Between-item Similarity Frees Up Working Memory Resources Through Compression: A Domain-General Property

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Author Note

Some of the ideas and data presented in this article have been presented elsewhere. The general idea of a domain-general compression mechanism to deal with item similarity was suggested at the Virtual Working Memory Symposium (VWMS, 2021) with a particular focus on the visual domain. The results of Experiment 1 replicate those published in the Journal of Memory & Language (2021) which were orally presented at the conferences EWOMS 2020, PIF 2020 and CogSci 2021. Results of Experiment 2, 3 and 4 were not presented anywhere else.

Abstract

Compression, the ability to recode information in a denser format, is a core property of working memory (WM). Previous studies have shown that the ability to compress information largely benefits WM performance. Importantly, recent evidence also suggests compression as freeing up WM resources, thus enhancing recall performance for other, less compressible information. Contrary to the traditional view positing that between-item similarity decreases WM performance, this study shows that between-item similarity can be used to free up WM resources through compression. Across a series of four experiments, we show that between-item similarity not only enhances recall performance for similar items themselves, but also for other, less compressible items within the same list, and this in the semantic (Experiment 1), phonological (Experiment 2), visuospatial (Experiment 3), and visual (Experiment 4) domains. Across these different domains, a consistent pattern of results emerged: between-item similarity proactively – but did not retroactively – enhanced WM performance for other items, and this as compared to a condition in which between-item similarity at the whole-list level was minimized. We propose that between-item similarity in any domain may impact WM using the same underlying machinery: via a compression mechanism, which allows an efficient reallocation of WM resources.

Keywords: Working Memory, Similarity, Compression, Attentional Resources

Introduction

The retention of information over the short-term is severely limited. Since the seminal work by Miller (1956) estimating working memory (WM) capacity equaling about 7 items, several studies suggest this capacity as being even more limited. When measured in procedures preventing strategies such as list segmentation and inter-item grouping strategies (Bunting et al., 2006; Cowan et al., 2005; Pollack et al., 1959), WM capacity appears instead to be limited to 3-4 elementary units. If the number of units we can maintain is so limited, how come that we nonetheless process information with relatively good efficiency in our daily lives? One response to this question is lying at the heart of the concept of compression. In daily life situations, elements are usually not processed in isolation, but as a whole. As such, pre-existing long-term memory associations are likely to play a critical role. Think about an everyday conversation. If each phoneme that composes the words we hear were processed as an individual unit, WM capacity would be overloaded extremely quickly, and humans would not be able to communicate through language at all. Instead, the human cognitive system can deal with complex information. Compression is of critical importance, because it frees up resources, which in turn allows the maintenance and processing of a larger quantity of information (Z. Chen & Cowan, 2005; Mathy & Feldman, 2012; Norris et al., 2020; Portrat et al., 2016; Thalmann et al., 2019). Among various forms of compression, this study investigates compression triggered by between-item similarity. Importantly, we tested the domain-generality of this principle using a convergent set of behavioral experiments tapping different domains.

A large body of evidence from laboratory experiments showed that information compression benefits WM capacity. In the verbal domain, words are better recalled as compared to nonwords (Brener, 1940; Guérard & Saint-Aubin, 2012; Kowialiewski & Majerus, 2018).

Likewise, acronyms (e.g., "FBI", "PDF", "CIA", etc.) and familiar sequences of digits ("2345") are better recalled than unfamiliar sequences, and this effect has been observed across a wide variety of WM tasks (Z. Chen & Cowan, 2005; Cowan et al., 2004; Mathy & Feldman, 2012; Norris et al., 2020; Portrat et al., 2016; Thalmann et al., 2019). Chunking effects have also been observed in the visual domain, for instance via the induction of cross-trial statistical regularities or by comparing populations with different expertise (Brady et al., 2009; Chase & Simon, 1973; Gobet et al., 2001; Huang & Awh, 2018; Oberauer et al., 2017).

Recently, an important characteristic of compression has been highlighted through a converging set of studies (Norris et al., 2020; Portrat et al., 2016; Thalmann et al., 2019). In these studies, participants were invited to encode and serially recall verbal sequences in which chunkable and unchunkable items were mixed-up (e.g., PDFVDHT). These were compared to control sequences composed of random letters (e.g., LKMVDHT). These studies converged toward the outcome that when chunks are included in to-be-remembered sequences, these chunks proactively enhance recall performance for the subsequent, non-chunked items of the list, and this compared to equivalent items not preceded by a chunk. When the chunks are presented at the end of the to-be-remembered sequences however, no retroactive impact on WM recall performance is observed. This suggests that the presence of chunks frees up WM resources, which in turn benefits subsequent non-chunked information.

The studies we described so far assessed the impact of compression by manipulating chunks that pre-exist in long-term memory (e.g., the acronym "PDF"), or by inducing chunking beforehand through a learning phase (e.g., learning the arbitrary association "fork – wall"). Recently, it has been claimed that between-item similarity may also be used to compress WM information online. In one study, Chekaf et al. (2016) manipulated the presence of between-item similarity in visual WM across different dimensions (i.e., size, color, shape), and showed that this manipulation enhanced WM performance. The authors interpreted these results as supporting a compression mechanism, through which participants can detect the redundancies within the flow of information. This compression, in turn, is supposed to increase the amount of information that can be stored and/or maintained in WM. Importantly, this compression yielded by between-item similarity might be a domain-general property of WM, as we will see.

Between-item similarity supports the temporary maintenance of item information

The fact that between-item similarity enhances recall performance in WM thanks to compression, as postulated by Chekaf et al. (2016), may appear surprising. This is because the temporary maintenance of information is typically considered to be negatively affected by similarity. This largely spread idea has been fed by the well-known decrease of recall performance for similar sounding against dissimilar sounding items (Baddeley, 1966; Farrell & Lewandowsky, 2003). This so-called phonological similarity effect has been a hallmark for the development of Baddeley's phonological loop model, as well as subsequent models including this phonological loop component (Baddeley & Logie, 1999; Camos & Barrouillet, 2014; Morra, 2015; Schweickert, 1993).

At the same time, an accumulating set of evidence shows that between-item similarity may nonetheless support the temporary maintenance of information in WM. *In the verbal domain*, it is true that phonological similarity decreases the ability to recall serial order information (i.e., the sequential order in which the items are presented). At the same time, phonologically similar words, such as rhyming words, enhance recall performance at the item level (i.e., the orthographic, phonological and lexico-semantic characteristics of the memoranda), when compared to phonologically dissimilar words (Fallon et al., 2005; Gupta et al., 2005; Neale

& Tehan, 2007). In other words, phonological similarity decreases the ability to discriminate items at the serial order level, but nonetheless increases the number of to-be-remembered items that one can recall. A similar phenomenon is observed at the semantic level. Between-item similarity, as characterized by semantic relatedness, leads to increased recall performance. This is usually shown by a recall advantage for words related at the semantic level (e.g., Mars – Pluto – Mercury) as compared to semantically unrelated words (e.g., dog – table – sky) (Poirier & Saint-Aubin, 1995; Saint-Aubin & Poirier, 1999; Tse, 2009; Tse et al., 2011). The impact of semantic similarity on memory for order appears however to be rather inconsistent (Baddeley, 1966; Neale & Tehan, 2007; Saint-Aubin & Ouellette, 2005; Saint-Aubin & Poirier, 1999; Tse et al., 2011).

In the visual domain, studies conducted so far converge toward a facilitative effect of between-item similarity on WM performance. Increased performance has been observed following the manipulation of color similarity, both in simultaneous and sequential presentations (Lin & Luck, 2009; Quinlan & Cohen, 2012; Sanocki & Sulman, 2011). This advantage for similar colors is all the more present that the similar colors are spatially close to each other during encoding (Peterson & Berryhill, 2013). Similar items appear furthermore to be represented with higher quality and precision than dissimilar items (Brady & Alvarez, 2015; Son et al., 2020). Critically, this effect has been extended toward other visual features and/or dimensions, such as shape, size (Chekaf et al., 2016), orientation (Son et al., 2020) and even faces (Jiang et al., 2016). This result is furthermore robust to changes in the experimental setup, as it expands to complex-span tasks involving the processing of distractors during the between-item retention interval (Mathy et al., 2018).

Between-item similarity also impacts the recall of *visuospatial information*. Studies assessing visuospatial WM used paradigms involving the encoding and order reconstruction of stimuli presented sequentially at different spatial locations. Similarity in the visuospatial dimension can be operationalized by the Euclidean distance between two successive presentations of memoranda. Studies conducted so far suggest that path length, the sum of the distance between memoranda, affects WM performance, with stimuli presented at similar (i.e., close) spatial locations leading to higher WM performance (De Lillo, 2004; Parmentier et al., 2005). Path length appears to be a critical characteristic in visuospatial WM, as spatial grouping manipulations are ineffective when controlling for it (Parmentier et al., 2006). This means that path length is at least partially independent from grouping manipulations which are known to affect WM, both in the verbal and visuospatial domains (Henson, 1999; Hurlstone, 2019; Hurlstone & Hitch, 2015).

Similarity frees up WM resources through compression

According to the account developed by Chekaf et al. (2016), this between-item similarity support may at least partially be accounted for by a compression mechanism. Between-item similarity may allow participants to rapidly identify the presence of redundant features and then recode the information in a more compact format. For instance, given the sequence “ghost – coast – most”, participants could extract the redundant phonological information /oʊst/ and use that information to maintain more efficiently the whole sequence. Likewise, when presented with the sequence “apple – pear – plum”, one efficient strategy could be to maintain the concept “fruit”. The same logic applies to the visual and visuospatial domains. When presented with three different shades of green, or three adjacent squares aligned, participants could use the Gestalt principles of the visual system to extract the relevant information and compress it

(Magen & Berger-Mandelbaum, 2018; Magen & Emmanouil, 2018; Peterson & Berryhill, 2013). If between-item similarity can be used to compress information, then increasing between-item similarity would logically result in a free up of WM resources[1]. What is the evidence supporting this account so far?

In the visual domain, between-item similarity has shown to enhance WM performance for non-similar items, compared to sequences composed of completely dissimilar items. Morey et al. (2015) showed that when items share the same colors in a to-be-remembered array, there is a general boost on WM performance for the similar items themselves. Critically, WM performance also benefits the dissimilar items. Although the boost was relatively subtle on dissimilar items, the effect is genuine and robust as it was subsequently replicated (C. C. Morey, 2018). Convergent results have been observed more recently. Ramzaoui and Mathy (2021) modulated the presence of between-item redundancies in to-be-remembered visual arrays across different set sizes. They showed that WM performance was well-predicted by an algorithmic complexity metric measuring sequence compressibility. Importantly, a high amount of compressibility not only improved recall performance for the similar items themselves, but also for the non-similar items. In the verbal domain, similar results have been observed when manipulating semantic relatedness (Kowialiewski, Lemaire, et al., 2021). Specifically, semantic relatedness was manipulated by including semantic triplets (e.g., leaf – tree – branch) among semantically unrelated items (e.g., wall – sky – dog) in lists to be remembered. The results of this experiment overall replicated those observed in chunking experiments: the semantic triplets proactively, but

[1] Note that compression may also lead to a loss of information. This aspect will be discussed further on.

did not retroactively, enhanced recall performance for the unrelated items, and this when compared to a condition in which all the items were semantically unrelated.

These pieces of evidence appear to support the idea that between-item similarity, both in the semantic and visual domains, may be used to recode the information into a compressed format, thereby allowing WM resources to be freed up. Evidence supporting this latter account remains however scarce. Critically, the domain-generality of this property of between-item similarity remains to be formally established. If between-item similarity allows participants to compress information, we expect to observe an overall boost on WM performance. If this compressed information leads to a free up of WM resources, we furthermore expect that between-item similarity would critically enhance recall performance for other, dissimilar items embedded in the same to-be-remembered lists. We expect to observe these effects regardless of the domain through which between-item similarity is being manipulated, in agreement with models postulating the existence of a central attentional resource for WM maintenance (Barrouillet et al., 2004, 2011; Cowan, 1999; Nee & Jonides, 2013; Oberauer, 2002).

In addition to the beneficial free up of WM resources, we also explored a potential deleterious impact of compression. Previous studies in the visual domain have shown that compression, although enhancing WM precision, can also lead to drawbacks (Haladjian & Mathy, 2015; Nassar et al., 2018). For instance, it has been shown that compression may lead to an oversimplification of information, thereby increasing the proportion of false recognition for more compressible sequences (Lazartigues et al., 2021). Similarly, participant's responses in visual array tasks appear to be biased toward the mean of the ensemble representation (Brady & Alvarez, 2011; Son et al., 2020), suggesting that some of the original representation is potentially lost during the compression process. The same phenomenon may explain why phonologically similar items are more poorly recalled at the serial order level than phonologically dissimilar items. In this study, we took advantage of our manipulations to assess the possibility that compression may lead to a loss of information at the serial order level. If compression is necessarily associated with a cost at the serial order level, we predict that similar sequences should be more poorly recalled at the serial order level than dissimilar sequences.

Across four experiments, we manipulated the presence of between-item similarity in to-be-remembered lists, such that similar and dissimilar items were mixed up. These sequences were then compared to sequences composed of dissimilar items. Immediately after the presentation of the memoranda, participants were invited to recall the list serially. Experiment 1 is an exact replication of the study conducted by Kowialiewski et al. (2021) involving the manipulation of semantic relatedness (e.g., leaf – tree – branch). Experiment 2 manipulated phonological similarity (e.g., ghost – most – coast). Experiments 3 and 4 involved the manipulation of visuospatial and visual similarity, respectively.

