Impact of concurrent temporal but not spatial processing on working memory for serial order

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Title Page

Impact of concurrent temporal but not spatial processing on working memory for serial order

Lucie Attout [ab], Robin Remouchamps [a], & Steve Majerus [ab]

[a] Psychology and Neuroscience of Cognition Research Unit, University of Liège

[b] Fund for Scientific Research FNRS, 1000 Brussels, Belgium

Author note

Lucie Attout, https://orcid.org/0000-0002-4494-9379

Steve Majerus, https://orcid.org/0000-0002-8206-8097

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Correspondence concerning this article should be addressed to Lucie Attout, , Psychology and Neuroscience of Cognition Research Unit, Université de Liège; Boulevard du Rectorat, B33, 4000 Liège – Belgium; Tel: 0032 4 3663991; Email: lucie.attout@uliege.be

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Author contribution

Lucie Attout: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Writing- Original draft preparation, Visualization. Robin Remouchamps: Investigation. Steve Majerus: Conceptualization, Methodology, Writing - Original Draft, Supervision.

Statements and declarations

There is no conflict of interest in connection with this work.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest in connection with this work.

Ethics approval

The study was approved by the ethics committee of the Comité d'Ethique Hospitalo-Facultaire Universitaire de Liège.

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Consent for publication

All the authors have approved the last version of the manuscript.

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Data and code availability

The full stimulus sets for the materials used in the present experiments, anonymized raw data files, statistical files and opensesame tasks are available on the Open Science Framework : osf.io/3xz54/

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Manuscript

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Abstract

Serial order is an essential but still poorly understood component of verbal working memory (WM). This study examined the role of spatial vs. temporal codes for the representation of serial order information by presenting spatial or temporal secondary tasks during the completion of a verbal WM task. The secondary tasks were dot detection tasks designed to impact spatial processing (the dots appeared in random vs. left-to-right spatial order) or temporal processing (the dots appeared in regular vs. irregular temporal order). In two experiments, we observed an exclusive, interfering impact of the temporal secondary task on serial order WM while evidence for the null was observed for the impact of the spatial secondary task. These data provide support for an intervention of temporal processes in the encoding of serial order information in WM. Furthermore, the effect of temporal interference was not limited to WM for serial order information, but also disrupted WM for item information. These findings highlight the role of temporal processes in encoding both item and serial order information in WM, possibly by allowing binding of the two types of information.

182 words

Keywords: Space, time, dual-tasks, serial order, working memory.

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Introduction

Serial order working memory (WM) is the ability to temporarily maintain verbal or visuo-spatial information in a specific order. This ability is essential for many sequential processing tasks such as mental calculation, problem-solving or repetition of novel verbal stimuli. Many different theoretical models of serial order processing have been proposed but there is still no agreement concerning the nature of the codes and processes that are used to represent serial order information in WM. The way how we code serial order WM can be partially inferred from the serial position curve observed in immediate serial recall tasks, which typically follows a U-shaped profile—showing better recall for the first and last items in a memory list (Hurlstone et al., 2014; Marshuetz & Smith, 2006 for a review). However, while this profile provides some insight into how serial order is coded, it can be explained by contrasting theoretical approaches, broadly categorized into two types: associative chaining accounts and positional-coding accounts. In associative chaining models, serial order is considered to be encoded by linking successive items in pairs, with the first item serving as a cue for its associated pair (Ebbinghaus, 1913; Logan, 2021; Murdock, 1993; Osth & Hurlstone, 2023). In contrast, positional models propose that items are encoded by associating them explicitly with specific serial order representational levels, taking the form of (absolute or relative) positional or contextual codes (e.g. Brown et al., 2000; Hartley et al., 2016; Henson, 1998, 1999; Lewandowsky & Farrell, 2008). This item-position coding, as opposed to item-item coding, involves the representation of the different serial positions within a list using markers, which are reinstated during the recall phase and cue associated items for recall. It is also important to note that while positional models have been widely adopted—largely because chaining models were considered to fail to account for several key empirical findings in serial recall (Henson, 1999; Oberauer et al., 2018; Osth & Hurlstone, 2023)—more recent models integrate both inter-item and item-position processes. These hybrid models suggest that both mechanisms contribute to the temporary maintenance of serial order information and

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help shape the observed behavioral recall patterns (Burgess & Hitch, 1992; Caplan et al., 2022; Logan & Cox, 2021; Osth & Dennis, 2015; Osth & Hurlstone, 2023). However, all these models differ in fundamental ways when it comes to defining the nature of these codes in a more concrete manner (Majerus & Attout, 2018). At a broad level, the existing studies make a distinction between spatial and temporal markers. The present study focuses on these two major positional accounts of serial order WM: the temporal and spatial accounts.

According to the temporal coding account, when encoding a list of items, each successive item is associated with a temporal context signal whose state evolves over time, in an analogous manner to the different states of the rotating hands (also called oscillators) on a clock face (Brown et al., 2000; Hartley et al., 2016), resulting in items from different serial positions being associated with different values of a temporal context signal. This account is supported by time-based computational models of serial order WM. These models are able to simulate hallmark effects of serial recall such as the U-shaped response curve, with better recall performance for start-of-list and end-of-list items relative to mid-of-list items (i.e., the standard primacy and recency effects in immediate serial recall tasks) (Hartley et al., 2016; Hurlstone et al., 2014). They are also able to simulate different types of serial order errors such as transposition (ACBD instead of ABCD), omission (AB/D) and intrusion (ABXD) errors.

Other types of studies also provide evidence for an interaction between temporal processing and verbal WM. The ability to reproduce rhythmical sequences has been found to be associated with verbal WM performance in adults (Saito, 2001). Moreover, a study observed a link between the temporal precision with which items are sequentially rehearsed and WM performance for the given sequence of items (Gilbert et al., 2017). An additional study demonstrated that time interacts with the position of an item in a WM list (De Belder et al., 2017). This study observed faster response times for judging items presented for short

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presentation durations when involving items from initial list positions and for judging items presented for long presentation durations when involving end-of-list positions items, revealing a facilitatory effect when temporal duration and serial order position converge. In the same line, other studies also observed a link between temporal variables and serial order WM. For example, several studies found that the presentation of a regular temporal signal (beat) along with the memory sequence (during the encoding and/or the maintenance phase) improved WM performance while concurrent tapping of an irregular rhythm impairs WM performance (Fanuel et al., 2018; Gorin et al., 2016; Henson et al., 2003; Plancher et al., 2018). However, we should note here that these effects are not always observed. For example, Hall and Gathercole (2011) observed no positive impact on WM performance from a regular paced sound presented during the encoding and maintenance intervals of a verbal WM task.

