WM loads. The results also support ATOM, emphasizing the intertwined nature of magnitude and space. Furthermore, this dissertation contributes to Oberauer's WM model by demonstrating how activated long-term representations interact with task-specific WM demands. By using MNL compatibility in magnitude-space-based WM loads, the study highlights the importance of considering not only the cognitive tasks but also the influence of long-term representations in shaping spatial-numerical associations.

Overall, this dissertation underscores the dynamic and context-sensitive nature of spatial-numerical associations, demonstrating their dependence on the interaction between LTM and WM. By integrating MNL compatibility as a cognitive load, this study extends the flexibility framework of the SNARC effect, contributing novel insights into the mechanisms governing spatial-numerical associations. These findings provide a foundation for future research to investigate how task-specific cognitive demands and other contextual factors further influence these associations.

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# APPENDICES

## *APPENDIX A. PARTICIPANT INFORMATION FORM*

### Katılımcı Bilgilendirme Formu

Bu çalışma büyüklük-uzam ilişkisine dair uzun süreli bellek temsili ile uyumlu ve uyumsuz durumların çalışma belleği kapsamında incelenmesi amacıyla yapılmaktadır.

Çalışma sırasında bilgisayar ekranından sunulan birtakım görsel uyarıcılara bilgisayar klavyesinin tuşları aracılığıyla tepki vermeniz beklenmektedir. Çalışma boyunca, ekrandan sunulan yönergeleri dikkatlice okumanız ve sizden istenenleri olabildiğince doğru bir biçimde yerine getirmeniz gerekmektedir.

Çalışma kapsamında katılımcılardan elde edilen veriler isim kullanılmaksızın analizlere dâhil edilecektir. Çalışma başında size bir katılımcı numarası verilecektir. Katılacağınız bu ön çalışma sonrası araştırmacı sizinle asıl çalışmaya katılmanız için vereceğiniz güncel e-mail adresiniz aracılığıyla iletişime geçebilir.

Katılımınız araştırma hipotezinin test edilmesi ve yukarıda açıklanan amaçlar doğrultusunda literatüre sağlayacağı katkılar bakımından oldukça önemlidir. Ayrıca katılımınızın psikoloji alanın gelişmesi açısından da birtakım faydaları bulunmaktadır.

Çalışmaya katılmanız tamamen kendi isteğinize bağlıdır. Katılımı reddetme ya da çalışma sürecinde herhangi bir zaman diliminde devam etmeme hakkına sahipsiniz. Eğer görüşme esnasında katılımınıza ilişkin herhangi bir sorunuz olursa, araştırmacıyla iletişime geçebilirsiniz.

Okudum, kabul ediyorum.

## *APPENDIX B. INFORMED CONSENT FORM*

### Katılımcı İzin Formu

Çalışmanın amacını ve içeriğini ........... numaralı katılımcıya açıklamış bulunmaktayım. Çalışma kapsamında yapılacak işlemler hakkında katılımcının herhangi bir sorusu olup olmadığını sordum ve katılımcı tarafından yöneltilen bütün soruları yanıtladım.

| | |
|---|---|
| Tarih | Araştırmacının imzası |
| ................................................ | ................................................ |

Çalışmanın amacı ve içeriği hakkında açıklamaların yer aldığı "Katılımcı Bilgilendirme Formu"nu okudum. Araştırmacı çalışma kapsamındaki haklarımı ve sorumluluklarımı açıkladı ve kendisine yönelttiğim bütün soruları açık bir şekilde yanıtladı. Sonuç olarak, uygulama esnasında şahsımdan toplanan verilerin bilimsel amaçlarla kullanılmasına izin verdiğimi ve çalışmaya gönüllü olarak katıldığımı beyan ederim.

| | |
|---|---|
| Tarih | Katılımcının imzası |
| ................................................ | ................................................ |

## *APPENDIX C. DEMOGRAPHIC INFORMATION FORM*

### Katılımcı Bilgi Formu

**Yaş: …..…………………………….**

**Cinsiyet: ….……………………….**

**Bölüm: ….……..…..…..…..…..…..**

**Yazışma adresi (telefon numarası ya da e-posta adresi):**

**…..……..…..…..…..…..…..…....**

1. İki dilli misiniz?