Experiment 1

In this first experiment, we manipulated between-item similarity through semantic relatedness. The critical experimental manipulation involved the presence of semantically related triplets (e.g., leaf – tree – branch), among semantically unrelated triplets (e.g., wall – sky – dog). In one condition, the triplet was presented at the beginning of the to-be-remembered list (e.g., leaf – tree – branch – wall – sky – dog). In another condition, the triplet was presented at the end of the to-be-remembered list (e.g., wall – sky – dog – leaf – tree – branch). These conditions were compared against a condition in which all the items were semantically unrelated (e.g., wall – sky – dog – arm – house – jacket). In a previous study of our own (Kowialiewski, Lemaire, et al., 2021), we observed that the semantically related triplets proactively enhanced recall performance for the other semantically unrelated items, without any retroactive impact. In this experiment, we assessed the robustness of this result and performed an exact replication.

Method

All the data and codes have been made available on the Open Science Framework: https://osf.io/y9xz2/. This study was not preregistered.

Participants. Thirty undergraduate students aged between 18 and 30 were recruited from the university community of the Université Grenoble Alpes. All participants were French native speakers, reported no history of neurological disorder or learning difficulty, and gave their written informed consent before starting the experiment. The experiment had been approved by the ethic committee of CER Grenoble Alpes: Avis-2019-04-09-2.

Material. We used a pool of stimuli composed of 120 French words. The words have a log-frequency value of M = 2.899 (SD = 1.689) counts per million and words were 1 to 3 syllables long (M = 1.483, SD = 0.594), composed of 2 to 7 phonemes (M = 4.058, SD = 1.11). The stimuli were created by selecting 40 different semantic categories composed of triplets a priori considered to be semantically related. The nature of the semantic relationships that composed the triplets was categorical (e.g., dog – wolf – fox) and/or thematic (e.g., sky – cloud – rain).

The stimuli that compose of the pool were used to create the three different experimental conditions:

- In the T1 condition (Triplet in first half), the first half of the items were semantically related, and the second half were semantically unrelated.
- In the T2 condition (Triplet in second half), the first half of the items were semantically unrelated, and the second half were semantically related.

- In the NT condition (No Triplet), all the items were semantically unrelated.

Each experimental condition comprised 20 trials. To create the sequences and triplets composed of semantically unrelated items, we mixed-up the items from different semantic categories. This way of manipulating semantic relatedness ensures that all the stimuli were perfectly matched on psycholinguistic variables known to impact WM recall performance, such as phonotactic frequency, lexical frequency, neighborhood density, imageability, number of phonemes and syllabic length (Guitard et al., 2018; Neath & Surprenant, 2019). Note that this way of manipulating the semantic relatedness effect implies that each word appeared three times throughout the entire experiment: once in a similar triplet, and twice in a dissimilar triplet. We further avoided that a given item is presented in the same serial position twice. This could not be completely avoided but was nevertheless minimized by considering all possible within-list permutations. Finally, a given experimental condition could not be repeated on more than three consecutive trials.

Thirty-six different versions of the lists to be remembered were generated, by first creating three different versions of the 20 lists that compose each experimental condition. These different versions were then combined using a pairwise procedure to create 9 different versions of the lists. These 9 different versions were then used again, but this time by exchanging the positions of the triplets within each list (i.e., the T1 condition became the T2 condition; [1:3, 4:6] => [4:6, 1:3]), resulting in 18 different versions. This latter manipulation ensured that any potential difference between the T1 and T2 conditions could not be imputed to the specific characteristics of the stimuli themselves, but rather by the serial position at which the triplets themselves were presented. In a final manipulation, these versions were duplicated, and the items within each triplet were randomly re-ordered. In the NT condition, the items were re-ordered randomly across the whole sequence.

The a priori defined between-item semantic relatedness was initially quantified in Kowialiewski et al. (2021), by collecting data on an independent group of 80 participants, through an online survey. To sum up the overall procedure, the participants were presented with pairs of words drawn from the experimental lists. They were invited to judge to what extent the two words that compose a pair are semantically related, on a scale ranging from 0 (completely unrelated) to 5 (completely related). A Bayesian independent samples T-Test (see statistical analysis below) confirmed that the a priori defined related and unrelated pairs did differ in term of semantic relatedness judgment, this difference being associated with decisive evidence (M = 4.463, SD = 0.5, and M = 0.427, SD = 0.601, for related and unrelated pairs, respectively, BF_{10} = 9.809e+387).

Next, between-item similarity at the phonological level was quantified using the Levenshtein distance. This was applied separately on the semantically related triplets on the one side, and the semantically unrelated triplets and sequences on the other side. Final analysis showed that both types of sequences had similar phonological similarity values (M = 4.25 and M = 4.881 for the semantically related and unrelated sequences, respectively), and an absence of difference was supported by strong evidence, as indicated by a Bayesian independent samples T-Test (BF_{01} = 7.133).

Procedure. Each trial began with a countdown starting from 3, written in white and presented on a black background. The countdown was followed by a black screen and the presentation of a 6-item list, aurally presented at a pace of 1 item every 2 seconds. After the presentation of the to-be-remembered list, the participants were presented with a question mark at the center of the screen, prompting them to recall the sequence out loud in the order in which the items were presented. The participants were invited to substitute any item they could not remember with the word “blanc” (i.e., “blank” in French). After recalling the sequence, the participants were invited to press the spacebar of the keyboard to initiate the next trial.

Before the beginning of the experiment, the experimenter performed one practice trial to demonstrate the exact procedure to follow. The participants were then invited to perform 3 practice trials to familiarize with the task. The stimuli presented in the practice trials were not used in the main experiment. The experimenter was present throughout the experiment and ensured that the participant complied with the task requirements. Task presentation and timing were controlled using OpenSesame (Mathôt et al., 2012) run on a desktop computer. The auditory stimuli were presented via headphones connected to the computer, in a soundproof booth at comfortable listening level. Participants’ responses were transcribed online by a research assistant blind to the main theoretical hypothesis, onto an electronic spreadsheet, and were also recorded using a digital recorder.

Scoring procedure. To determine the impact of the different semantic conditions (T1, T2, NT) on WM processing, recall performance was first assessed using a *strict serial recall criterion*. By this criterion, an item was considered to be correctly recalled only if it was recalled at the correct serial position. For instance, given the target sequence “Item1 – Item2 – Item3 – Item4 – Item5 – Item6” and the recall output “Item1 – Item2 – blank – Item3 – blank – Item5”, only “Item1” and “Item2” would be considered as correct.

The strict serial recall criterion provides only a gross picture of recall performance, as it confounds the ability to recall item and serial order information. In addition to this first criterion, we used an *item recall criterion,* in which an item was considered as correct, even if recalled at a wrong serial position. For the previous example, “Item1”, “Item2”, “Item3” and “Item5” would be considered as correct. This criterion is generally considered to measure the ability to recall item information in the most straightforward way possible, without any contamination from serial order.

We also computed an *order recall* score. This is computed as the number of items recalled at a correct position out of the number of items recalled regardless of their position. This proportion was computed by first coding all items not recalled at all as missing values, and then averaging for each participant the number of items correctly recalled in correct order at each serial position. Keeping our initial example, the sequence would be scored as follows: [1, 1, 0, N/A, 0, N/A]. This criterion allowed us to explore the impact of between-item similarity on order memory across serial position.

Statistical analysis. We performed a Bayesian analysis, as this reduces Type-1 error probabilities relative to frequentist statistics (Schönbrodt et al., 2017). The Bayesian approach has the further advantage of computing continuous values against or in favor of a given model, rather than deciding for the presence of an effect based on an arbitrary statistical threshold. Evidence in favor of a model is given by the Bayesian Factor (BF). This reflects the likelihood ratio of a given model relative to other models, including the null model. The null model and the effect of interest can be tested simultaneously, by directly comparing the alternative hypothesis against the null hypothesis, and vice versa. The BF_{10} is used to determine the likelihood ratio for the alternative model (H_1) relative to the null model (H_0), and the BF_{01} to determine the likelihood ratio for H_0 relative to H_1. We use the classification of strength of evidence proposed in previous studies (Jeffreys, 1998): a BF of 1 provides no evidence, $1 < BF < 3$ provides anecdotal evidence, $3 < BF < 10$ provides moderate evidence, $10 < BF < 30$ provides strong evidence, 30 < BF < 100 provides very strong evidence and 100 < BF provides extreme/decisive evidence. In Bayesian ANOVAs, we performed Bayesian model comparisons using a top-down testing procedure, which first computes the BF value for the most complex model possible (i.e., the model including all main effects and all possible interactions). The BF value for each term is then assessed by directly comparing the full model against the same model, but by dropping the term under investigation. To minimize error of model estimation, the number of Monte Carlo simulations generated was set to $N_{iterations} = 100{,}000$. For some critical contrasts of interest, we also report the 95% Bayesian Credible Intervals using the highest density intervals of the sampled posterior distribution of the model under investigation ($N_{iterations} = 100{,}000$). All analyses were performed using the BayesFactor package implemented in R using the default medium Cauchy prior distribution with $r = \frac{\sqrt{2}}{2}$.

On each graph we report the 95% Confidence Intervals for each mean. We follow the recommendations made by Baguley (2012). After correcting the data for between-subject variability (R. D. Morey, 2008), the confidence intervals of each mean j were computed using the following formula:

$$(1)\ \mu^{\wedge}{}_{j} \pm t_{n-1,1-\frac{a}{2}}\sqrt{\frac{2J}{4(J-1)}}\,\sigma^{\wedge\prime}{}_{\mu^{\wedge}{}_{j}}$$

where $\mu^{\wedge}{}_{j}$ is the j^{th} mean, $t_{n-1,1-\frac{a}{2}}$ is the two-tailed critical t value with $n-1$ degrees of freedom, J is the number of means included in the graph, and $\sigma^{\wedge\prime}{}_{\mu^{\wedge}{}_{j}}$ is the standard error of the j^{th} mean.

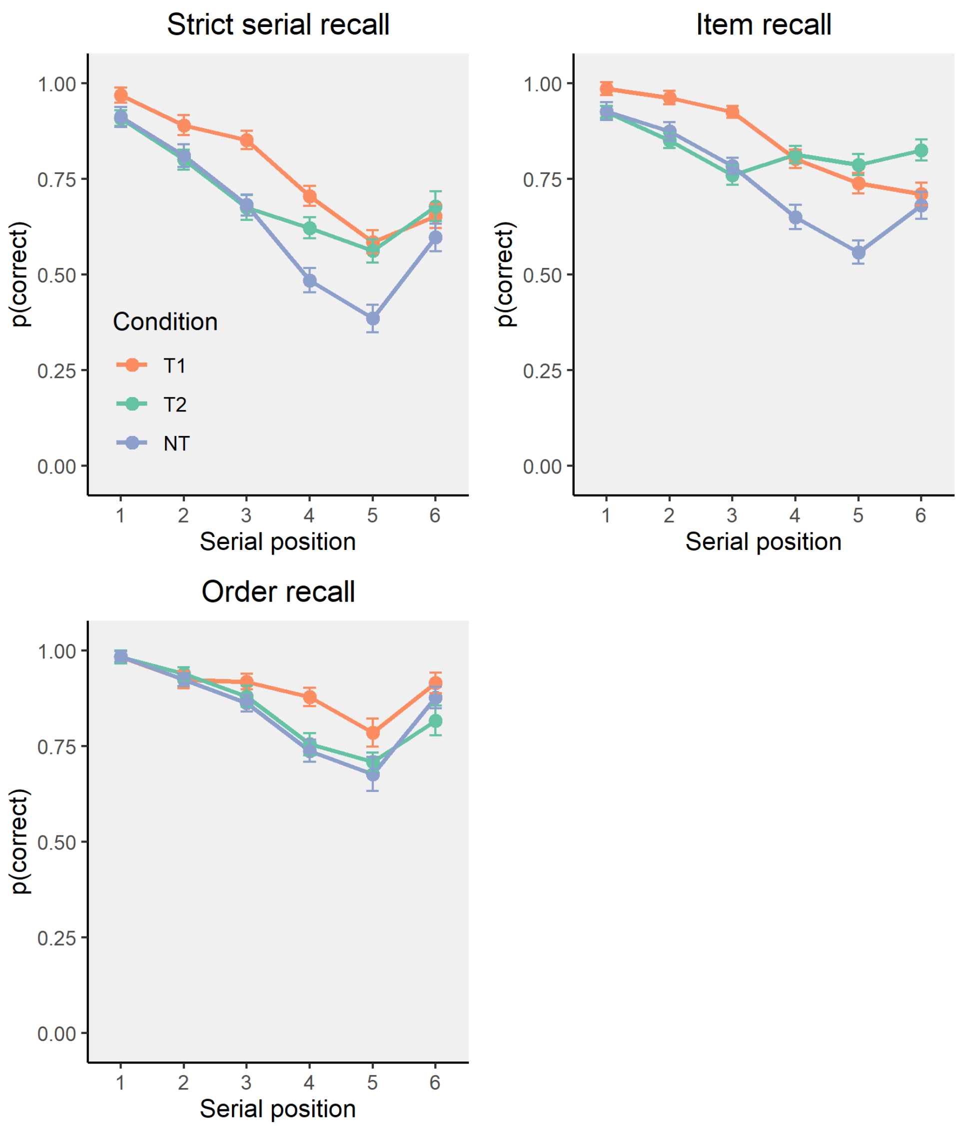
Results

First, recall performance was assessed as a function of semantic condition (T1, T2 and NT) and serial position (1 through 6) using a Bayesian Repeated Measures ANOVA. Using the strict serial recall criterion, we found decisive evidence supporting the main effect of semantic condition (BF_{10} = 3.698e+21), serial position (BF_{10} = 3.027e+103), and the interaction term (BF_{10} = 2.205e+7). The same results were observed using the item recall criterion, with both main effects of semantic condition (BF_{10} = 2.753e+22) and serial position (BF_{10} = 1.015e+67) being supported by decisive evidence. The interaction term was also supported by decisive evidence (BF_{10} = 2.176e+20). Under the order recall criterion, we found decisive evidence supporting both main effects of semantic condition (BF_{10} = 4.919e+5) and serial position (BF_{10} = 1.509e+58), and the interaction term (BF_{10} = 188.872).