Another positional account of serial order coding is the spatial account, also termed the mental whiteboard hypothesis (Abrahamse et al., 2014, 2017). It considers that positional markers are defined by spatial codes, according to a left-to-right spatial dimension, with earlier items of a stimulus list represented in the left mental space and end-of-list items represented in the right mental space. This account is supported by different types of empirical studies. In their seminal work, van Dijck and colleagues showed that sequentially presented information automatically triggers an associated spatial representation in WM, items from early serial positions of a verbal WM list being responded to more rapidly with the left hand (when reactivated during the maintenance delay), and items from later serial positions being responded to more quickly with the right hand (van Dijck & Fias, 2011). van Dijck et al. (2013) further showed that reactivating start-of-list WM items induced a leftward attentional spatial bias in a concurrent dot detection task, while end-of-list items induced a rightward spatial bias. Another type of study showed that, serial order WM performance can be increased when each successive item is presented in distinct spatial positions on the screen

DOI: 10.1177/17470218251346745

that move from left-to-right, rather than from right-to-left (Fischer-Baum & Benjamin, 2014). Moreover, WM recall performance can interact with spatial cues presented during retrieval, a spatial cue on the left of the screen leading to faster retrieval of the first WM items and a spatial cue on the right of the screen leading to faster retrieval of the last WM items (De Belder et al., 2015). These data have led to the assumption of an internal attentional spatial reference frame for the representation of serial order information in WM, and supporting evidence has also been observed in recent neuroimaging, electrophysiological and eye-tracking data (Attout et al., 2022; Cristoforetti et al., 2022; Rasoulzadeh et al., 2021; Sahan et al., 2022). At the same time, spatial coding of serial order WM may not characterize all serial order WM situations. Other studies have shown that spatialization effects of verbal WM content mainly appear for relatively short WM lists and when memoranda can be processed semantically such as concrete words (Ftaïta et al., 2023; Ginsburg et al., 2017; Guida et al., 2018).

So far, no study has directly compared spatial and temporal accounts of serial position coding. Studies focused on only one type of codes, and used very different methodologies, leaving open the question of which type of code is used by the human cognitive apparatus to represent serial order. It could also be the case that both codes are used simultaneously, given the inherent complexity of creating a representation for a type of information that has no instantaneous materiality. When encoding a memory list, different pieces of information reach our mind at any successive moment, and serial order information needs to be recomputed based on the developing history of these successive encoding events. The aim of this study was to directly contrast the temporal and spatial accounts of serial order encoding in WM. We used a dual-task paradigm that allowed us to examine of the impact of spatial as well as temporal processing tasks on the encoding of serial order information in WM.

DOI: 10.1177/17470218251346745

To induce temporal interference/facilitation, we used a regular/irregular rhythm, previously employed in past studies from different fields. For instance, several previous studies in WM field (Fanuel et al., 2018; Henson et al., 2003; Plancher et al., 2018) have used a tapping or detection task involving regular and irregular sound sequences as a secondary task in WM experiments. They effectively observed an effect (either deleterious or enhancing) on WM maintenance abilities. In the field of temporal attention, several studies have shown that detecting and perceiving a visual or auditory target is slower when it occurs outside a regular auditory rhythm compared to within it, and also slower after an irregular rhythm compared to a regular one (e.g. Herbst & Landau, 2016; Sanabria et al., 2011). Therefore, this rhythmic manipulation has been shown to influence both temporal attention and WM abilities. To induce spatial interference/facilitation, we developed a task inspired by previous task designs that had been used to evidence spatial coding effects in verbal WM. While lateralized detection dots during the maintenance interval is facilitates by the position of the item to be recalled (van Dijck et al., 2014), cueing with rightward/leftward dots enhanced the recall of an item positioned in the same mental hemispace as the cue (De Belder et al., 2015). Finally, a congruent left-to-right lateralization of items during encoding also improved WM abilities (Fischer-Baum & Benjamin, 2014). Therefore, in the present study, we used secondary dot detection tasks for all condition. For the temporal conditions, the dots could appear at a regular pace, mimicking a regular temporal signal supposed to be used for encoding successive serial positions in WM, and which should lead to facilitatory performance (temporal facilitatory condition). The dots could also appear at irregular temporal intervals, which should interfere with the regular temporal signal used for encoding serial order information in WM, and which should lead to decreased WM performance (temporal interfering condition). For the spatial conditions, the dots were presented at specific spatial coordinates, either progressively shifting from left to right (spatial facilitatory condition),

DOI: 10.1177/17470218251346745

mirroring the supposed left-to-right spatial representation used for encoding the serial order information of successive list items, or appearing randomly on the left or right side of the screen (spatial interfering condition), interfering with the left-to-right spatial codes used for encoding the serial order of the memoranda.

Experiment 1

We assessed WM performance with an auditory immediate serial recall (ISR) task for 7-letter-name lists. While encoding the memoranda, participants performed a concurrent dot detection task. In the temporal processing condition, the dots appeared centrally either at a regular (temporal facilitatory) or at an irregular (temporal interfering) pace. In the spatial processing condition, the dots were presented in a left-to-right (spatial facilitatory) direction or in random horizontal directions (spatial interfering). For all conditions, participants pressed a button each time a dot was presented. Finally, there was also a baseline WM condition without any temporal or spatial secondary task.