   ☐ Evet ☐ Hayır

   Yanıtınız Evet ise lütfen ana dilinizi belirtiniz……………………………..

2. Düzeltilmemiş bir görme bozukluğunuz var mı?

   ☐ Evet ☐ Hayır

3. Daha önce psikiyatrik/psikolojik bir rahatsızlık tanısı aldınız mı?

   ☐ Evet ☐ Hayır

   Yanıtınız Evet ise lütfen konulan tanıyı belirtiniz ……………………………..

4. Daha önce nörolojik bir rahatsızlık tanısı aldınız mı?

   ☐ Evet ☐ Hayır

   Yanıtınız Evet ise lütfen konulan tanıyı belirtiniz ……………………………..

5. Herhangi bir ilaç kullanıyor musunuz?

   ☐ Evet ☐ Hayır

   Yanıtınız Evet ise lütfen ilacın adını belirtiniz ……………………………..

6. Daha önce kafa travması geçirdiniz mi?

   ☐ Evet ☐ Hayır

7. Aşağıda belirtilen bozukluklardan herhangi birine dair tanı aldıysanız, lütfen işaretleyiniz (Birden fazla işaretleme yapabilirsiniz)

   ☐ Disleksi ☐ Diskalkuli ☐ Uzamsal İhmal

8. Daha önce laboratuvarda yürütülmüş bir psikoloji deneyine katıldınız mı?

☐ Evet ☐ Hayır

Yanıtınız Evet deneyin ne ile ilgili olduğunu kısaca belirtiniz

## Edinburgh El Tercihi Envanteri

Lütfen aşağıdaki tabloda ilk sütunda sıralanmış olan aktiviteleri yaparken veya söz konusu aletleri kullanırken hangi elinizi tercih ettiğinizi ilgili sütundan işaretleyiniz.

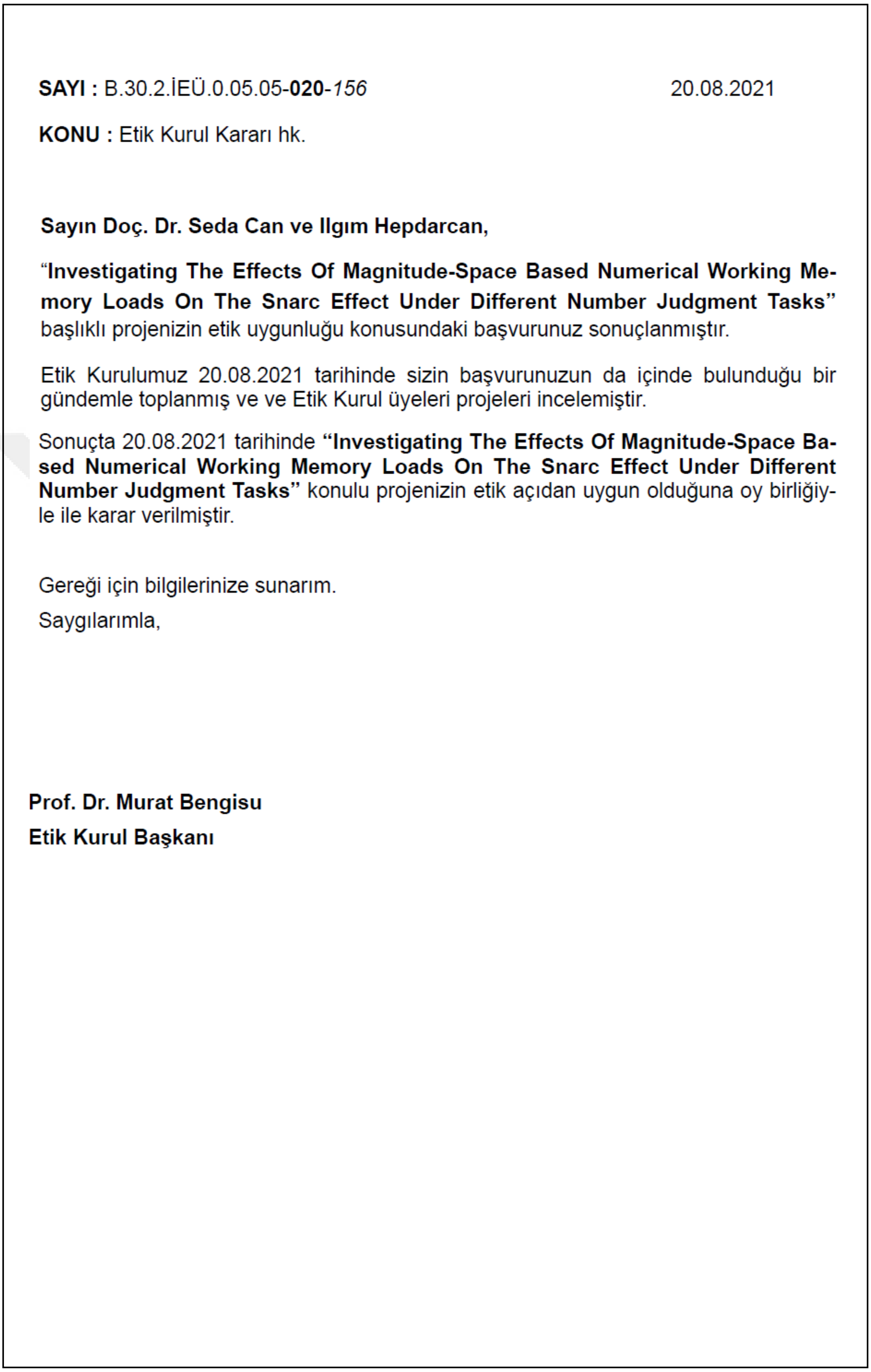
| | Her zaman sol | Genelde sol | Tercihim yok | Genelde sağ | Her zaman sağ |
|---|---|---|---|---|---|
| Yazma | | | | | |
| Fırlatma | | | | | |
| Makas | | | | | |
| Diş fırçası | | | | | |
| Bıçak | | | | | |
| Kaşık | | | | | |
| Kibrit | | | | | |
| Mouse | | | | | |