As can be seen in **Figure 1**, semantic relatedness had a robust impact on recall performance. The presence of the interaction suggests that the semantic condition did not impact serial position in an equivalent manner across serial position. This interaction was explored using specific Bayesian T-Tests. To reduce the number of statistical contrasts and increase the statistical power of our analyses, we averaged recall performance across the first (i.e., positions 1 through 3) and second (i.e., positions 4 through 6) halves of the lists.

Figure 1

Results of Experiment 1 – Semantic Relatedness Manipulation



Note. Recall performance as a function of serial position for each semantic condition (Experiment 1). T1 = Triplet in the first half of the list. T2 = Triplet in the second half of the list. NT = No triplet. Error bars represent confidence intervals corrected for between-subject variability (see statistical procedure).

Semantic relatedness effect. We first assessed the specific impact of the semantic relatedness dimension on recall performance. Recall performance over the first half of the list was higher in the T1 condition as compared to the NT condition, and this difference was supported by decisive evidence, both using the strict serial recall criterion (BF_{10} = 1378.12, $CI_{95\%}$ = [0.585; 1.506], d = 1.109, M_{diff} = 0.102) and the item recall criterion (BF_{10} = 4.765e+4, $CI_{95\%}$ = [0.663; 1.609], d = 1.199, M_{diff} = 0.096). In contrast, semantic relatedness did not credibly impact memory for order information for the related items themselves (BF_{10} = 0.849, $CI_{95\%}$ = [-0.054; 0.657], d = 0.334, M_{diff} = 0.018). Likewise, recall performance over the second half of the list was also higher in the T2 as compared to the NT condition. This difference was supported by decisive evidence across the strict serial recall criterion (BF_{10} = 2.648e+4, $CI_{95\%}$ = [0.632; 1.557], d = 1.156, M_{diff} = 0.132), the item recall criterion (BF_{10} = 2.522e+7, $CI_{95\%}$ = [1.05; 2.174], d = 1.678, M_{diff} = 0.179). The order recall criterion was associated with moderate evidence supporting an absence of difference (BF_{01} = 4.997, $CI_{95\%}$ = [-0.388; 0.292], d = -0.046, M_{diff} = -0.004). The results of this analysis are straightforward: semantic relatedness enhances recall performance for the items within the semantic triplet, and this across the strict serial recall and the item recall criteria. However, semantic relatedness did not credibly impact memory for order.

Proactive benefit of the semantic triplets. When the items over the first halves of the lists were semantically related, recall performance over the items in the second halves of the lists enhanced, and this as compared to the same items that were not preceded by semantically related items (see **Figure 1**, positions 4 through 6, T1 vs. NT). This recall advantage was supported by decisive evidence, both using the strict serial recall criterion (BF_{10} = 4.87e+6, $CI_{95\%}$ = [0.946; 2.022], d = 1.547, M_{diff} = 0.158), the item recall criterion (BF_{10} = 1.053e+6, $CI_{95\%}$ = [0.846; 1.875], d = 1.429, M_{diff} = 0.121), as well as the order recall criterion (BF_{10} = 150.826, $CI_{95\%}$ = [0.314; 1.132], d = 0.783, M_{diff} = 0.095). Therefore, the presence of semantic relatedness proactively enhanced recall performance.

Retroactive effect of the semantic triplets. When the items over the second halves of the lists were semantically related, recall performance over the items in the first halves of the lists did not enhance, and this as compared to the same items that were not followed by semantically related items (see **Figure 1**, positions 1 through 3, T2 vs. NT). This absence of retroactive impact was supported by moderate evidence, both using the strict serial recall criterion (BF_{01} = 4.809, $CI_{95\%}$ = [-0.4; 0.28], d = -0.07, M_{diff} = -0.007), the item recall criterion (BF_{01} = 3.259, $CI_{95\%}$ = [-0.502; 0.185], d = -0.183, M_{diff} = -0.016) and the order recall criterion (BF_{01} = 3.621, $CI_{95\%}$ = [-0.194; 0.486], d = 0.16, M_{diff} = 0.011). Contrary to the previous analysis investigating a proactive effect, the presence of semantic relatedness *did not* retroactively impact recall performance.

Discussion

In this experiment, we showed that semantic relatedness enhanced recall performance for the semantically related items themselves, as classically observed (Poirier & Saint-Aubin, 1995). Furthermore, semantic relatedness did not credibly impact memory for order information. Critically, the presence of semantic relatedness also proactively enhanced recall performance for the other semantically unrelated items within the same lists, and this as compared to the same items not preceded by a semantic triplet. In contrast, the semantic triplets did not have any retroactive impact. These results replicate those we already observed in a previous study on an independent group of participants (Kowialiewski, Lemaire, et al., 2021), showing that this ability of semantic relatedness to free up WM resources is robust.

This result is consistent with the idea that between-item similarity allows compression of information in WM (Chekaf et al., 2016; Mathy et al., 2018). Accordingly, if the redundant information that composes the semantically related items allows participants to recode information in a denser format (e.g., maintaining for example “planet” when presented with

"Saturn – Mercury – Pluto"), this naturally frees up WM resources that can then be reallocated to encode and maintain a higher amount of information, as observed with chunks as memoranda (Norris et al., 2020; Portrat et al., 2016; Thalmann et al., 2019).

The results of Experiment 1 were observed using verbal items as memoranda. However, verbal items are not solely characterized by their semantic representations. Instead, the content of verbal WM is known to be affected by phonological factors (Baddeley et al., 1975), suggesting that WM is strongly represented at the phonological level. Therefore, it remains to be shown whether the results we observed so far extend towards the manipulation of between-item similarity in the phonological domain. This is what we investigated in the next experiment.

Experiment 2

In this second experiment, we manipulated phonological similarity using an open pool composed of 120 words. As in Experiment 1, the presence of phonological similarity was manipulated using triplets composed of phonologically similar items (e.g., ghost – most – coast). These triplets were presented either in the first (e.g., ghost – most – coast – wall – sky – dog) or the second halves of the to-be-remembered lists (e.g., wall – sky – dog – ghost – most – coast). Recall performance for these sequences was compared to sequences in which all the items were phonologically dissimilar (e.g., wall – sky – dog – arm – road – jacket).

The use of an open set of stimuli is an important feature of the experiment. It allows us to track and quantify the specific impact of the phonological similarity dimension, and this separately on the ability to recall item and serial order information. Closed sets, such as letters, minimize the production of omission errors while stressing serial order maintenance. More generally, an open pool of stimuli strongly reduces the likelihood that idiosyncratic aspects of the stimuli would lead to spurious conclusions upon the experimental manipulation. Hence, the methodological aspects we took in the present experiment increase the generalizability of our results.

Overall, we expect phonological similarity to increase recall of item information, while also decreasing recall of serial order information for items enclosed within the phonologically similar triplets, as previously observed (Fallon et al., 2005; Gupta et al., 2005; Neale & Tehan, 2007). If the between-item similarity that characterizes the phonologically similar items allows participants to free up WM resources, then recall performance for the other phonologically dissimilar items of the list should be enhanced, i.e., a proactive benefit should be observed.

Method

Participants. Thirty undergraduate students aged between 18 and 30 were recruited from the university community of the Université Grenoble Alpes. All participants were French-native speakers, reported no history of neurological disorder or learning difficulty, and gave their written informed consent before starting the experiment. None of the subjects participated in Experiments 1, 2 & 3. The experiment was approved by the ethic committee of CER Grenoble Alpes: Avis-2019-04-09-2.

Material. The pool of stimuli we used is a set composed of 120 words, selected from the French Lexique 3.83 (http://www.lexique.org/) database. The words have a log-frequency value of M = 2.09 (SD = 1.94) counts per million. The final pool comprised 40 sets composed of phonologically similar triplets, selected using the following constraints. We first selected the stimuli based on their number of phonemes, such that only items with a phonological length between 4 and 6 were included. In the final pool, 84, 27 and 9 items were 4, 5 and 6 phonemes long, respectively. These lengths were used to ensure that enough between-item phonological overlap could be induced, while ensuring that recall performance would be sufficiently high (i.e., avoiding floor effects). Among these stimuli, we kept only those that had at least two phonological neighbors. To be included, the stimuli and their phonological neighbors had to (1) have the same phonological length, (2) have the same consonant-vowel (CV) structure and (3) all differ by only one phoneme at their onset. These constraints ensured that between-item phonological overlap was maximized, while keeping other phonological properties equivalent. Only phonological neighbors differing by one phoneme at their onset were kept, as between-item phonological similarity effects have shown to be maximal with rhyming stimuli (Gupta et al., 2005).

From this pool of stimuli, three different experimental conditions were created:

- In the T1 condition (Triplet in first half), the first half of the items were phonologically similar, and the second half were phonologically dissimilar.
- In the T2 condition (Triplet in second half), the first half of the items were phonologically dissimilar, and the second half were phonologically similar.
- In the NT condition (No Triplet), all the items were phonologically dissimilar.

Each experimental condition comprised 20 trials. The items that compose the phonologically dissimilar sequences or triplets were created by mixing-up the items from different phonologically similar triplets. This procedure ensured that the sequences were perfectly matched across all possible psycholinguistic variables, except between-item similarity. Accordingly, the words appeared three times across the whole experiment: once in a phonologically similar triplet, and twice in a phonologically dissimilar triplet and/or sequence.

The sequences that compose each condition were automatically created, by guaranteeing that the Levenshtein distance between any dissimilar items within the sequence is above or equal to 3. Specifically, we computed the Levenshtein distance between the items that compose each possible pair of items within each sequence, based on the items' phonological form[2]. Sequences including any pair of items with a Levenshtein distance less or equal to two were automatically discarded, and a new attempt to create the sequence was made. We also avoided the possibility that a given item could be presented at the same serial position twice. This could not be completely avoided but was nonetheless minimized by assessing all possible within-list permutations. Finally, we also ensured that a given experimental condition (i.e., T1, T2 and NT) could not be presented on more than three consecutive trials.

Using these aforementioned constraints, we created 15 different versions of the lists to be remembered. We then created from these lists 15 new versions by reversing the within-list order (i.e., Items [1:6] became Items [6:1] across all trials). This last constraint ensured that the T1 and T2 conditions were strictly equivalent for the first and second half of the participants.

A pairwise comparison showed that the items that compose the phonologically dissimilar sequences and triplets had a greater Levenshtein distance between each other (M = 4.178, SD = 0.515) than the items enclosed in the phonologically similar triplets (M = 1, which is always the case due to the way we constructed the phonologically similar items, see above), and this difference was supported by decisive evidence, as shown by a Bayesian One-sample T-Test (BF_{10} = 9.065e+143). Similarly, the Levenshtein distance between the phonologically dissimilar items and the phonologically similar items embedded in the same lists in the T1 and T2 conditions was also important (M = 4.173, SD = 0.542), and this difference was credibly different from 1, as supported by a Bayesian One-sample T-Test (BF_{10} = 4.783e+925).

[2] This notation is the one provided in the Lexique 3.0 database.

Next, we assessed to what extent the phonologically similar and dissimilar lists are equivalent in terms of semantic relatedness values. One way this can be achieved is by collecting subjective semantic relatedness judgements between the adjacent pairs that compose the experimental lists from an independent group of participants, as we did in Experiment 1. However, we were concerned that the strong similarity that characterizes the phonologically similar pairs would prime the participants towards responding “related”. To avoid this potentially confounding factor, we chose to use instead an objective measure of semantic relatedness, i.e., LSA-cosine (Landauer & Dumais, 1997), which estimates the extent to which two words are semantically related based on the similarity of the context in which they occur in a huge corpus. Basically, LSA computes the word-paragraph occurrence matrix and reduces it to about 300 dimensions in order to remove noisy information. All words are then represented as 300-dimensional vectors that can then be compared by a simple cosine measure. Our analysis was performed using a 24-million-word French corpus representing all articles published in the Le Monde newspaper in 1999. As expected, we found that both the phonologically similar and dissimilar pairs were associated with equivalent LSA-cosine values (M = 0.059, SD = 0.075 and M = 0.062, SD = 0.077 for the similar and dissimilar pairs, respectively), and moderate evidence supported an absence of difference (BF_{01} = 8.859).

All other aspects of the experiment, including the general procedure, scoring procedure and statistical analyses were identical to Experiment 1.