If serial order coding in WM is based exclusively on spatial or on temporal codes, then we should observe better/decreased performance only in the spatial or only in the temporal facilitatory/interfering conditions. If both types of codes are used to represent serial order information in WM, both spatial and temporal concurrent tasks should impact serial order recall performance. To assess serial order recall performance, we determined strict serial order recall accuracy (items recalled in correct serial position) as well as serial order transposition gradients for recall errors. We furthermore examined the generality of the impact of the concurrent tasks by also determining item recall scores (items recalled independently of their correct serial position). If coding of serial order information is prevented by the concurrent task, then this may also impact the recall of item information given that, according to a number of computational models of WM (Botvinick & Plaut, 2006; Burgess & Hitch, 1999; Hartley et al., 2016) retrieval is initiated by serial position codes

DOI: 10.1177/17470218251346745

which provide cues for retrieving item information. For example, in the model by Burgess and Hitch, the dynamic context signal layer that encodes serial order information is reset to its initial state during recall and items are successively activated via the replay of the different context signal states and the associations that have been created between each state and the item layer.

Materials and Methods

Participants

Forty-five French-speaking young adults with no history of neurological disorder, sensory impairment or learning difficulties were recruited for this study. Data from 2 participants were excluded due to technical problems arising during task administration. The data from 43 participants (32 women and 35 right-handed) were retained for analysis (mean age = 23.95 ± 4.81 years old, age range = 19-35). Minimal number of years of education was 12 (mean = 14.21 ± 1.81, range = 12-20). Sample size was estimated based on a simulation procedure using the BayesFactor package for R (5000 simulations; Brysbaert, 2019; Morey et al., 2016). Our effect of interest was a Bayesian paired t-contrast for each ISR-secondary task condition vs. the ISR baseline condition, by assuming a large effect size of d = 0.80 based on the temporal secondary task condition effects observed by Henson et al. (2003). This analysis showed that if the effect of interest exists, the minimal sample size needed for reaching a specific level of evidence (BF_{10}>3) in favour of the effect in 96% of simulated samples was N = 30. If the effect of interest does not exist, the minimal sample size needed for reaching a specific level of evidence (BF_{01}>3) in favour of the absence of an effect in 77% of simulated samples was N = 40. The ethics committee of the Faculty of Medicine of the University of Liège had approved the study. In line with the Declaration of Helsinki, all participants gave their written informed consent prior to inclusion in the study.

DOI: 10.1177/17470218251346745

Material

To create the memory sequences (e.g., L K P V R S N), we sampled from all the consonants used in the French language except for the consonant W, which is the only letter whose name is composed of three syllables ([dublZve]), while the names for all other letters are monosyllabic. The letter names were recorded by a neural, female voice. They were edited as individual sound files and then combined to form each WM sequence. The dots used in the secondary, dot-detection task were white-coloured and sized 2.38°. A black display background was adopted during the entire experiment.

Task description

The different tasks are depicted in Figure 1.

ISR tasks - Each trial started with the presentation of a white-coloured exclamation mark during 500 ms and was followed by the presentation of an auditory list of 7 letter names at the rate of one letter per second. 1000 ms after the last item of the memory list, a white-coloured question mark appeared on the screen and the participants had to recall aloud each letter in correct serial position. If the participant forgot a specific word, they were invited to say aloud "blank" to ensure accurate scoring of serial position information for recalled items. Participants pressed the space bar to proceed to the next trial. A total of 100 memory lists were administered, equally spread over 5 task conditions (baseline; temporal facilitatory + spatial neutral; temporal interfering + spatial neutral; spatial facilitatory + temporal interfering; spatial interfering + temporal interfering).

Secondary tasks - Four secondary tasks were constructed. In each of these tasks, participants had to detect, as quickly as possible, a white-coloured dot appearing during 200 ms on the screen. Seven dots were presented during the encoding phase of the ISR task, with one dot appearing after each letter of the memory sequence, with the following constraints:

DOI: 10.1177/17470218251346745

Temporal facilitatory + Spatial neutral task: The dots appeared on the center of the screen at a regular pace of 1 dot / 1000 ms, with an offset of 500ms relative to the memory list items, and participants had to push the space bar each time a dot occurred, amounting to the reproduction of a regular temporal sequence.

Temporal interfering + Spatial neutral task: The task setup was the same except that the dots occurred at an irregular pace, with an offset varying between 250 to 750 ms relative to each memory list item; this task therefore corresponded to the reproduction of an irregular temporal sequence.

Spatial facilitatory + Temporal interfering task: Each successive dot was spatially displaced to the right relative to the previous one, leading to a left-to-right spatial presentation pattern; participants had to push a button each time a dot appeared. More precisely, all the dots were centered on the vertical axis of the screen but differed on the horizontal axis, with a -416 pixel displacement to the left (relative to the center of the screen) for the first dot, a -288 pixel displacement to the left for the second dot, a -160 pixel displacement to the left for the third dot, no displacement for the fourth dot (at the center of the screen), a +160 pixel displacement to the right for the fifth dot, a +288 pixel displacement to the right for the sixth dot and a +416 pixel displacement to the right for the last dot. In order to avoid contamination by a temporal facilitation effect (regular rhythm), the successive dots appeared at an irregular pace (randomly varying offset of 250 to 750 ms relative to each item).

Spatial interfering + Temporal interfering task: The task setup was the same as for the spatial facilitatory task except that the -416 to +416 pixel displacements occurred in random succession, leading to a multi-directional spatial sequence on the horizontal axis.

Scoring method

For each task, strict serial order recall accuracy (i.e., the proportion of items recalled in correct position) as well as item recall accuracy (i.e., the proportion of correct items

DOI: 10.1177/17470218251346745

regardless of their position) were computed. An item recalled in correct position was credited 1 point for the overall score. An item recalled in any position was credited 1 point for the item score. We computed *transposition gradients* for items recalled in incorrect serial order by determining the distance of negative displacements (items recalled ahead of their correct positions) and positive displacements (items recalled after their correct position). Taking the example of "F J P R N" recalled as "F R J P N", "F" and "N" will result in a displacement score of 0 (no displacement), "R" will result in a displacement score of -2, "P" will result in a displacement score of +1, and "J" will result in a displacement score of -1.