## *APPENDIX D. THE BACKWARDS DIGIT SPAN TASK: PARTICIPANTS' ANSWER RECORDING SHEET*

| **Span** | **Trial** | **Key** | **Answer** | **Evaluation** |
|---|---|---|---|---|
| 2 Digits | 1 | 1 5 | | |
| | 2 | 8 3 | | |
| 3 Digits | 1 | 3 9 4 | | |
| | 2 | 6 2 5 | | |
| 4 Digits | 1 | 4 1 8 3 | | |
| | 2 | 5 9 7 1 | | |
| 5 Digits | 1 | 3 7 9 2 6 | | |
| | 2 | 7 2 5 8 4 | | |
| 6 Digits | 1 | 6 8 2 5 1 7 | | |
| | 2 | 4 6 9 1 3 8 | | |
| 7 Digits | 1 | 8 2 1 9 3 7 4 | | |
| | 2 | 5 6 3 9 2 1 8 | | |
| | | | **Score** | |

**Not:** Her iki denemede de başarısız olunduysa testin uygulanmasına son verilmiştir.

## *APPENDIX E. ETHICAL BOARD APPROVAL*



**SAYI :** B.30.2.İEÜ.0.05.05-**020**-*156* 20.08.2021

**KONU :** Etik Kurul Kararı hk.

**Sayın Doç. Dr. Seda Can ve Ilgım Hepdarcan,**

“**Investigating The Effects Of Magnitude-Space Based Numerical Working Memory Loads On The Snarc Effect Under Different Number Judgment Tasks**” başlıklı projenizin etik uygunluğu konusundaki başvurunuz sonuçlanmıştır.

Etik Kurulumuz 20.08.2021 tarihinde sizin başvurunuzun da içinde bulunduğu bir gündemle toplanmış ve ve Etik Kurul üyeleri projeleri incelemiştir.

Sonuçta 20.08.2021 tarihinde **“Investigating The Effects Of Magnitude-Space Based Numerical Working Memory Loads On The Snarc Effect Under Different Number Judgment Tasks”** konulu projenizin etik açıdan uygun olduğuna oy birliğiyle ile karar verilmiştir.