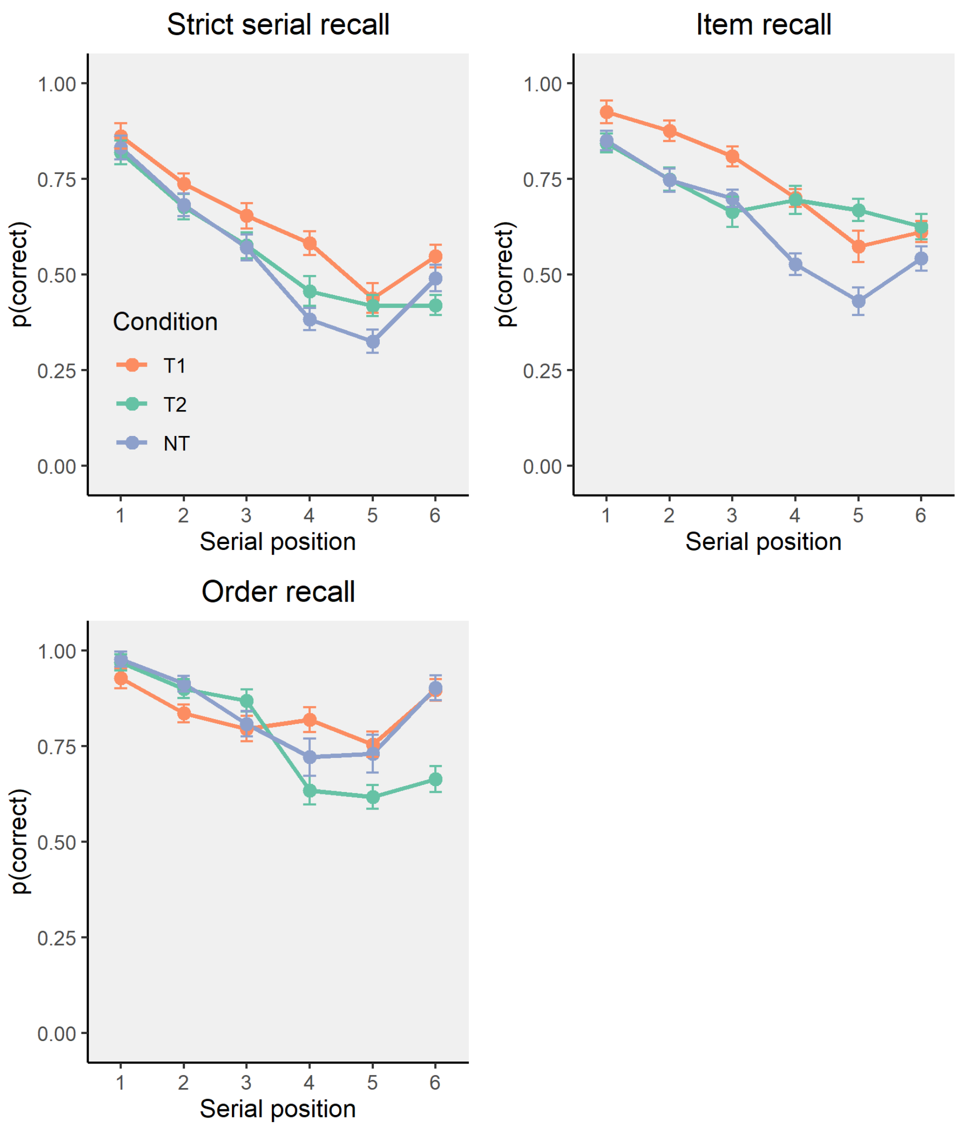
Results

Recall performance as a function of phonological condition (T1, T2, NT) and serial position (1 through 6) was assessed using a Bayesian Repeated Measures ANOVA. Using the strict serial recall criterion, we found decisive evidence supporting both main effects of phonological condition (BF_{10} = 5.293e+9) and serial position (BF_{10} = 1.529e+101). The interaction term was associated with strong evidence (BF_{10} = 25.199). Similarly, when the same analysis was performed using an item recall criterion, we found decisive evidence supporting the effect of phonological condition (BF_{10} = 2.934e+16), serial position (BF_{10} = 2.465e+69) and the interaction term (BF_{10} = 3.855e+9). Using the order recall criterion, we found decisive evidence supporting the effect of phonological condition (BF_{10} = 1.541e+5), serial position (BF_{10} = 1.674e+43) and the interaction term (BF_{10} = 6.694e+14).

Phonological similarity enhanced recall performance in a general manner, as can be seen in **Figure 2**. The only exception being the impact of phonological similarity on memory for order, for which WM performance decreased. The presence of the interaction furthermore suggests that phonological similarity differently impacted recall performance across serial positions. We explored this interaction using specific Bayesian Paired-Samples T-Tests.

Figure 2

Overall Results of Experiment 2 – Phonological Manipulation



Note. Recall performance as a function of serial position for each phonological condition (Experiment 4). T1 = Triplet in the first half of the list. T2 = Triplet in the second half of the list. NT = No triplet. Error bars represent confidence intervals corrected for between-subject variability (see statistical procedure).

Phonological similarity effect. First, we assessed the impact of phonological similarity on recall performance. Following previous studies, we expect that the impact of phonological similarity should not be equivalent across the item and strict serial recall criteria. This is because phonological similarity negatively impacts the ability to recall serial order information, which the strict serial recall criterion is sensitive to. Using the strict serial recall criterion, the phonological similarity was supported by anecdotal evidence in the T1 condition (i.e., positions 1 through 3: BF_{10} = 2.375, $CI_{95\%}$ = [0.055; 0.782], d = 0.444, M_{diff} = 0.056). In the T2 condition, phonological similarity did not credibly impact recall performance (i.e., positions 4 through 6: BF_{10} = 0.723, $CI_{95\%}$ = [-0.054; 0.652], d = 0.315, M_{diff} = 0.032). Using the item recall criterion, we observed this time a rather different pattern of results: phonological similarity credibly enhanced recall performance in the T1 (BF_{10} = 1.157e+4, $CI_{95\%}$ = [0.585; 1.491], d = 1.096, M_{diff} = 0.104) and T2 (BF_{10} = 2.573e+5, $CI_{95\%}$ = [0.765; 1.757], d = 1.323, M_{diff} = 0.163) conditions. This apparent contradiction between the strict serial and item recall criteria is explained by the fact that phonological similarity decreased memory for order. In the T1 condition, a negative impact of phonological similarity was supported by anecdotal evidence (BF_{10} = 2.381, $CI_{95\%}$ = [-0.775; -0.044], d = -0.444, M_{diff} = -0.047). This weak impact of phonological similarity on memory for order is likely due to a ceiling effect, since in the T2 condition this was supported by decisive evidence (BF_{10} = 1.917e+5, $CI_{95\%}$ = [-1.735; -0.752], d = -1.301, M_{diff} = -0.146).

Hence, the results of the analyses conducted so far show that phonological similarity strongly enhanced recall performance at the item level, while negatively impacting recall performance at the serial order level. In the next analysis, we directly assessed to what extent phonological similarity freed up WM resources, by enhancing recall performance for the other, phonologically dissimilar items within the same list.

Proactive benefit of the phonological triplet. The results of this analysis are straightforward: when the items over the first half of the lists were phonologically similar (i.e., the T1 condition), recall performance for the items in the second half of the list increased (see

Figure 2, positions 4 through 6). This is as compared to the same items not preceded by phonologically similar items (i.e., the NT condition). This proactive benefit was consistently observed across the strict serial recall (BF_{10} = 6.097e+5, $CI_{95\%}$ = [0.806; 1.827], d = 1.387, M_{diff} = 0.123) and the item recall (BF_{10} = 4.218e+7, $CI_{95\%}$ = [1.08; 2.217], d = 1.72, M_{diff} = 0.129) criteria. When assessed using the order recall criterion, no credible evidence was found (BF_{10} = 0.684, $CI_{95\%}$ = [-0.065; 0.637], d = 0.308, M_{diff} = 0.039). Hence, phonological similarity *proactively enhanced* recall performance, and this was specifically observed at the item level.

Retroactive effect of the phonological triplet. In a final analysis, we assessed whether the presence of phonological similarity retroactively impacted recall performance. Recall performance over positions 1 through 3 did not differ between the T2 and NT conditions, and this absence of difference was supported by moderate evidence using a strict serial recall criterion (BF_{01} = 5.082, $CI_{95\%}$ = [-0.375; 0.307], d = -0.03, M_{diff} = -0.004). Moderate evidence was found using the item recall (BF_{01} = 4.191, $CI_{95\%}$ = [-0.461, 0.225], d = -122, M_{diff} = -0.013) and order recall (BF_{01} = 3.438, $CI_{95\%}$ = [-0.185; 0.5], d = 0.171, M_{diff} = 0.013) criteria. Therefore, there was no credible retroactive impact of phonological similarity on recall performance.

Discussion

The results of this second experiment show that phonological similarity enhanced recall performance at the item level for the phonologically similar items themselves. At the same time, phonological similarity also decreased the ability to recall serial order information. These results replicate those observed in previous studies using an open pool of stimuli (Fallon et al., 2005; Gupta et al., 2005; Neale & Tehan, 2007). This furthermore demonstrates and confirms the complexity underlying the phonological similarity effect.

The critical result of this experiment is that phonological similarity also enhanced recall performance for the other, phonologically dissimilar items in the same list. This benefit of phonological similarity occurred proactively, but not retroactively. In other words, this benefit was observed only when the phonologically dissimilar items were preceded by the similar items. Again, these results further support the idea that between-item similarity allows the compression of information through the identification of redundant information within the WM content (Chekaf et al., 2016; Mathy et al., 2018). In the next experiment, we aimed at assessing the domain generality of this resource freeing up mechanism by studying the effects of similarity in the visuospatial domain.

Experiment 3

In experiment 3, we manipulated the presence of between-item similarity in the visuospatial domain, using squares sequentially presented at different spatial locations. Previous studies have shown that the between-item transitional information that characterizes visuospatial sequences impacts WM performance. More specifically, it has been shown that successive stimuli presented at close (*versus* distant) spatial positions lead to enhanced performance in reconstruction tasks (Parmentier et al., 2005, 2006; Parmentier & Andrés, 2006). Whether this transitional information can also be used to free up WM resources has never been assessed directly.

Most studies investigating WM in the visuospatial domain used reconstruction paradigms in which the memoranda, once encoded, are presented again on the screen. The participants are then invited to reconstruct the original presentation order (see for instance Parmentier et al., 2006). This paradigm provides a strong assessment of the ability to maintain serial order information. At the same time, this strongly differs from standard immediate serial recall tasks in which the maintenance of item information is also required. In the present experiment, we used a WM paradigm in which both item identity and the serial order of memoranda had to be maintained. Participants were presented with a 6-by-6 grid composed of gray squares on a white background. Six of the gray squares briefly turned black sequentially at different spatial locations. At the end of the sequence, the participants were invited to reproduce the original sequence by clicking on the correct squares corresponding to each serial position. Because the memoranda were not presented again at recall, maintenance of item information was also required. This paradigm should be a strong equivalent of the immediate serial recall paradigm we used in Experiments 1 & 2, which should facilitate between-experiment comparisons.

Between-item similarity was here characterized by the spatial proximity between items presented at consecutive serial positions. As in Experiments 1 and 2, we presented triplets of squares whose spatial locations were close to one another, followed (T1) or preceded (T2) by triplets of squares that were distant from each other. Recall performance for these sequences was then compared against sequences in which all the squares were presented at very different spatial locations to each other (NT). If between-item similarity in the visuospatial domain allows participants to free up WM resources in the same way as in the verbal domain (i.e., through compression), we expect to observe the same pattern of results as previously found, i.e., a proactive benefit following similar items, and an absence of retroactive benefit in addition to the more classical benefit on the similar items themselves.

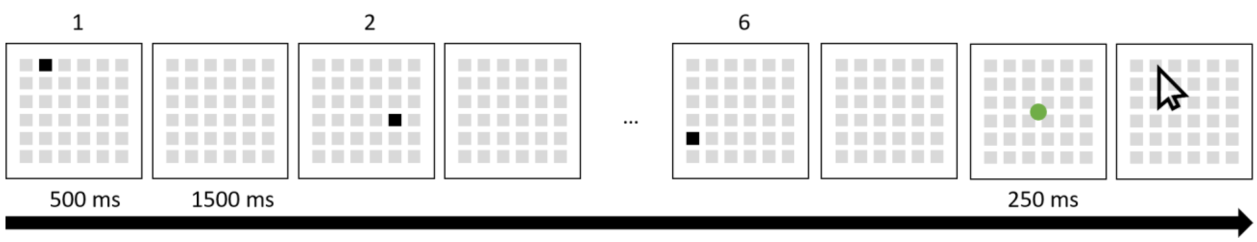
Method

Participants. Thirty undergraduate students aged between 18 and 30 were recruited from the university community of the Université Grenoble Alpes. All participants were French native speakers, reported no history of neurological disorder or learning difficulty, and gave their written informed consent before starting the experiment. None of the subjects participated in Experiments 1 and 2. The experiment had been approved by the ethic committee of CER Grenoble Alpes: Avis-2019-04-09-2.

Material. A grid composed of 36 (6-by-6) grey squares on a white background was used to present the stimuli. In each experimental condition, 6 items to be remembered were included. The squares to be remembered were indicated by briefly switching them from grey to black, as can be seen in **Figure 3.**

Figure 3

Time Course of The Experiment (6-item List)



Note. Each square appeared sequentially on a different spatial location for 500 ms, followed by a 1,500 ms empty interval. The end of the to-be-remembered list was signaled with a brief (250 ms) green dot at the center of the screen. Participants were then invited to reproduce the sequence using the mouse. After each click, the selected response briefly (100 ms) turned black.

The first item within a sequence was always chosen randomly. The transition between one square to another was also chosen randomly, nonetheless constrained by an a priori defined Euclidean distance, such that the distance between any squares in the whole list should be higher than 2 (the distance between two adjacent squares along the horizontal or vertical axes being defined as 1). This latter constraint does not apply to the spatially similar items. Instead, these items were selected such that the Euclidean distance between consecutive items was always equal to 1. We ensured that a given square never appeared twice within the same sequence. A square never appeared in a corner. We reasoned that corners should be particularly salient and easy to remember. Finally, we ensured that participants were never presented with the same sequence twice throughout the experiment.