--- Insert Figure 1 about here ---

General procedure

Each of the five ISR conditions (baseline; temporal facilitatory + spatial neutral; temporal interfering + spatial neutral; spatial facilitatory + temporal interfering; spatial interfering + temporal interfering) was presented in a single block; the five conditions were presented in a blocked manner in a single experimental session, with the order of blocks being randomized between participants. Also, the assignment between WM lists and conditions was randomized across participants. Each block was preceded by two practice trials that could be repeated if requested by the participant. Due to the Covid-19 pandemic situation, the experiment was conducted online, with the task being presented via OpenSesame software (https://osdoc.cogsci.nl/) implemented in the Jatos web interface (https://www.jatos.org/). The experimenter was virtually present via a video conferencing platform during the entire procedure to give the task instructions to the participant, to ensure participant's compliance to task instructions and to record and transcribe the participants' oral response. All participants completed the experiment on their own computer in a quiet environment and were asked to

DOI: 10.1177/17470218251346745

keep their cameras turned on for the entire duration of the experiment. Anonymized data and analysis scripts are available on the Open Science Framework platform at osf.io/7tmdc.

Data analysis

For data analysis, we used a Bayesian model comparison strategy to select and quantify the strength of evidence associated with each model (Dienes, 2011; Morey & Rouder, 2011; Wagenmakers, 2007). The Bayesian framework does not involve traditional *p*-values, thereby avoiding difficulties associated with multiple testing, such as alpha inflation or loss of power when adopting a stricter alpha level (Klugkist et al., 2011). The Bayesian approach has also the advantage to not only give evidence in favour of the alternative model but also to appreciate evidence in favour of the null model, allowing to reject the null hypothesis more confidently (Wagenmakers, 2007). The BF_{10} value represents the result of the likelihood ratio of the alternative model (*H*1) relative to the null model (*H*0) and the BF_{01} value represents the likelihood ratio of *H*0 relative to *H*1. The following classification of evidence strength was used (Jeffreys, 1961; Lee & Wagenmakers, 2014): A BF of 1 or less provides no evidence, 3>BF>1 provides anecdotal evidence, 10>BF>3 provides moderate evidence, 30>BF>10 provides strong evidence, 100>BF>30 provides very strong evidence, and BF>100 provides extreme/decisive evidence. Bayesian analyses were conducted with Version 0.18.3 of the JASP software package, using default settings for the Cauchy prior distribution (JASP Team, 2017, jasp-stats.org).

Results

Accuracies for each task are presented in Figure 2. The distribution of the different measures was assessed by determining skewness and kurtosis parameters (Tabachnick & Fidell, 1996). All measures showed acceptable skewness and kurtosis values (values within the recommended 2 *SD* range, from -0.39 to 0.66 with a Standard error skewness cut-off = .72 and from -0.77 to 0.82 with a Standard error kurtosis cut-off = 1.42).

DOI: 10.1177/17470218251346745

We first conducted a Bayesian repeated measures ANOVA with the 5 Task conditions as a within-subject variable on the serial recall accuracy measure (see Figure 2). Strong evidence in favour of a main effect of Task condition (BF_{10}=625.10, n^2_p=0.14) was observed. The Task condition effect was decomposed via a set of Bayesian paired t-tests to compare each secondary task condition to the baseline condition. We observed strong evidence in favour of a detrimental effect for the temporal interfering + spatial neutral condition (BF_{10}=42.60, Cohen's d=0.56) but also in favour of a detrimental effect for the spatial facilitatory + temporal interfering condition (BF_{10}=40.46, Cohen's d=0.56). The two other secondary task conditions were associated with evidence for the null: spatial interfering + temporal interfering (BF_{10}=0.30 <=> BF_{01}=3.33, Cohen's d=0.17) and temporal facilitatory + spatial neutral (BF_{10}=0.20 <=> BF_{01}=5.88, Cohen's d=0.09). When running the same analysis on the item recall accuracy measure (see Figure 2), we observed again strong evidence for a main effect of Task condition (BF_{10}=6842.46, n^2_p=0.17). Bayesian paired t-tests showed that both the temporal interfering + spatial neutral (BF_{10}=785.88, Cohen's d=0.72) and the spatial interfering + temporal interfering (BF_{10}=15.67, Cohen's d=0.50) conditions led to decreased performance relative to the baseline condition, but the spatial facilitatory + temporal interfering condition was also again associated with decreased performance (BF_{10}=16.91, Cohen's d=0.51). At the same time, there was no conclusive evidence for a temporal facilitation effect + spatial neutral (BF_{10}=0.88, Cohen's d=0.29).

--- Insert Figure 2 about here ---

Next, we examined the impact of the different secondary task conditions on the transposition gradients for serial order recall errors. We determined the amount of transposition errors as a function of serial position displacement distance and as a function of task condition, (see Figure 3) by running a series of 2 (Task condition: baseline vs. one of the secondary task

DOI: 10.1177/17470218251346745

conditions) × 12 (Displacement distance: -6, -5, -4, -3, -2, -1, 1, 2, 3, 4, 5, 6) Bayesian repeated-measures ANOVAs. None of the analyses yielded evidence in favour of a task condition effect or an interaction between task condition and transposition distance; instead, positive evidence for their absence was observed. When comparing the baseline to the spatial facilitatory + temporal interfering condition, the strongest model included only the Displacements distance factor (BF_{10}=1.17E+119, $\eta^2 p$ =0.73). This model was 35.05 times more likely than the following model including the interaction between Task condition and Displacement distance (BF_{10} = 0.003 <=> BF_{01} = 333.33, n^2_p=0.03) or the Task condition factor (BF_{10} = 0.12 <=> BF_{01} = 8.33, n^2_p=0.07). When comparing the baseline to the spatial interfering + temporal interfering condition, the strongest model included only the Displacement distance factor (BF_{10}=1.49E+107, $\eta^2 p$ =0.69), this model being 61.93 times more likely than the following model including the interaction between Task condition and Displacement distance (BF_{10} = 0.02 <=> BF_{01} = 333.33, n^2_p=0.03) or the Task condition factor (BF_{10} = 0.21 <=> BF_{01} = 8.33, n^2_p=0.05). When comparing the baseline to the temporal facilitatory + spatial neutral condition, the strongest model included only the Displacement distance factor (BF_{10}=3.27E+105, $\eta^2 p$ =0.69), this model being 842.27 times more likely than the following model including the interaction between Task condition and Displacement distance (BF_{10} = 0.00, n^2_p=0.01) or the Task condition factor (BF_{10} = 0.12 <=> BF_{01} = 8.33, n^2_p=0.01). Finally, when comparing the baseline to the temporal interfering + spatial neutral condition, the strongest model included only the Displacement distance factor (1.13E+119, n^2_p=0.73), this model being 347.02 times more likely than the following model including the interaction between Task condition and Displacement distance (BF_{10} = 0.00, n^2_p=0.02) or the Task condition factor (BF_{10} = 0.11 <=> BF_{01} = 9.09, n^2_p=0.00).The absence of a main effect of Task condition indicates that the secondary tasks had no overall impact on the amount of serial order errors. The absence of an interaction means that the task condition did not change

DOI: 10.1177/17470218251346745

the distribution of serial order errors as a function of displacement distance either, indicating that the precision of serial order coding was not impacted by any of the secondary tasks. As shown in Figure 3, in all task conditions, adjacent serial position transpositions were the most frequent error type, in line with previous studies reporting transposition gradients in ISR tasks.