Gereği için bilgilerinize sunarım.

Saygılarımla,

**Prof. Dr. Murat Bengisu**
**Etik Kurul Başkanı**

# CURRICULUM VITAE

## Ilgım HEPDARCAN SEZEN

## EDUCATION

İzmir University of Economics, İzmir/TURKEY

- Ph. D. (Experimental Psychology) 2019 – January 2025

İzmir University of Economics, İzmir/TURKEY

- M. Sc. (Experimental Psychology) 2013 – 2017

İzmir University of Economics, İzmir/TURKEY

- B. Sc. (Psychology) 2009 – 2013

## EMPLOYMENT

İzmir University of Economics, İzmir/TURKEY

- Neuroscience of Mind and Behavioral Research Laboratory Supervisor 2014 – 2025

İzmir University of Economics, İzmir/TURKEY

- Department of Psychology Research Assistant 2013 – 2014

## PEER-REVIEWED PUBLICATIONS

**Hepdarcan**, I., & Can, S. (2025). Psychometric characteristics of the n-back task: Construct validity by aging and stimulus type, internal consistency, test-retest and alternate forms reliability. *Current Psychology*. https://doi.org/10.1007/s12144-025-07318-9

**Hepdarcan**, I., Çetinkaya, H. & Dural, S. (2024). Magnitude-space representations in the n-back task: Long-term representations of magnitudes alter the working memory performance. *Memory & Cognition*. https://doi.org/10.3758/s13421-024-01667-9

Zebil, B., Gökçe, N., **Hepdarcan**, I. & Kocak, A. (2024). Attachment security and peer pressure among Turkish university students: A mediation role of rejection sensitivity. *Nesne Psychology*, *11*(30), 551-563. https://doi.org/10.7816/nesne-11-30-03

Bulut, M., **Hepdarcan**, I., Palaz, E., Çetinkaya, H. & Dural, S. (2023). No SNARC effect among left-to-right readers: Evidence from a Turkish sample. *Advances in Cognitive Psychology*, *19*(3), 224-236. https://doi.org/10.5709/acp-0394-x

Koçak, A., **Hepdarcan**, I., Mumcu, Y., Apuhan, S., & Şensöz, B. (2023). The mediating role of needs frustration in relation between adolescent triangulation and adjustment. *Current Psychology*. https://doi.org/10.1007/s12144-023-05106-x

**Hepdarcan**, I., Bulut, M., Palaz, E., Can, S., & Dural, S. (2021). The distance effect on discrimination ability and response bias during magnitude comparison in a go/no-go task. *Attention, Perception & Psychophysics*. *83*(5), 2052-2060. https://doi.org/10.3758/s13414-021-02274-5

## MANUSCRIPTS IN PROGRESS

**Hepdarcan**, I., Korkut, İ., Gür, E., Çetinkaya, H. & Dural, S. (under review). Revisiting the SNARC effect: Testing magnitude comparison in a Turkish sample lacking SNARC effect in parity judgment task. *Journal of Cognitive Psychology*. (Submission ID: JCP-247637866R).

## FUNDING / RESEARCH SUPPORT

The Scientific and Technological Research Council of Türkiye (122K186) (1002-Short Term R&D Funding Program) 2022 – 2023

Title: Investigating the Effects of Magnitude-Space-Based Numerical Working Memory Loads on the SNARC Effect Under Different Number Judgment Tasks

Role: Co-Investigator

İzmir University of Economics Scientific Research Project Grant (BAP 2019-15) 2020 – 2022

Title: An Investigation of Space-Size Association in the Context of Long-Term Memory Representations

Role: Researcher

İzmir University of Economics Scientific Research Project Grant (BAP 2018-11) 2018 – 2020

Title: Validity and Reliability of the N-back Task as a Working Memory Task

Role: Researcher

## CONGRESS PRESENTATIONS

Korkut, İ., Çetinkaya, H. **Hepdarcan, I.,** Gür, E., & Dural, S. (July, 2024). *Revisiting the SNARC effect with magnitude comparison task in a null-SNARC sample*. 33rd International Congress of Psychology, Prague, Czech Republic.