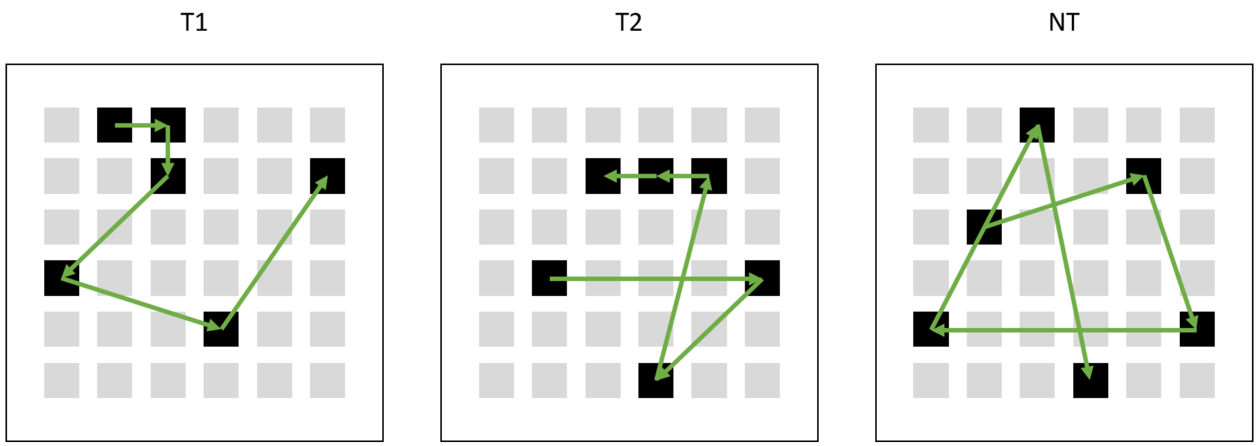
As in Experiment 1, three different experimental conditions were created:

- In the T1 condition (Triplet in first half), items of the first half were spatially similar, and items of the second half were spatially dissimilar.
- In the T2 condition (Triplet in second half), the first half of the items were spatially dissimilar, and the second half were spatially similar.
- In the NT condition (No Triplet), all the items were spatially dissimilar.

Each experimental condition comprised 20 trials. The T1 and NT conditions were created using the constraints mentioned above. The T2 condition was created by reversing the presentation order of the T1 sequence. This ensured that the T1 and the T2 conditions were strictly equivalent, except in terms of order arrangement. The three different experimental conditions were randomly presented, with the further constraint that the same experimental condition could not be presented on more than three consecutive trials. Examples of transitional patterns characterizing each experimental condition are presented in **Figure 4.**

Figure 4

Path Pattern for Each Spatial Condition



Note. In T1, the three first squares were presented close to each other, followed by squares presented at more distant spatial locations. In T2, this pattern was reversed. In NT, the squares were presented at distant spatial locations to each other.

Procedure. Each trial began with a countdown starting from 3, written in black and presented on a white background. The countdown was followed by the main grid presented during 1,000 ms, followed by the 6-item sequence to be remembered at a pace of 1 item every 2 seconds. As can be seen in **Figure 3**, each square to be remembered was indicated by switching its color to black during 500 ms, after which the square's color switched back to grey (i.e., its original color) during 1,500 ms, followed by the next item. After the presentation of the to-be-remembered list, a green round was briefly (250 ms) presented at the center of the screen, prompting the participants to reproduce the sequence in the order in which the items were presented. Participants were invited to do so by selecting the squares using the mouse. They were also invited to substitute any item they could not remember by clicking outside the grid. These items were considered as being omitted. After 6 clicks, the main grid was automatically replaced by a blank screen, inviting the participants to click anywhere to initiate the next trial. Note that during the presentation of the stimuli, the mouse cursor disappeared, and re-appeared only during the recall phase. This procedure ensured that participants did not put the mouse cursor on the location of a square to reduce the WM load.

Before the beginning of the experiment, the experimenter performed one practice trial to demonstrate the exact procedure to follow. Participants were then invited to perform 4 practice trials to familiarize with the task. The stimuli presented in the practice trials were not used in the main experiment. The experimenter was present throughout the experiment and ensured that the participant complied with the task requirements. Task presentation and timing were controlled using OpenSesame run on a desktop computer.

Scoring procedure. In addition to the standard item recall, strict serial recall, and order recall criteria used in Experiments 1 & 2, we also included a measure of deviation between the target and the participant's response, computed as the average Euclidean distance between each target square and the response square at the same position. This was made to assess the impact of spatial similarity on WM performance in a more fine-grained manner. Indeed, the measure of deviation has the further advantage to consider the possibility that participants may more or less strongly deviate from the original target.

Statistical analysis. The statistical analyses were identical to Experiments 1 & 2.

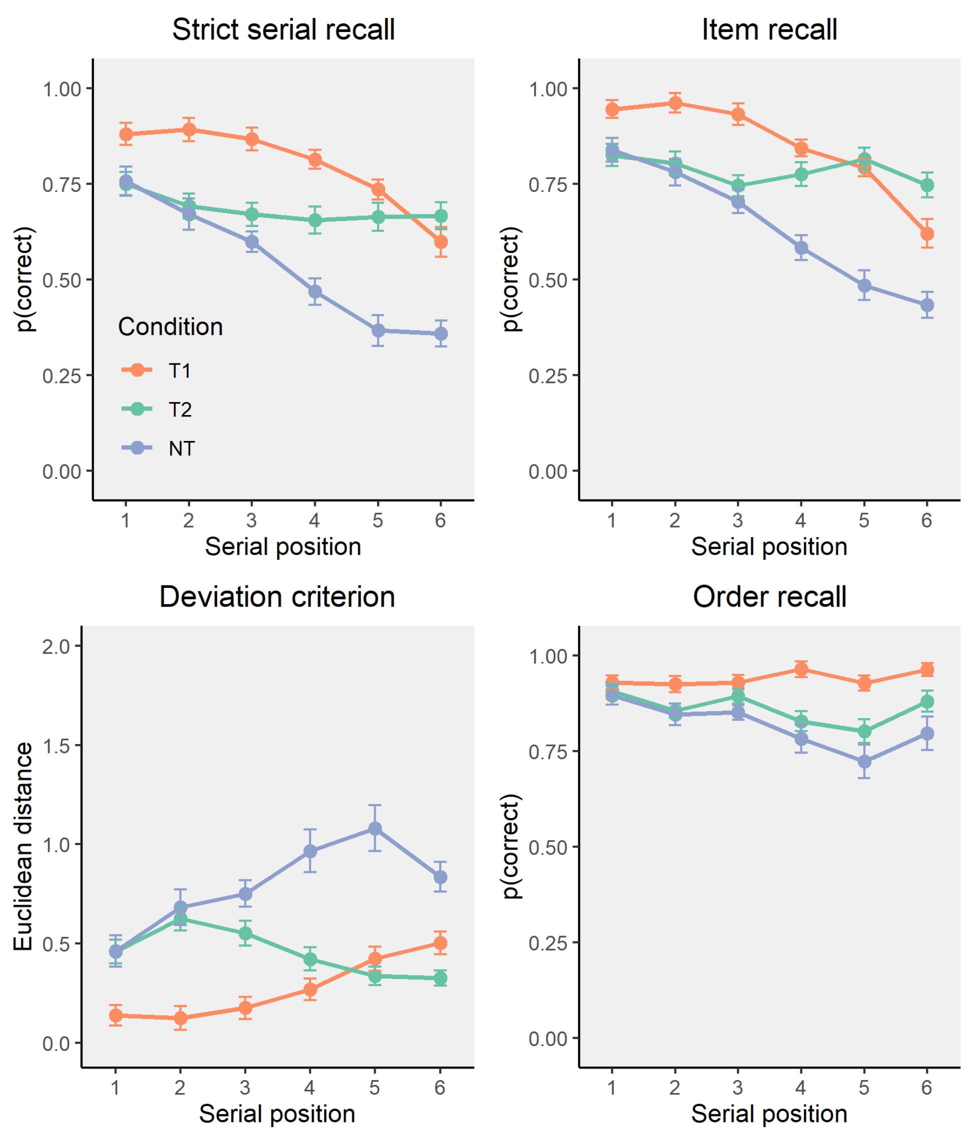
Results

Recall performance as a function of spatial condition (T1, T2, NT) and serial position (1 through 6) was assessed using a Bayesian Repeated Measures ANOVA. Using a strict serial recall criterion, we found decisive evidence supporting both main effects of spatial condition (BF_{10} = 1.976e+59) and serial position (BF_{10} = 3.102e+41). The interaction term was also supported by decisive evidence (BF_{10} = 1.433e+15). Similar results were observed using the item recall criterion, with decisive evidence supporting both main effects of spatial condition (BF_{10} =

1.863) and serial position (BF_{10} = 7.941e+51). The interaction term was also associated with decisive evidence (BF_{10} = 9.359e+21). The results using the deviation score converged with these observations, with decisive evidence supporting the main effects of spatial condition (BF_{10} = 2.167e+57) and serial position (BF_{10} = 6.693e+5), but also the interaction term (BF_{10} = 1.654e+18). Results using the order recall criterion showed decisive evidence supporting both main effects of spatial condition (BF_{10} = 2.648e+24) and serial position (BF_{10} = 3.468e+5), and the interaction term (BF_{10} = 415.233).

Figure 5

Results of Experiment 3 – Visuospatial Manipulation



Note. Recall performance as a function of serial position for each spatial condition (Experiment 2). T1 = Triplet in the first half of the list. T2 = Triplet in the second half of the list. NT = No triplet. Error bars represent confidence intervals corrected for between-subject variability (see statistical procedure).

Hence, recall performance was largely impacted by the presence of spatially similar information (see **Figure 5**), and this impact did differ across serial position, as demonstrated by the interaction. In the next analyses, this interaction was further explored.

Spatial similarity – overall performance. We first assessed the overall impact of spatial similarity on recall performance. Using a strict serial recall criterion, we observed that the spatially similar items in the T1 condition were better recalled than the spatially dissimilar items in the NT condition across positions 1 through 3. This difference was supported by decisive evidence (BF_{10} = 3.09e+5, $CI_{95\%}$ = [0.777; 1.771], d = 1.336, M_{diff} = 0.204). This recall advantage for spatially similar items was also observed in the T2 as compared to the NT condition across positions 4 through 6 and was also associated with decisive evidence (BF_{10} = 2.63e+7, $CI_{95\%}$ = [1.048; 2.174], d = 1.682, M_{diff} = 0.264). This pattern of results was consistently observed using an item recall criterion, both in the T1 (BF_{10} = 3.92e+6, $CI_{95\%}$ = [0.921; 1.992], d = 1.53, M_{diff} = 0.172) and the T2 (BF_{10} = 4.762e+9, $CI_{95\%}$ = [1.4; 2.719], d = 2.134, M_{diff} = 0.278) conditions, when compared to the NT conditions. We found converging evidence using the deviation score. Compared to the NT condition, less deviation from the targets was observed in the T1 (BF_{10} = 2.448e+5, $CI_{95\%}$ = [0.757; 1.748], d = 1.319, M_{diff} = 0.486) and the T2 (BF_{10} = 9.227e+6, $CI_{95\%}$ = [0.994; 2.083], d = 1.598, M_{diff} = 0.599) conditions. Finally, the order recall criterion produced convergent results, with spatially similar items being better recalled as compared to spatially dissimilar items (T1 vs. NT: BF_{10} = 13.354, $CI_{95\%}$ = [0.177; 0.939], d = 0.596, M_{diff} = 0.064, T2 vs. NT: BF_{10} = 3.885, $CI_{95\%}$ = [0.078; 0.815], d = 0.49, M_{diff} = 0.069).

Proactive benefit of the spatial triplet. The results of this analysis are overall consistent: recall performance in positions 4, 5 and 6 in the T1 condition increased as compared to the same items in the NT condition, as can be seen in **Figure 5**. This increase of recall performance was supported by decisive evidence, and this across the strict serial recall (BF_{10} = 2.803e+10, $CI_{95\%}$ = [1.531; 2.915], d = 2.303, M_{diff} = 0.318), the item recall (BF_{10} = 2.226e+10, $CI_{95\%}$ = [1.515, 2.89], d = 2.28, M_{diff} = 0.251), the deviation (BF_{10} = 6.171e+5, $CI_{95\%}$ = [0.809; 1.82], d = 1.388, M_{diff} = 0.563) and the order recall (BF_{10} = 1.064e+5, $CI_{95\%}$ = [0.718; 1.684], d = 1.258, M_{diff} = 0.184), criteria. Therefore, the presence of spatial similarity proactively enhanced recall performance.

Retroactive impact of the spatial triplet. Finally, recall performance in positions 1, 2 and 3 in the T2 condition did not increase as compared to the same items in the NT condition. Using the strict serial recall criterion, an absence of difference between the two spatial conditions was only associated with anecdotal evidence (BF_{01} = 1.615, $CI_{95\%}$ = [-0.083; 0.617], d = 0.295, M_{diff} = 0.029). Using the item recall criterion, moderate evidence supported the absence of difference between the two spatial conditions (BF_{01} = 3.177, $CI_{95\%}$ = [-0.168; 0.519], d = 0.188, M_{diff} = 0.017). This absence of difference was associated with anecdotal evidence using the deviation criterion (BF_{01} = 1.035, $CI_{95\%}$ = [-0.033; 0.679], d = 0.349, M_{diff} = 0.086), but also the order recall criterion (BF_{01} = 1.455, $CI_{95\%}$ = [-0.076; 0.628], d = 0.308, M_{diff} = 0.021). Overall, a retroactive impact of spatial similarity was not credibly supported.