--- Insert Figure 3 about here ---

Interim discussion

In line with our expectations, we observed a negative impact of the temporal interfering + spatial neutral condition on serial order recall performance for both the strict serial recall score and the item recall score, as well as of the spatial interfering + temporal interfering condition for the item recall score. On the other hand, we observed a negative impact of the spatial facilitatory + temporal interfering condition for both the strict serial recall and item recall scores, while a facilitatory impact had been expected. The latter finding could be a result of the specific parameters used for the spatial secondary tasks: the dots had been presented at an irregular temporal pace to avoid contamination by a temporal regularity effect. This design choice could, however, have led to a reverse contamination effect caused by the temporal irregularity of the dots, which may explain the detrimental impact observed in both interfering and facilitatory spatial secondary task conditions. One of the aims of Experiment 2 was to control for these possible confounds.

Experiment 2

Experiment 2 pursued two aims. The first aim was to determine to what extent the irregular temporal pace of the spatial secondary task conditions could have explained the general detrimental effect observed for both the interfering and the facilitatory spatial secondary task conditions observed in Experiment 1. This was achieved by using the same task setup as in

DOI: 10.1177/17470218251346745

Experiment 1 but by presenting the dots at a regular pace in both spatial secondary conditions. It could be argued that this choice may induce a reverse bias, by leading to general facilitatory effect by the temporal regularity of the dots in the spatial interfering and facilitatory task conditions (Fischer-Baum & Benjamin, 2014; Plancher et al., 2018). On the other hand, note that we did not observe such a facilitatory effect of the temporal facilitatory secondary task in Experiment 1, thereby reducing the likelihood of such a bias. The second aim of this study was to replicate the effects for the temporal secondary tasks, by expecting a general detrimental effect for the interfering task condition on both item and serial order recall accuracy scores, but no effect for the facilitatory task condition.

Materials and Methods

Participants

Forty-five other French-speaking young adults with no history of neurological disorder, sensory impairment or learning difficulties were recruited for this study (15 women, 30 right-handed, mean age = 23.29 ± 3.82 years old, age range = 18-35). The sample size was determined in the same manner as in the previous experiment.

Task description

The same five task conditions as in Experiment 1 were administered, using the same online data collection method. The only change was that the dots appeared at a regular temporal pace (500 ms after hearing each memory item) in both spatial secondary task conditions.

Results

Accuracies for each task are presented in Figure 3. The distribution of scores for the different tasks was assessed by determining skewness and kurtosis parameters (Tabachnick & Fidell, 1996). All measures had acceptable skewness and kurtosis values (values within the recommended 2 *SD* range, from -0.67 to 0.55 with a Standard error skewness cut-off = .70 and from -0.85 to 1.11 with a Standard error kurtosis cut-off = 1.40).

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We first conducted a Bayesian repeated measures ANOVA on the serial recall accuracy. As in Experiment 1, we observed moderate evidence for a main effect of Task condition (BF_{10}=3.37, n^2_p=0.08) against a null model. However, Bayesian paired t-test showed this time moderate evidence in favour of a detrimental effect of the temporal interfering + spatial neutral condition only, (BF_{10}=5.66, Cohen's d=0.43); the detrimental impact that had been observed in Experiment 1 for the spatial facilitatory + temporal facilitatory condition was this time associated with evidence for the null (BF_{10}=0.18, Cohen's d=0.06) (see Figure 4). Like in Experiment 1, evidence also favoured the absence of an effect of the two other secondary task conditions (spatial interfering + temporal facilitatory: BF_{10}=0.28, Cohen's d=0.16; temporal facilitatory + spatial neutral: BF_{10}=0.20, Cohen's d=0.10). When running the same analysis on the item recall accuracy score, we observed again strong evidence for a main effect of Task condition (BF_{10}=240.63, n^2_p=0.08). When decomposing the effect, we observed again evidence in favour of a detrimental effect of the temporal interfering + spatial neutral secondary task only (BF_{10}=68.85, Cohen's d=0.57); there was no evidence supporting a general detrimental effect of the spatial secondary task conditions (spatial facilitatory + temporal facilitatory: BF_{10}=0.41, Cohen's d=0.21; spatial interfering + temporal facilitatory: BF_{10}=0.50, Cohen's d=0.23). Also, the temporal facilitatory + spatial neutral condition remained associated with evidence for its absence (BF_{10}=0.19, Cohen's d=0.09).

--- Insert Figure 4 about here ---

The final analyses examined the task condition effects on the transposition gradients of serial order recall errors, by running the same 2 (Task condition: baseline vs. one of the secondary task conditions) × 12 (Displacement distance: -6, -5, -4, -3, -2, -1, 1, 2, 3, 4, 5, 6) Bayesian repeated-measures ANOVA as in Experiment 1. The analyses confirmed evidence for an

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effect of Displacement distance only, and evidence for the absence of a Task condition effect as well as of the Task condition by Displacement distance interaction.