Bulut, M., **Hepdarcan, I.,** Palaz, E., Çetinkaya, H., & Dural, S. (October, 2022). *The SNARC effect: Can reading direction and finger counting habits explain the spatial-numerical associations?* 21th National Congress of Psychology, İstanbul, Turkey.

Gören, B. Ş., Fidan, B., Bağcı, B., Gedik, S., Kayaanıt, B. E., Süel, S., Tosun, C., **Hepdarcan, I.,** & Can, S. (October, 2022). The effects of *positive, negative, and neutral facial expressions on short-term memory performance*. 21th National Congress of Psychology, İstanbul, Turkey.

Tükel, Ş., Aktan, R., **Hepdarcan, I.,** Can, S., & Özaevli, S. (July, 2020). *Prefrontal cortex hemodynamic responses during cognitive tasks in patients with Chronic Obstructive Pulmonary Disease (COPD)*. 12th Federation of European Neuroscience Societies, Glasgow, UK (Virtual Forum).

Dural, S., Bulut, M., Palaz, E., & **Hepdarcan, I.,** & Can, S. (July, 2020). *The distance effect in a response inhibition task*. 32nd International Congress of Psychology, Prague, Czech Republic.

Tükel, Ş., Aktan., R., **Hepdarcan, I.,** & Can, S. (October, 2019). *Prefrontal cortex hemodynamic responses during cognitive tasks in patients with COPD: Presentation of preliminary data*. 41st National Congress Respiration, Bodrum, Turkey.

**Hepdarcan, I.,** Can, S., Alankuş, G., & Çetinkaya, H. (July, 2018). *The reliability of hemodynamic measures obtained via functional near infrared spectroscopy (fNIRS) by using n-back task.* International Neuropsychological Society 2018 Mid-Year Meeting, Prague, Czech Republic.

**Hepdarcan, I.,** Can, S., Alankuş, G., & Çetinkaya, H. (July, 2017). *Gender-specific hemodynamic measures obtained via functional near infrared spectroscopy (fNIRS) by using n-back task*. 20th Conference of the European Society for Cognitive Psychology, Potsdam, Germany.

**Hepdarcan, I.,** Can, S., Alankuş, G., & Çetinkaya, H. (July, 2017). *The reliability of hemodynamic measures obtained via functional near infrared spectroscopy (fNIRS) by using n-back task.* 15th European Congress of Psychology, Amsterdam, The Netherlands.

**Hepdarcan, I.,** Can, S., Alankuş, G., & Çetinkaya, H. (July, 2017). *Gender-specific hemodynamic measures obtained via functional near infrared spectroscopy (fNIRS) by using n-back task.* 15th European Congress of Psychology, Amsterdam, The Netherlands.

**Hepdarcan, I.,** Can, S., & Çetinkaya, H. (September, 2016). Validity *and reliability of the hemodynamic measures obtained via fNIRS- functional near infrared spectroscopy using the n-back task.* 19th National Congress of Psychology, İzmir, Turkey.

Çetinkaya, H., **Hepdarcan, I.,** İçağası, B., & Palaz. E. (June, 2014). *A search for cognition in nonhuman animals.* 19th National Congress of Psychology Students, Samsun, Turkey.

Barutçuoğlu, C., **Hepdarcan, I.,** Toprak, N., Mert, S., & Dönmez, Y. (July, 2012). *The effects of disgust and anger on aggressive behavior and facial expression detection.* 17th National Congress of Psychology Students, İstanbul, Turkey.

**Hepdarcan, I.,** Can, B., Oğan, İ., Özgören, S., & Toran, T. (September, 2011). *Can't take my eyes off of you: Investigating female physical attractiveness with attentional adhesion paradigm*. V. Congress of Psychology Graduate Students, İstanbul, Turkey.

## PROGRAMS

SPSS

RStudio

SuperLab 4 & SuperLab 6

MATLAB (Psychtoolbox)

fNIRSOFT & fNIRSOFT-PRO

## AWARDS AND HONORS

İzmir University of Economics, Experimental Psychology Program, High Honors Degree 2017

Young Psychologists Research, Turkish Psychological Association Awards, 2$^{nd}$ Prize 2014

İzmir University of Economics, Psychology Department, Honors Degree 2013