Discussion

The results of Experiment 3 show that similar items were associated with higher WM performance levels than dissimilar items. In addition, similarity did not consistently impact memory for serial order information. The presence of spatial similarity proactively enhanced recall performance for the subsequent items of the to-be-remembered lists. In contrast, no retroactive impact was observed. This pattern of results is akin to those observed in Experiments 1 & 2 manipulating semantic and phonological similarity. In the next experiment, we tested the impact of between-item similarity in the visual domain.

Experiment 4

In Experiment 4, we tested the impact of between-item similarity using colors. Previous studies showed that similarity between colors enhances WM performance for other, dissimilar colors (C. C. Morey et al., 2015; Ramzaoui & Mathy, 2021). However, these studies used paradigms in which all the memoranda were simultaneously presented. This prevents the possibility to draw conclusions regarding the way between-item similarity frees up WM capacity over the time-course of WM processing. Furthermore, in these studies between-item similarity was manipulated by including colors that were repeated over spatial locations. Hence, between-item similarity was manipulated in a binary manner because items could only be repeated or not within a trial.

In the present experiment, items were always presented sequentially. Moreover, between-item similarity was manipulated in a more fine-grained manner, analogous to Experiments 1, 2 & 3, by using non-repeated items whose colors were sampled from a continuous scale. Similar colors were presented among dissimilar colors. The similar colors were presented either at the beginning (S1) or at the end (S2) of the to-be-remembered lists. Performance for these lists was compared to lists for which all the colors were maximally dissimilar (DIS). If between-item similarity frees up WM capacity in a domain-general manner, we expected to replicate the overall results observed so far, that is, a general beneficial effect of similarity, as well as a proactive benefit and an absence of retroactive impact for other, dissimilar colors embedded in the same list.

Method

Participants. Thirty-two undergraduate students aged between 18 and 30 were recruited from the university community of the Université Grenoble Alpes. All participants were French-native speakers, with a normal or correct vision, reported no history of neurological disorder or learning difficulty, and gave their written informed consent before starting the experiment. None of the subjects participated in the previous experiments. The experiment was approved by the ethic committee of CER Grenoble Alpes: Avis-2019-04-09-2.

Material. All the stimuli involved four colored squares presented on a gray background (see **Figure 6**). We chose to use four stimuli instead of six in order to reach reasonable performance levels, as informed by a pilot study. Colors were always sampled along the hue dimension in the HSL (hue, saturation, lightness) model. The hue dimension takes values between 0 and 360 (for instance, 0 is red, 120 is green, 240 is blue). The saturation and lightness dimensions were always set to 100% and 50%, respectively. The dissimilar colors were created by randomly sampling values in the hue dimension, by ensuring that any two dissimilar colors were separated by at least 60° of angular distance, with a maximal distance of 90°. The similar colors were randomly sampled, with the further constraint that the angular distance between any two similar colors should be between 15° and 30°.

As in the previous experiments, three different experimental conditions were created:

- In the S1 condition (Similar in first half), items of the first half were similar, and items of the second half were dissimilar.
- In the S2 condition (Similar in second half), the first half of the items were dissimilar, and the second half were dissimilar.
- In the DIS condition (Dissimilar), all the items were dissimilar.

Each experimental condition comprised 20 trials. The S1 and DIS conditions were created using the constraints mentioned above. The S2 condition was created by reversing the presentation order of the S1 sequence. As in the previous experiments, the three different experimental conditions were randomly presented. An example of each condition is illustrated in **Figure 7**.

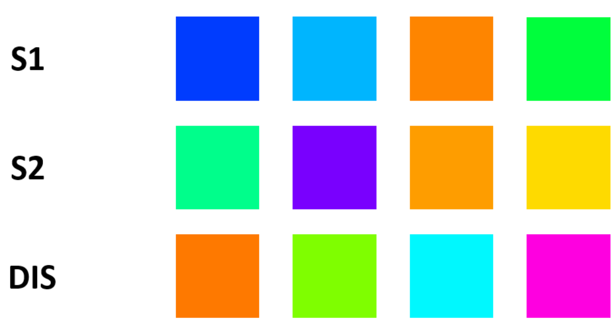
Figure 6

Time Course of The Experiment (4-item List)

Note. Each square appeared sequentially in the middle of the screen along the vertical dimension. Along the horizontal dimension, the squares were presented from left to right. Each item appeared for 1,000 ms, followed by a 1,000 ms empty interval. The end of the to-be-remembered list was directly followed by the retrieval phase. Participants were invited to reproduce the color of each square using the color wheel. After each click, the wheel turned a random angle.

Figure 7

Example of Colors Used in Each Condition



Note. In S1, the colors of the two first squares differed by an angular distance ranging from 15° to 30°. The subsequent items differed between 60° and 90° in angular distance with all the other items. The S2 condition was identical to the S1 condition, except that the sequences were reversed. In the DIS condition, all the items differed by an angular distance ranging from 60° to 90°.

Procedure. Due to the SARS-CoV-19 pandemic, all participants were tested remotely through the Skype® software. Participants were invited to follow a web link through which they arrived on an online platform where the experiment was hosted. To ensure that they complied with task requirements, participants were invited to share their screen with the experimenter, which remained present throughout the whole experiment. Participants initiated each trial by clicking on a red button displayed on the center of the screen, which automatically triggered the presentation of the 4 items to be remembered. Items were presented at a pace of 1 item every 2 seconds (1,000 ms ON, 1,000 ms OFF). The items were presented at different spatial locations from left to right in the middle of the screen, as also illustrated in **Figure 6**. After the presentation of the to-be-remembered list, four empty squares were presented at the bottom of the screen, along with a color wheel centered in the middle of the screen. The four empty boxes were presented to help participants keep track of each to-be-remembered position over successive responses. Participants were asked, using their computer mouse, to click on the wheel to report the color of each square in the original order in which they were presented. After each click, the square associated with the current to-be-remembered color briefly (i.e., 333 ms) displayed visual feedback of participant's response and directly disappeared afterward. In addition, the color wheel briefly (i.e., 100 ms) turned black and was randomly rotated after each successive retrieval attempt. This last manipulation was done to prevent participants from associating the colors along a spatial dimension. Likewise, participants were invited to perform complex articulatory suppression (i.e., saying "ba-be-bi-bo-bu" out loud) throughout all WM phases (encoding + retrieval) to prevent the involvement of verbal maintenance processes. A complex articulatory suppression was chosen, as phonological recoding has shown to be possible even in simple articulatory suppression forms (Norris et al., 2018). Reporting all items' colors resulted in the reappearance of the red button, inviting participants to initiate the next trial. During the presentation of the stimuli, the mouse cursor disappeared, and re-appeared only during the retrieval phase.

Participants performed three practice trials before the beginning of the main experiment. The experimenter was present throughout the experiment and ensured that the participant complied with the task requirements. The experiment was coded in JavaScript. Task presentation and timing were controlled using the jQuery library, which ensures an efficient communication between JavaScript, HTML and CSS.

Scoring procedure. Contrary to Experiments 1 & 2, participants reported here their response on a continuous scale (i.e., the color wheel). With continuous response, there is no straightforward way to compute the strict serial, item and order recall criteria as reported in the previous experiments. Instead, in this experiment we used the mean absolute angular error (in degree) between the target and participant's response.

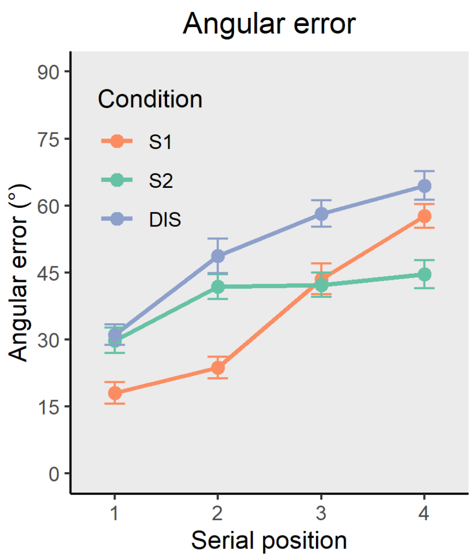
Statistical analysis. The statistical analyses were identical to previous experiments.

Results

Angular error as a function of visual condition (S1, S2, DIS) and serial position (1 through 4) was assessed using a Bayesian Repeated Measures ANOVA. This analysis showed decisive evidence supporting both main effects of visual condition (BF_{10} = 1.325e+19) and serial position (BF_{10} = 3.405e+48). The interaction term was supported by decisive evidence (BF_{10} = 2.114e+10).

Figure 8

Results of Experiment 4 – Visual Manipulation



Note. Angular error as a function of serial position for each condition (Experiment 4). S1 = Similar items in the first half of the list. S2 = Similar items in the second half of the list. DIS = Dissimilar items. Error bars represent confidence intervals corrected for between-subject variability (see statistical procedure).

There was therefore a robust impact of between-item similarity on WM performance (see also **Figure 8**). The presence of the interaction suggests that the impact of similarity was not similarly observed across all serial positions. This was explored using Bayesian paired samples T-Tests.

Visual similarity. We contrasted the angular error between the DIS and S1 conditions across positions 1 and 2, and between the DIS and S2 conditions across positions 3 and 4. Both analyses showed that visual similarity reduced angular errors, and this was observed both in the S1 (BF_{10} = 6.066e+5, $CI_{95\%}$ = [-1.737; -0.778], d = 1.314, M_{diff} = 19.008) and S2 (BF_{10} = 3.92e+6, $CI_{95\%}$ = [-1.886; -0.886], d = 1.446, M_{diff} = 17.928) conditions.

Proactive benefit of visual similarity. When assessing the proactive impact of visual similarity, the results were consistent with those previously observed. Angular error decreased for items that followed similar items in the S1 as compared to the DIS condition, as can be seen in **Figure 8**. This difference was supported by decisive evidence (BF_{10} = 129.58, $CI_{95\%}$ = [1.081; -0.303], d = 0.741, M_{diff} = 10.725).

Retroactive impact of visual similarity. In contrast, results did not show a consistent change of angular errors for items preceding the similar items. A difference between the S2 and DIS conditions over positions 1 and 2 was only supported by anecdotal evidence (BF_{10} = 1.584, $CI_{95\%}$ = [-0.712; -0.013], d = 0.392, M_{diff} = 4.103).

Discussion

The results observed in Experiment 4 confirmed those already found in previous studies (C. C. Morey et al., 2015; Ramzaoui & Mathy, 2021). Similarity between colors not only increased WM performance for the similar items themselves, but also for other, dissimilar colors within the same list. We extend these results by showing that the benefit of similarity occurs proactively, with little evidence showing a retroactive benefit on WM performance.

Across the four experiments we conducted, a convergent pattern emerged: the presence of between-item similarity enhanced recall performance for the similar items themselves. Critically, between-item similarity proactively, but not retroactively, impacted WM performance. These effects are summarized in **Table 1**, where the BF_{10} values for Experiments 1, 2, 3 and 4 are reported across all recall criteria. As can be seen, these effects are strong, robust, and consistent when assessed at the item level. Results on memory for order information were more inconsistent. In the next section, we discuss the theoretical implications of our results.

Table 1
Summary of the Patterns of Results Across the Experiments

		Similarity (T1)	Similarity (T2)	Proactive	Retroactive
Exp. 1 Semantic	Strict	> 100	> 100	> 100	0.208
	Item	> 100	> 100	> 100	0.307
	Order	0.849	0.2	150.826	0.276
Exp. 2 Phonological	Strict	2.375	0.723	> 100	0.197
	Item	> 100	> 100	> 100	0.239
	Order	**2.381**	**1.917e+5**	0.684	0.291
Exp. 3 Visuospatial	Strict	> 100	> 100	> 100	0.619
	Item	> 100	> 100	> 100	0.315
	Deviation	> 100	> 100	> 100	0.966
	Order	13.354	3.885	> 100	0.687
Exp. 4 Visual	Angular error	> 100	> 100	> 100	1.584

Note. The values represent the Bayes Factor in favor of H1 (BF_{10}) specific to each effect (similarity, proactive and retroactive effects). These values are reported for each recall criteria: strict serial recall, item recall, order recall, deviation (visuospatial domain only) and angular error (visual domain only). Values in bold indicate effects going in the opposite direction (i.e., deleterious impact).

General discussion

In this study, we demonstrated that between-item similarity can free up WM resources across the semantic, phonological, visuospatial, and visual domains. Specifically, when similar items were included in a list to be remembered, this enhanced recall performance at the item level through a subtle pattern of results. First, the similar items themselves were more often recalled compared to dissimilar items. Second, the subsequent items within the same list also benefited from the similar items, compared to completely dissimilar lists. Third, when the similar items appeared at the end of the list, no retroactive impact was found. Critically, this was observed when between-item similarity was manipulated in the semantic (Exp. 1), phonological (Exp. 2) visuospatial (Exp. 3) and visual (Exp. 4) domains. These outcomes are consistent with those previously observed in the visual domain (C. C. Morey et al., 2015; Ramzaoui & Mathy, 2021). They are furthermore consistent with the idea that between-item similarity can be used to compress information in a more compact format (Chekaf et al., 2016). This in turn frees up WM resources that can be used to maintain more items. In the following paragraphs, we first discuss the underlying mechanisms of similarity effects in WM. Second, we discuss the general impact of similarity on memory for order, which produced an inconsistent pattern of results in our experiments. Third, we tackle the implications of the present findings regarding the domain-generality of resource freeing up. Finally, we narrow the plausible range of WM mechanisms that could explain the origin of resource freeing up in WM.