Specifically, when comparing the baseline to the spatial facilitatory + temporal facilitatory task condition, the strongest model included only the Displacement distance factor (BF_{10}=6.92E+119, $\eta^2 p$ =0.71). This model was 19.49 times more likely than the following model including the interaction between Task condition and Displacement distance (BF_{10} = 0.05 <=> BF_{01} = 20, n^2_p=0.03) or the Task condition factor (BF_{10} = 0.15 <=> BF_{01} = 6.67, n^2_p=0.02). When comparing the baseline to the spatial interfering + temporal facilitatory task condition, the strongest model included only the Displacement distance factor (1.24E+111, n^2_p=0.69), this model being 914.28 times more likely than the following model including the interaction between Task condition and Displacement distance (BF_{10} = 0.00, n^2_p=0.01) or the Task condition factor (BF_{10} = 0.11 <=> BF_{01} = 9.09, n^2_p=5.30E-5). When comparing the baseline to the temporal facilitatory task + spatial neutral condition, the strongest model included only the Displacement distance factor (BF_{10}=3.24E+117, $\eta^2 p$ =0.71), this model being 1750.79 times more likely than the following model including the interaction between Task condition and Displacement distance (BF_{10} = 5.73E-4 <=> BF_{01} = 2000, n^2_p=0.01) or the Task condition factor (BF_{10} = 0.10 <=> BF_{01} = 10, n^2_p=3.27E-4). Finally, when comparing the baseline to the temporal interfering + spatial neutral task condition, the strongest model included only the Displacement distance factor (1.15E+119, n^2_p=0.70), this model being 2400 times more likely than the following model including the interaction between Task condition and Displacement distance (BF_{10} = 0.00, n^2_p=0.01) or the Task condition factor (BF_{10} = 0.11 <=> BF_{01} = 9.09, n^2_p=4.24E-31).

As shown in Figure 5, in all task conditions, adjacent serial position transpositions were the most frequent error type, in line with previous studies reporting transposition gradients in ISR tasks. The absence of a main effect of Task condition and of its interaction with Displacement

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distance indicates again that the precision of serial order coding was not impacted by any of the secondary tasks.

--- Insert Figure 5 about here ---

Interim discussion

The results of Experiment 2 confirmed those of the first experiment by highlighting a detrimental effect of the temporal interfering + spatial neutral condition on both strict serial order and item recall scores, but no direct impact on the precision of serial order coding as reflected by an analysis of transposition gradients. Critically, the overall detrimental impact of both facilitatory and interfering spatial + temporal interfering secondary task conditions observed in Experiment 1 was not observed anymore (spatial conditions coupled with temporal facilitatory condition), indicating that the irregular temporal presentation rate of the dots in the spatial secondary tasks was most likely at the origin of the detrimental effect in Experiment 1.

Discussion

This study confronted the temporal and spatial serial order coding hypotheses of information in verbal WM. We observed that the concurrent processing of an irregular temporal rhythm led to decreased verbal WM performance, but no effect was observed for concurrent processing of spatially disorganized information once temporal presentation parameters of the spatial information were held constant. The temporal interfering effect was general, impacting recall of both item and serial order information.

The present results provide support for the temporal serial order coding hypothesis, through the demonstration of a detrimental effect of the concurrent processing of an irregular temporal rhythm on verbal WM performance. Specifically, we observed not only a consistent detrimental effect from the interfering temporal condition but also from both interfering and

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facilitatory spatial tasks when the dots were also presented at an irregular temporal rhythm. These results are in line with a number of other studies demonstrating a deleterious effect of an irregular temporal rhythm during WM tasks (Fischer-Baum & Benjamin, 2014; Gorin et al., 2016; Henson et al., 2003). For example, Henson et al., (2003) observed a deleterious effect of a concurrent finger tapping task on verbal WM performance when the rhythm was different from the one guiding the presentation of the memory items. It should, however, be noted that some studies did not observe an effect of temporal information either when irregular rhythms were passively presented during the maintenance delay (Plancher et al., 2018) or when the memory items were themselves presented at an irregular rhythm (Gorin, 2020). At the same time, Gorin et al. (2016) observed a detrimental effect of an irregular rhythm when presented during the maintenance delay and when it had to be reproduced by the participant. This suggests that an important methodological factor determining whether a concurrent temporal signal will interfere with the one supporting the encoding of the memory list could be its depth of processing. A detrimental effect of an irregular temporal rhythm appears to occur when the rhythm must be processed in an explicit manner, such as through finger tapping, requiring participants to directly focus their attention on the characteristics of the rhythm, but not when it is only processed in a more passive (via mere listening) and incidental (via the timing of memory list presentation) manner.

At a more theoretical level, these data support the temporal coding account considering that each item should be associated with a specific temporal context signal whose state evolves over time, resulting in items from different serial positions being associated with different values of a temporal context signal analogous to the rotating hands on a clock face (Brown et al., 2000; Hartley et al., 2016). The model of Hartley et al. (2016) suggests that a population of oscillators driven in a bottom-up way can structure the serial order of an auditory WM list. These oscillators are considered to be time-based and are sensitive to

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numerous local variations such as the time of presentation, the ISI between items (i.e. grouping effect), or interference by a competing temporal signal. Our data, showing an impact from the processing of an irregular temporal signal on the encoding of verbal WM information, broadly support this type of time-based model. Our results are therefore more in line with computational models predicting positional-coding rather than associative inter-item coding. However, our results do not rule out hybrid models integrating inter-item and item-position coding of serial order, provided that item-position coding remains based on temporal contextual codes (Caplan, 2015; Osth & Dennis, 2015; Osth & Hurlstone, 2023).

Importantly however, our results show a general deleterious effect on verbal WM performance, not limited to serial order aspects of WM recall. By demonstrating a global impact on both item and order recall, our data may demonstrate an impact of temporal interference on the binding of both types of information, in line with recurrent network models of verbal WM assuming unified item-order representations (Botvinick & Plaut, 2006; see also Stroud et al., 2024; Wan et al., 2024; Xie et al., 2022). At the same time, our results of an impact of temporal irregularity on both item and serial order recall are not incompatible with time-based models of verbal WM. For example, the model by Burgess and Hitch (1999, 2006) assumes that the dynamic context signal layer that encodes serial order information is reset to its initial state during recall. Items are successively activated via the replay of the different context signal states and the associations that have been created between each state and the item layer. Therefore, if there is a disruption in the encoding of order, this should also have a direct impact on item recall because the link between the two will be weakened or become non-existent. Interestingly, this disruption does not seem to have an impact on the transposition gradients *per se*. On the one hand, we may predict that weakened associations between serial order and item representational levels will decrease the precision of serial order coding, leading to flattened transposition gradients. We did not find evidence for such a

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flattening. Alternatively, in line with the above-mentioned role of contextual cueing for initiating item recall, we could predict that the concurrent processing of an irregular temporal signal leads to a more all-or-none encoding and retrieval pattern of serial order information, leading to an increase of omission errors for those items with absent item-serial order signal bindings, but leaving the overall shape of the transposition gradient unchanged.