What makes similar items better remembered?

Our results show that similar items are better recalled at the item level, when compared to dissimilar items. In other words, participants recalled more items in the similar vs. dissimilar condition. This recall advantage associated with similar items can be explained either by supposing that the individual representations that compose the similar items are co-activated, or by postulating a compression mechanism as we initially assumed. In this section, we discuss these two accounts in a more detailed manner.

A co-activation process. Some models consider that WM relies on direct activation within the long-term memory system, and that this activation provides the representational basis for WM maintenance (Cowan, 2001; Majerus, 2019; Martin & Saffran, 1997; Nee & Jonides, 2013; Oberauer, 2002). As long as items are kept sufficiently active in long-term memory, they can be accessed and therefore recalled. One possibility is that similar items reactivate each other in long-term memory via spreading activation, which in turn makes them more resistant to forgetting. Due to this high activation level, fewer WM resources are required to keep them active. These resources can then be devoted towards the other, dissimilar items.

Regarding semantic relatedness, related items may reactivate each other within a semantic network via spreading of activation toward neighboring concepts. This is assumed to occur either due to shared semantic features that characterize semantically related items (Dell et al., 1997), or through lateral excitatory connections (Hofmann & Jacobs, 2014). A similar phenomenon could explain the impact of phonological similarity in our experiment. The phonologically similar words we used are also phonological neighbors[3]. Models from network science have been applied to the psycholinguistic domain and assume that phonological neighbors are strongly connected in the phonological lexicon (Levy et al., 2021). The structure of the phonological lexicon in turn affects human performance in linguistic and memory tasks (Q. Chen & Mirman, 2012; Guitard et al., 2018; Roodenrys et al., 2002; Siew & Vitevitch, 2016; Vitevitch, 2002, 2008). These ideas could be extended toward the visual and visuospatial domains: when activating a color or a spatial location, neighboring representations may also

[3] In the psycholinguistic domain, phonological neighbors are usually identified as items differing by one phoneme from the target. Differences include additions, deletions and substitutions (Yarkoni et al., 2008).

become active to some extent[4]. This in turn should ease the processing of subsequent information if this information is similar to what has previously been encountered. We already demonstrated the plausibility of this reactivation process to account for the proactive effect caused by semantic relatedness in a previous study of our own involving simulations in the TBRS* architecture (Kowialiewski, Lemaire, et al., 2021), a computational implementation of the TBRS (Time-Based Resource Sharing) model (Barrouillet et al., 2004).

A compression mechanism. Compression is another way to explain similarity effects. When some pieces of information are somehow related to each other, they can be compressed within a more general structure. This can then be stored using a smaller quantity of information. Usually, these elements are characterized as being associated with each other more strongly than with the others (Gobet et al., 2001). Even if memoranda in WM experiments are presented one after the other, people can still group these distinct percepts into chunks. This is the case even when they are interleaved with sequences of distractors (Portrat et al., 2016).

One way to compress information is via summary statistics. The visual system can extract a summary statistic from objects' properties, a phenomenon also called *ensemble representation* (Alvarez, 2011; Ariely, 2001). This summary statistic can be used to represent items in a hierarchical structure, which in turn boosts the quality of WM representations (Brady & Alvarez, 2015). The more compact the representation, the better its quality and precision (Son et al., 2020). Evidence supporting this mechanism comes from visual working memory tasks involving participants to reproduce grouped object's features such as size, color, or orientation on a

[4] Contrary to the phonological and semantic domains, these neighbors in the visual and visuospatial domains are not categorical but continuous. This could be formally implemented by using for instance a Gaussian distribution around the activated values each time a stimulus is presented.

continuous scale. It has been shown that participant's responses for individual items are biased toward the mean of the ensemble representation (Brady & Alvarez, 2011; Son et al., 2020), suggesting that summary statistics are indeed extracted and then encoded into WM. Hence, when the individual representations of items are imprecise, ensemble representations can be used to get an accurate representation of the ensemble itself. It must be noted that the extraction of a summary statistics does not mean that the original representations are completely lost. The summary statistics could act as a retrieval cue or boost the original representations via feedback activations right at encoding.

As regards WM, it is worth making a distinction between lossless and lossy compression (Norris & Kalm, 2021). The former refers to the fact that memoranda are chunked without losing any information. This is for instance the case when P, D and F are grouped into "PDF", or Lennon, McCartney, Harrison and Ringo Starr grouped into "Beatles". The chunk contains all the original information and can be stored without any need to maintain the individual elements because they would be easily retrieved at recall. However, compression can be lossy when there is not an existing long-term memory item that fully represents the set of memoranda. For instance, even if pear, plum and apple can be chunked under the concept "fruit", this chunk does not contain all the information needed to retrieve the initial elements. Maintaining "fruit" alone is therefore not enough to guarantee a fruitful retrieval of all elements. In our experiments, triplet elements are only associated with each other, without any higher-level concept able to retrieve them for sure. Compression is therefore lossy.

How does similarity impact memory for order?

The deleterious impact of similarity on memory for order is a robust phenomenon. An increase of order errors for similar vs. dissimilar items has been reported in the phonological

(Baddeley, 1966), auditory (Visscher et al., 2007), and visual (Jalbert et al., 2008) domains. Likewise, in standard immediate serial recall tasks, order errors occur more often for items associated with adjacent vs. distant serial positions. According to many contemporary models of WM, adjacent positions are assumed to be represented by similar positional and/or contextual markers (Burgess & Hitch, 1999; Farrell, 2012; Farrell & Lewandowsky, 2002; Henson, 1998; Oberauer et al., 2012; Oberauer & Lewandowsky, 2011). The general deleterious effect of similarity on memory for order can be explained by a simple discriminability problem: similar WM representations are more difficult to discriminate than dissimilar ones, which increases the probability to select a wrong competitor at retrieval. In the present study, this negative impact of similarity has been observed only in the phonological domain. This contradicts the hypothesis according to which compression would necessarily come with a cost at the serial order level.

Why did we not find this deleterious impact of similarity when manipulated in the semantic domain? While some studies found no impact of semantic similarity on memory for order (Kowialiewski, Lemaire, et al., 2021; Neale & Tehan, 2007; Saint-Aubin & Poirier, 1999), some did find small, but observable effects (Baddeley, 1966; Ishiguro & Saito, 2020; Saint-Aubin & Ouellette, 2005; Tse et al., 2011), and some found mixed results (Poirier & Saint-Aubin, 1995). From those who found an effect, sometimes the stimulus properties were not carefully controlled (Baddeley, 1966), and some of them were never replicated (Saint-Aubin & Ouellette, 2005; Tse et al., 2011). Sometimes, studies did not use a proper measure of memory for order (Ishiguro & Saito, 2020)[5]. Hence, evidence supporting a deleterious impact of semantic

[5] The Ishiguro and Saito study is a meta-analysis. The authors were able to find an increase of order errors for related versus unrelated items when combining several studies from the literature. However, Ishiguro and Saito used the absolute number of order errors as a dependent variable, without correcting for the total number of items

similarity on memory for order is at best inconclusive. The reason why semantic similarity does not appear to consistently impact memory for order remains to be understood. One possibility is that semantic knowledge might not be directly represented in WM, or at least not the same way as (for instance) phonology.

In the visuospatial domain, we found that similarity *increased* memory for order. In our manipulation, similarity created patterns that helped memorizing the relative order of items (see **Figure 4**). In line with the lossy/lossless distinction discussed above, the 3 similar items could be compressed quite easily by storing the initial location and two directions (e.g., right-right or down-left), even as a gestalt. This form naturally contains the order, as opposed to a 3-item semantic sequence like "cherry-pear-apple" for which the order is harder to represent. This is a specific case for which between-item similarity may increase, rather than decrease, memory for order. The existence of an order relation between the to-be-remembered items reduces the complexity of the sequence and therefore makes it more compressible. In some simple cases, that complexity can be even estimated using algorithmic complexity measures (Mathy & Feldman, 2012). This idea could be applied to any domain. In the semantic domain, recalling the sequence “Monday, Tuesday, Wednesday, Thursday, Friday, Saturday, Sunday” would be easier than recalling the same items in a random order. Similarly, in the visual domain, if three colors are presented in this order: “red, orange, yellow”, it can be expected that the order of these items would be easier to remember as compared to the same colors in a random order.

Recently, Kowialiewski, Gorin, et al., 2021 showed that semantic relatedness constrains the pattern of transposition errors occurring in typical serial recall tasks. They used lists

recalled in each condition. As semantically related words are overall recalled more often, this provides more opportunity for order errors to occur, even if the proportion of order errors is the same in both conditions.

composed of items related in sub-groups (e.g., piano, guitar, violin, arm, leg, hand). As compared to unrelated lists, they observed that the semantic grouping structure influenced the way items migrate. When a transposition error occurred, it did so more often toward the position of another related item, and this as compared to the same positions in the unrelated lists. The authors interpreted this result as reflecting the activation of a superordinate category, through which participants can compress information and maintain the items more easily. If such a superordinate category is used to recall the similar items, it is predicted that these items will be recalled more often together and hence transposed more often between each other, rather than with items from a different category. This idea fits well with our initial hypothesis, according to which proactive benefits of similarity are explained by a compression mechanism. If this is the case, we should therefore replicate the results observed by Kowialiewski and colleagues in the present study. Actually, we report in **Appendix A** an exploratory analysis showing that this phenomenon also happened across Experiments 1 through 3[6].

A domain-general free up of WM resources

In the present study, we observed consistent patterns of similarity effects across four different domains, often studied separately in the WM literature. Given the strikingly similar patterns of results observed across these different domains, we propose that information compression may impact WM maintenance processes in a domain-general manner. Such a proposal is consistent with a widespread view according to which the different domains share common resources or systems supporting WM maintenance (Barrouillet & Camos, 2015; Cowan, 2005; Engle et al., 1999; Lovett et al., 1999; Oberauer, 2002). Recent empirical findings have shown a systematic dual-task cost between the storage of verbal and visuospatial

[6] We are thankful to an anonymous reviewer for suggesting this analysis.

information, suggesting that WM storage is at least in part domain-general (Uittenhove et al., 2019). The verbal and visuospatial WM activities furthermore compete for a common domain-general pool of resources, as shown by robust and consistent trade-offs between storage and processing across domains in complex span tasks (Vergauwe et al., 2010, 2012). A domain-general impact of compression in WM is congruent with models assuming controlled attention at the heart of WM functioning. This is the case for the TBRS model (Barrouillet & Camos, 2015) or the embedded-processes model (Cowan, 2005) in which the domain-general focus of attention could be the fuel of the impact of compression in WM.

Although we claim the domain-general reallocation effects we observed could originate from a common attentional process, we cannot rule out the possibility that our results could be explained by modular models considering that distinct mechanisms are responsible for the maintenance of verbal and visuospatial materials (Baddeley & Logie, 1999; Logie, 2011). In these models, when a given buffer is overloaded, the others interact to support the WM representation. Verbal and visuospatial would have their own and distinct resources. However, given the striking resemblances we observed across the four domains we tested, postulating the existence of distinct modules for WM maintenance appears to be not parsimonious. In light of this old debate within the WM literature, we propose that whatever the specificity of each domain (e.g., memory for order), and the way information is compressed within them, repercussions of this compression on WM performance manifest equally at the general level of functioning. Critically, its temporal dynamic appears to be a key factor.

One possibility regarding this temporal dynamic observed in the present study, but also in previous studies assessing the impact of chunking (Norris et al., 2020; Portrat et al., 2016; Thalmann et al., 2019), is that proactive benefits emerge from a reallocation of attentional resources. According to the TBRS theory (Barrouillet et al., 2004), items encoded in WM constantly decay when out of attention. However, the deleterious impact of decay can be counteracted using the focus of attention, a central bottleneck limited to one item at a time. The role of the focus of attention is to refresh the decaying WM representations, provided there is enough free time to do so. Importantly, the focus of attention is supposed to be a domain-general attentional mechanism acting on any domain. In TBRS, WM capacity is therefore constrained by the constant balance between refreshing and decay. When framed through the TBRS model, the beneficial effect of compression is straightforward. Since WM load is reduced following compression, this frees up some time that can be devoted to refreshing more items. These items can in turn be saved from forgetting. Accordingly, this free time should benefit the other items, which should be better recalled. One way participants could reallocate their refreshing episodes is by favoring the less activated WM representations (Lemaire et al., 2018). This way of reallocating attention is consistent with experiments suggesting that participants can redirect their attentional resources in a strategic manner as a function of the statistical constraints imposed by the experimental setup (Bruning & Lewis-Peacock, 2020). Finally, contrary to what has been previously claimed (Thalmann et al., 2019), the TBRS theory also predicts an absence of retroactive impact of chunked items. This is because when items at the end of a list to be remembered are compressed, items that have already been forgotten during the inter-item maintenance interval cannot be saved anymore (see Kowialiewski et al., 2021 for a detailed interpretation). Hence, the general principles of the TBRS theory represent a likely candidate explaining the patterns of results found in this study.

Alternative accounts

Although the decay and refreshing framework presented above seems to be a plausible candidate to account for our observations, there exists several other possibilities. In this section, we present alternative theories that may account for free up effects in WM.