Finally, while we observed a temporal interfering effect for concurrent processing of an irregular rhythm, we did not observe a temporal facilitatory effect for concurrent processing of a regular rhythm, i.e., a rhythm that is identical to the one governing the presentation of memoranda. This finding contrasts with studies by Plancher et al. (2018) and Fanuel et al. (2018), which showed a facilitatory effect when a verbal WM task was coupled with a regular rhythm. We need to note here that in the latter studies, the regular rhythm involved the passive listening to an auditory sequence of tones, which was presented during the maintenance delay, after the encoding of the memory sequence. The authors made the assumption that the regular rhythm cued the participants to mentally refresh the memoranda during the maintenance stage, when no items are physically present. This design thus differs in several key points from the design of the present study, which focused on the processing of a competing temporal signal during the *encoding* of items in memory. Furthermore, even though a regular rhythm is often associated with better performance in different modalities, a recent study on the enhancement of temporal attention demonstrated that the impact of a temporal rhythm may be more effective for auditory temporal signals as compared to visual signals (Attout et al., 2024). Further studies focusing on the modality of presentation of a temporal sequence and the WM phase on which it is applied should be conducted.

While our data provide evidence for a role of temporal processing in the representation of item and serial order information in WM, they provided no evidence for a role of spatial processes. Once temporal parameters of the spatial processing task were held constant, we did

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not observe any detrimental or facilitatory impact of a concurrent spatial processing task on verbal WM performance. This was the case despite the spatial processing task having the same depth of processing than the temporal processing task, by requiring explicit reproduction of the sequences. Supported by a range of empirical data (e.g. Guida et al., 2020; Sahan et al., 2022; van Dijck et al., 2013), the mental whiteboard hypothesis considers that successive items in a memory list are associated with distinct locations of an internal left-to-right spatial reference frame (Abrahamse et al., 2017, 2014). Several studies showed that, when memoranda have to be reactivated during a maintenance delay, items from the beginning of the WM list are responded to faster with the left hand and items from the end of the list are responded to faster with the right hand, indicating left-right spatialization of verbal memory representations (e.g., Van Dijck & Fias, 2011). However, the way we manipulated spatial processing factors differed from previous studies in several aspects. First, we manipulated spatial processing during the encoding stage while the majority of previous studies have assessed signs of spatial coding during the maintenance stage of WM (e.g. Sahan et al., 2022; van Dijck et al., 2013b; van Dijck & Fias, 2011) or during the recall/recognition phase (Ftaïta et al., 2023; Guida et al., 2020, 2016). Only two studies have studied the impact of spatial processes on WM encoding. First, Fischer-Baum and Benjamin (2014) found more accurate WM performance when successive memoranda were presented on the screen with progressive spatial shifts from left to right, but the effect was only observed for specific serial positions (final position 5 and 6) and not the overall WM performance. Second, Guida et al. (2020) obtained no specific impact of mode of memory item presentation (simultaneous, from left to right or from right to left) on WM performance. Overall, while several signs of spatial processing can be observed during verbal WM task, studies so far do not provide overwhelming support for a direct interfering or facilitatory effect of spatial manipulations on WM encoding, in line with our own results. It may be that spatial recoding of temporally

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encoded memoranda occurs at a post-encoding stage, with temporal codes being remapped to spatial codes to provide additional representational support for the memoranda and their serial order. Finally, a recent study by van Dijck et al. (2022) showed that, while spatialization effects can be observed at the group level during a verbal WM task, only 20 percent of study participants would present a significant left-to-right spatialization effect. These data suggest that spatial coding of serial order information in verbal WM may reflect individual re-coding strategies rather than a universal and obligatory coding mechanism for serial order information.

Limitations

It could be argued that the temporal vs. spatial secondary tasks differed in the strength of their effect, given that the rhythm of the temporal stimuli were associated with the temporal succession of the memory items (a dot followed each memory item) while there was no physical spatial dimension that characterized the memory items (which were presented auditorily). This aspect could have increased the sensitivity of our WM task to the temporal vs. the spatial manipulation. It should, however, be noted here if the effect observed in this study was only due to this association between the temporal aspects of the memory items and the secondary task stimuli, that are perfectly synchronized, then we should have expected also the occurrence of a facilitation effect, the physical rhythm of the dot sequence reinforcing the rhythm of the memory sequence. This was not the case. Furthermore, even in the absence of a physical association of WM and secondary task spatial dimensions, if a spatial mental code is being used for encoding serial order information in WM, the processing of a spatial sequence that is in the opposite direction of this code should have exerted a negative effect on WM task performance. It should be noted that studies having directly manipulated spatial aspects of memory sequence presentation have not led to strong effects either. When comparing left-to-right vs. right-to-left presentation modes for visually presented verbal memory items, Fischer-

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Baum and Benjamin (2014) observed relatively limited spatial interference effects in direct forward recall conditions as used in the present experiment (stronger effects were observed when mixing forward and backward recall directions in addition to encoding direction manipulations). A recent study also suggests that the use of spatial codes in verbal WM may depend on interactions with spatial WM, and therefore may not necessarily reflect a default mechanism used for coding serial order information (Tian & Fischer-Baum, 2025). Also in line with a more indirect and context-dependent nature of spatial influences on serial order coding in verbal WM are studies that have shown that spatialization effects in verbal WM such as the SPoARC effect only appear for short WM lists (up to 4 or 5 items), the effects tending to disappear for longer lists as used in the study here (Ftaïta et al., 2023; Huber et al., 2016). A further limitation of our design is that it does not allow for the crossing of the two spatial conditions and the two temporal conditions in a 2*2 design. Indeed, although this does not cast doubt on our conclusions, based on direct comparisons between each condition and the baseline, our design does not allow us to directly examine the interactions between spatial and temporal facilitation/interference. However, it is important to note that two experiments were carried out in order to control for these possible interactions.