The encoding-resource hypothesis. Recently, Popov & Reder (2020) proposed a limited-resource mechanism, according to which items deplete resources from a limited pool during encoding. In this encoding-resource account, encoding strength is proportional to the amount of available resources: a larger amount of resources provides stronger encoding. This way of encoding items naturally creates a primacy gradient whose existence is empirically supported (Oberauer, 2003). The plausibility of the encoding-resource account has recently received support from fine-grained investigations of the beneficial effect of free time in immediate serial recall tasks (Mizrak & Oberauer, 2021). Critically, this model can explain the presence of proactive effects in WM. Items that are easier to process, such as high frequency items, are assumed to deplete fewer resources. Their simulations have shown that this leaves a larger quantity of resources that can be devoted to encoding subsequent items. This mechanism also predicts an absence of retroactive effects because the depletion of resources is critical for the to-be-encoded items, not for those already encoded. When combined with the co-activation principles we discussed earlier, a resource-limited mechanism could explain the similarity effects we observed in this study. If similar items deplete fewer resources because they benefit from stronger co-activations, this mechanism predicts the proactive effects we observed.

Interference-based forgetting. An important theoretical framework postulates WM as being limited by interference (Oberauer et al., 2012, 2016). The computational equivalent of this account, SOB-CS, postulates that items are encoded in WM using position-item associations through Hebbian learning in a superimposed matrix. Due to this superimposition of representations, items retrieved from WM constitute a blurry version of the original ones. Limitations in WM occur because each newly encoded item interferes with the existing WM representations. One way SOB-CS could explain the beneficial impact of similarity is via a compression mechanism, as proposed by Thalmann et al. (2019). When similar items occur at the beginning of the list, they can be compressed and the no-more-relevant items can be easily and rapidly removed from WM (Lewis-Peacock et al., 2018), a phenomenon also called "wipe-out" (Ecker et al., 2014). This creates a proactive benefit due to a reduction of WM load. However, when the related items appear at the end of the list, specific item-position removal is difficult to perform (Oberauer, 2018) and the irrelevant items still interfere with the WM representations[7]. This creates an absence of retroactive benefit. Note that the plausibility of this explanation remains to be formally tested.

Retrieval-based account. In the context of immediate serial recall tasks, psycholinguistic effects such as the lexicality effect (i.e., recall advantage for words vs. nonwords) have been explained through the redintegration framework. Simply put, this account postulates the influence of long-term memory knowledge as occurring exclusively at the recall stage (Schweickert, 1993) through a comparison process between the degraded WM traces and stored long-term memory knowledge. This framework has shown to account for important effects, such as lexicality, word frequency (Hulme et al., 1997), and to some extent semantic relatedness

[7] These two phenomena (i.e., wipe-out and selective removal) can be compared to what happens in modern programming languages such as Matlab and Python: resetting values across a whole matrix is technically easier to do compared to selectively resetting values for specific indices. We thank Klaus Oberauer for suggesting this comparison.

(Saint-Aubin & Poirier, 1999). Similarly, it could be argued that the similarity effects we observed here could be explained by assuming that similar items re-activate each other via a cueing mechanism. Recalling “Item A” would automatically provide a cue for “Item B” when A and B are similar. However, a model that would consider that gains operate only at retrieval would not be able to explain proactive effects. To observe a proactive effect, there must be some gains at the time of processing similar items and a redistribution throughout the trial for the processing of other, non-similar items. Overall, the problem with a retrieval-based account is that it acts on the items locally, not globally.

The role of output interference. Finally, and in the same vein as the retrieval-based account, we cannot discard the possibility that the proactive benefits and absence of proactive effect observed in the present study could be at least partially explained by a reduction of output interference. In typical serial recall tasks, a significant part of memory traces is lost as people recall the items (Cowan et al., 2002; Oberauer, 2003). This could occur because recalling an item takes time (Cowan et al., 1992) or induce noise (Oberauer et al., 2012). Similarly, it could be argued that items that are easier to remember (i.e., the similar triplets in our experiments) could induce less time-based forgetting and/or noise. This in turn could proactively benefit the subsequent items when compared to a condition in which participants produce more errors. This is what we observed in a previous study (Kowialiewski, Lemaire, et al., 2021), where omission errors took more than twice the time to be recalled as compared to correct responses. There is evidence arguing against output interference as the sole contributor of the phenomena we observed. First, proactive effects in the semantic domain remain robustly observed when response time is taken as a regressor (Kowialiewski, Lemaire, et al., 2021). Second, we report in supplementary material an additional experiment and analyses suggesting that proactive effects in the visuospatial domain are not completely explained by the time it takes to recall the items. Third, the fact that proactive effects emerge during encoding is supported through the study conducted by Thalmann et al. (2019). They were able to deconfound the influence of chunking at encoding and recall, by testing WM performance independently of encoding position. They observed a robust proactive impact of chunking, regardless of the encoding position at which WM was assessed first. Fourth, the study by C. C. Morey et al. (2015) observed the usual benefit for dissimilar items, even though only one item was tested in each trial. The relative influence of output interference on proactive benefits remains to be quantified. This could be easily done in future studies, for instance by instructing participants to recall items in random order, or at specific serial positions.

Conclusion

It has long been known that the relationships between memoranda affect WM performance. Through a set of behavioral experiments, we proposed a specification of the underlying mechanisms that could explain similarity effects. The human cognitive system seems able to free up resources on the fly by taking advantage of similarities between memoranda to compress information. The important contribution of this work was to show that this phenomenon is observed regardless of the domain observed: semantic, phonological, visuospatial and visual. This study brings consistent support for WM representations as strongly interacting with maintenance mechanisms in any domain, and supports a domain-general functioning characterizing maintenance processes in WM.

Context

The complexity of the mechanisms responsible for working memory (WM) limitation has been the object of intensive investigations. Similarly, long-term memory knowledge is known to support the maintenance of information over the short-term in a very robust and consistent manner. However, the way WM maintenance mechanisms and long-term memory knowledge interact is poorly understood. This study is the emerging product of a collaborative project between SP and BL who are experts in the computational modeling of WM maintenance, and BK who is specialized on the impact of linguistic knowledge on WM. BK was hired as a postdoc on the “CHUNKED” project, whose aim is to understand the compression mechanisms occurring in working memory, with a strong focus on computational modeling. The common research interests between SP, BL and BK naturally led to assessing the impact of linguistic knowledge on WM maintenance in a previous study (Kowialiewski, Lemaire, et al., 2021). This was done by combining several main ideas already developed by all three authors (Kowialiewski & Majerus, 2020; Lemaire et al., 2018). The present study is the logical extension of this previous combined work, in an aim to generalize the core properties of WM functioning toward a larger range of domains.

Appendix A

In this analysis, we computed the proportion of *within-group transpositions*, following the same procedure used by Kowialiewski, Gorin & Majerus (2021). We first computed the total number of transposition errors occurring for items 1, 2 and 3 in the C1 condition, and items 4, 5 and 6 in the C2 condition. We then identified each error as being a within-group or between-group transposition. Within-group transpositions correspond to transpositions occurring between similar items (e.g., transposing “Item 1” at position 3 in the C1 condition). Between-group transpositions correspond to transpositions occurring outside of the similar triplet (e.g., transposing “Item 4” at position 3 in the C2 condition). We then divided the number of within-group transpositions by the total number of transpositions occurring for the similar items. This score gives an indication of the *pattern* of transposition errors occurring for the similar items. A score of 1.0 means that when a transposition occurred, it always did between two similar items. Both the C1 and C2 conditions were compared to the NC condition. To do this, two within-group transpositions analyses were performed in the NC condition: one analysis involved positions 1, 2 and 3 (for comparison with the C1 condition) and another one involved positions 4, 5 and 6 (for comparison with the C2 condition). If the triplets of similar items across Experiments 1, 2 and 3 modified the pattern of transposition errors, we should observe an increase of within-group transpositions in the C1 and C2 conditions, as compared to the same positions in the NC condition. Experiment 4 was not included in the analyses, as there is no straightforward way to track transposition errors in this study.

Across all analyses, we discarded 11, 2 and 11 data points from Experiments 1, 2 and 3, respectively. This is due to participants producing zero errors in one condition, leading to a score of 0/0. When a participant does not produce an order error, within-group transposition cannot be produced and hence was considered as missing data. To compensate for this lack of missing data, we used a Bayesian Repeated Measures ANOVA, which in the BayesFactor package, allows the inclusion of missing information without discarding an entire subject. The similarity condition (C1 vs. NC or C2 vs. NC) was treated as a within-subject factor.

Semantic relatedness. We found an increase of within-group transpositions when the items were semantically related, and this was supported by strong evidence when comparing the C1 and NC conditions (BF_{10} = 49.78, d = 0.776, M_{diff} = 0.327), and decisive evidence between the C2 and NC conditions (BF_{10} = 1.429e+8, d = 1.254, M_{diff} = 0.23).

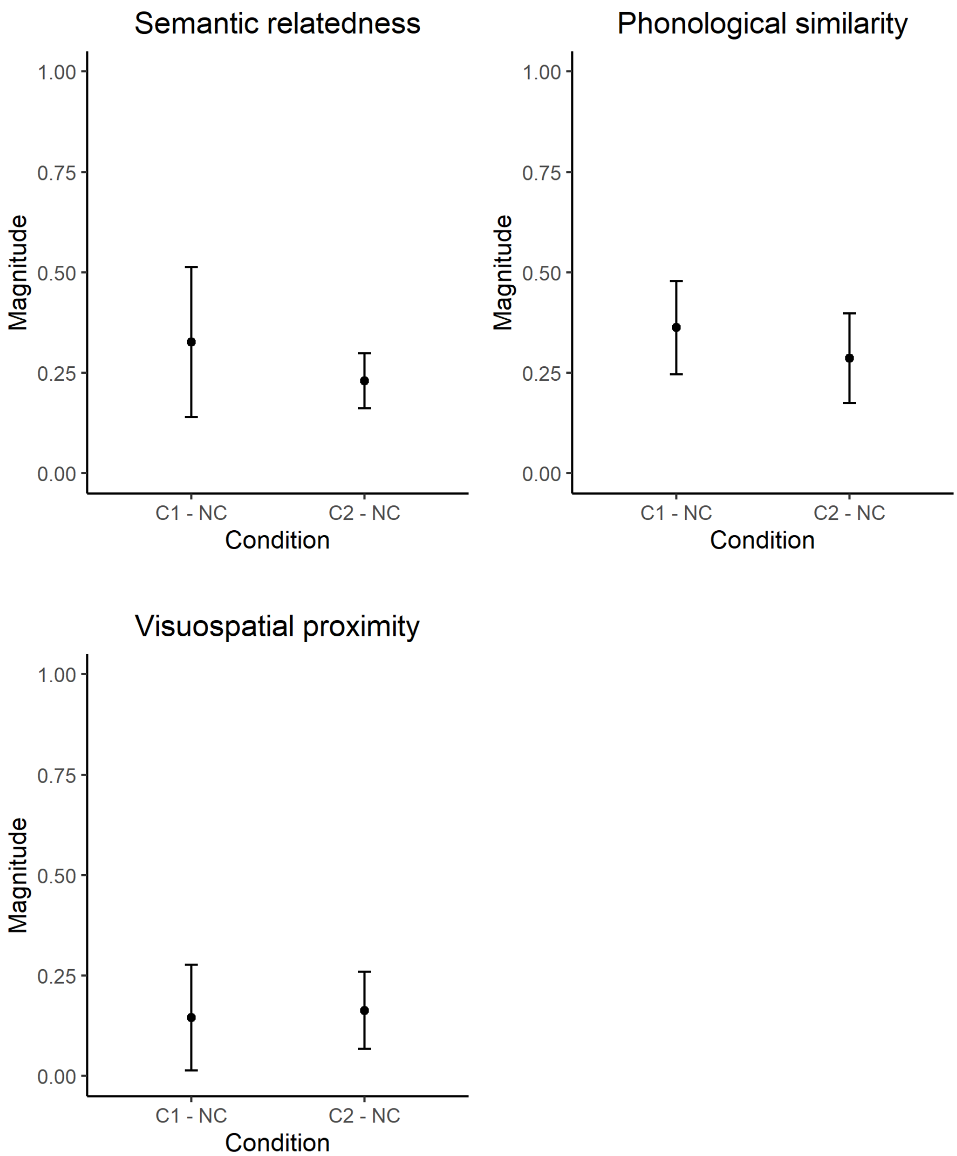
Phonological similarity. Decisive evidence supported a difference of within-group transpositions when items were similar, and this was observed in the C1 vs. NC conditions (BF_{10} = 1.583e+6, d = 1.193, M_{diff} = 0.362), and the C2 vs. NC conditions (BF_{10} = 1.441e+5, d = 0.983, M_{diff} = 0.286).

Visuospatial proximity. Similar results were found in the visuospatial domain, with similar items being associated with higher within-group transpositions than dissimilar items. This was supported by strong evidence when comparing the C1 and NC conditions (BF_{10} = 10.883, d = 0.504, M_{diff} = 0.146), and decisive evidence when comparing the C2 and NC conditions (BF_{10} = 128.02, d = 0.652, M_{diff} = 0.164).

These results, as illustrated in **Figure A1**, demonstrate a credible impact of similarity on the pattern of within-group transposition errors. When an item migrated, it did so more often at the position of another related item, rather than toward the position of another dissimilar item, and this as compared to the same positions of a dissimilar condition.

Figure A1

Magnitude of the difference between the C1 vs. NC and C2 vs. NC conditions across Experiments 1 (semantic relatedness), 2 (phonological similarity) and 3 (visuospatial proximity).



Note. Error bars not including zero indicate a credible difference between the two conditions.

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All the data and codes have been made available on the Open Science Framework: https://osf.io/y9xz2/.

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