Conclusions

In sum, this study provides evidence for a role of temporal processes in the encoding of memoranda in verbal WM, in line with several models of memory for serial order. Future studies will need to examine the exact role of these processes, and the mechanisms that explain the impact of temporal processes on the encoding not only of serial order information, but also of the items themselves.

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Author contribution

XXX

Statements and declarations

There is no conflict of interest in connection with this work.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest in connection with this work.

Ethics approval

The study was approved by the ethics committee of the XXX

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Consent for publication

All the authors have approved the last version of the manuscript.

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Data Accessibility Statement

The data and materials from the present experiment are publicly available at the Open Science Framework website: https://osf.io/3xz54.

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Figure Captions

Figure 1. Illustration of the different task conditions. The participants had to memorize and recall an auditory sequence of 7 letter names after a one-second post-encoding delay. In a reference condition, participants encoded the letter list without conducting a secondary task (ISR baseline). For the other conditions, the participants had to detect dots presented while encoding the letter name sequence, the dots varying in terms of the regularity of their temporal or spatial arrangement.

Figure 2. Item and serial order recall accuracy as a function of task condition in Experiment 1. Mean and SE are depicted.

Figure 3. Transposition gradients for serial order recall errors as a function of task condition in Experiment 1. Mean and SE are depicted.

Figure 4. Order and item WM performance as a function of task condition in Experiment 2. Mean and SE are depicted.

Figure 5. Transposition gradients for serial order recall errors as a function of task condition in Experiment 2. Mean and SE are depicted.

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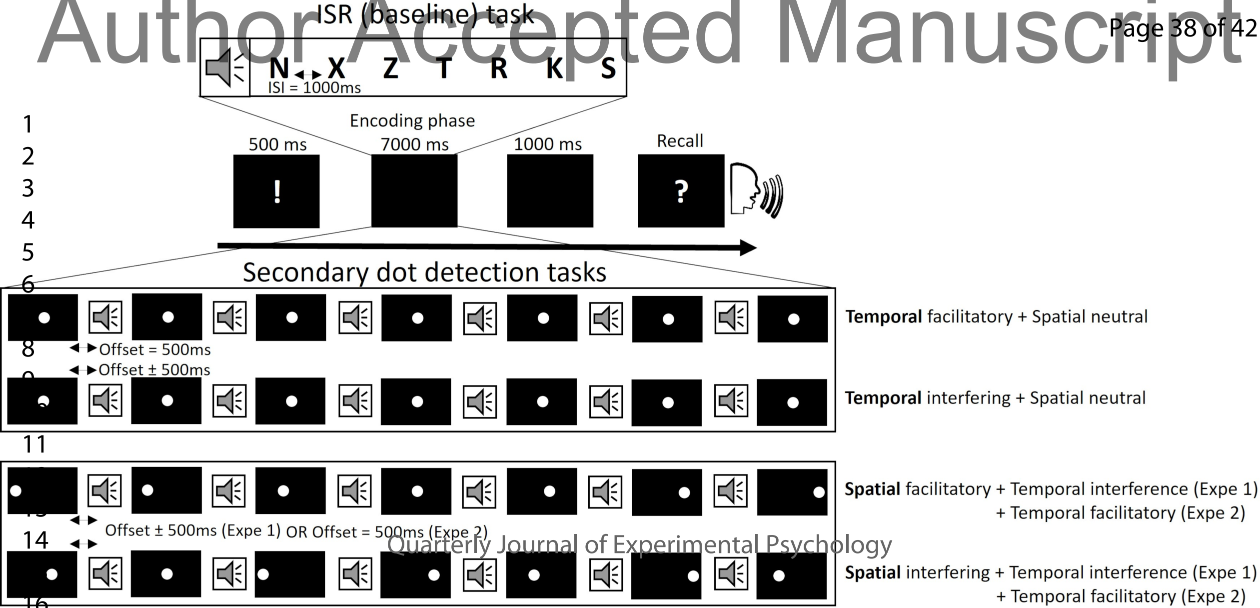

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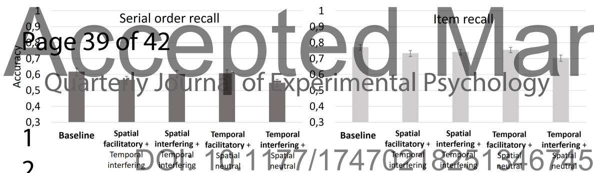

1

2

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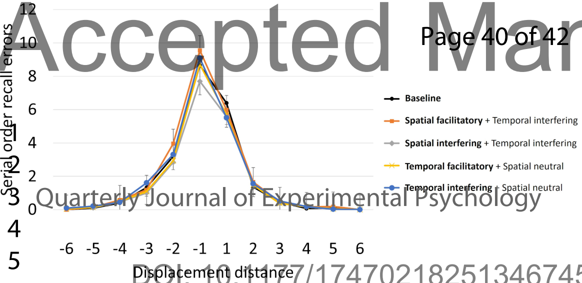
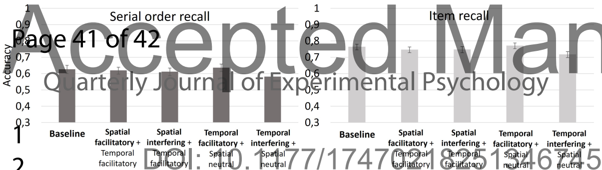


Serial order recall errors
12
10
8
6
4
2
0
-6
-5
-4
-3
-2
-1
1
2
3
4
5
6
Displacement distance
Baseline
Spatial facilitatory + Temporal interfering
Spatial interfering + Temporal interfering
Temporal facilitatory + Spatial neutral
Temporal interfering + Spatial neutral



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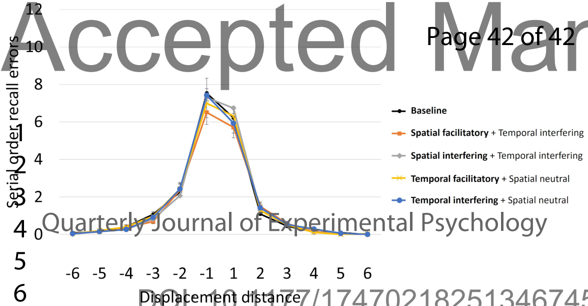

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