## Title
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# Verbal Working Memory in Sentence Comprehension

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## Abstract

This paper investigates the nature of verbal working memory (WM) in sentence comprehension and provides evidence for overlapping pools of verbal WM resources between on-line sentence comprehension and other verbally-mediated tasks. We report the results of two dual-task experiments. In Experiment 1, participants simultaneously performed a self-paced reading task and a self-paced arithmetic addition task in a 2x2 design crossing syntactic complexity (low, high) and arithmetic complexity (low, high). In addition to two main effects, the most interesting result was a significant interaction between syntactic and arithmetic complexity during the critical region of the linguistic materials: participants processed the complex/complex condition more slowly than would be expected if the two tasks relied on independent resource pools. To address a potential confound of shared attentional resources, Experiment 2 was conducted, where participants simultaneously performed a self-paced reading task and a self-paced spatial-rotation task in a similar 2x2 design crossing syntactic complexity with the complexity of the spatial task. As in Experiment 1, there were two main effects of complexity in the critical region. However, in contrast to Experiment 1, these effects were strictly additive, with no trace of interaction. The results of the two experiments therefore support a WM framework where on-line linguistic processing and on-line arithmetic processing rely on overlapping pools of verbal WM resources.

## Introduction

A major question in psycholinguistic research concerns the nature of the working memory (WM) resources used in language processing. Empirical research has suggested that different pools of WM resources are used for processing visuo-spatial information and verbal information (e.g., Baddeley & Hitch, 1974; Baddeley, 1986; Vallar & Shallice, 1990; Hanley et al., 1991; Jonides et al., 1993; Shah & Miyake, 1996). Some researchers (Caplan & Waters, 1999; cf. Just & Carpenter, 1992) have hypothesized that the verbal WM pool can be further divided into two sub-pools: (1) verbal WM for natural language comprehension and production; and (2) verbal WM for non-linguistic verbally-mediated cognitive tasks. This paper attempts to empirically evaluate this hypothesis.

One way to address this question is via dual-task paradigms in which participants perform two tasks simultaneously: (1) on-line sentence processing, and (2) a non-linguistic verbally-mediated task. The underlying assumption is that we should observe a super-additive interaction when the complexity of both tasks is high only if the two tasks rely on overlapping pools of resources.

Previous dual-task experiments found either no interaction or only a suggestion of one (e.g. King & Just, 1991; Just & Carpenter, 1992; Caplan & Waters, 1999; Gordon et al., 2002). In all of the previous experiments, however, the secondary task involved storage of words or digits across the sentence-processing task. Although storage – in a very general sense of keeping track of previously encountered information – plays an important role in on-line sentence comprehension (e.g., Chomsky & Miller, 1963; Kimball, 1973; Gibson, 1991; 1998; Lewis, 1996), it may be qualitatively different from the kind of storage involved in the secondary tasks in the earlier experiments.

According to one recent resource-based theory of on-line syntactic processing, the dependency locality theory (DLT; Gibson, 1998, 2000), there are two working memory components to sentence comprehension: storage and integration. The *storage* component involves keeping track of partially processed syntactic dependencies that are still awaiting their second element in order for the sentence to be grammatical, whereas the *integration* component involves connecting a newly input word into the structure that has been built so far. Critically, the storage component of on-line sentence comprehension is unlike the storage involved in keeping track of a list of unconnected items. Consequently, it is possible that the lack of on-line interactions between syntactic complexity and memory load in earlier studies could be a result of the distinct nature of the storage processes involved. Moreover, there have been no previous attempts to explore the potential interaction between integration processes in sentence comprehension and secondary verbally-mediated tasks, which involve similar but non-linguistic on-line integration processes. In the current paper, we propose a novel paradigm to address this issue.

## Experiment 1

This experiment had a dual-task design, in which participants read sentences phrase-by-phrase, and at the same time were required to perform simple additions. The on-line addition task is similar to on-line sentence comprehension in that an incoming element – a number – must be integrated into (i.e., added to) the representation constructed thus far: the working sum. Both tasks had two levels of complexity, resulting in a 2x2 design. Critically, there was no difference in linguistic complexity between the easy and hard arithmetic conditions: the complexity of the arithmetic task was manipulated in terms of the difficulty of the arithmetic operations (by making the addends larger), while keeping the linguistic form of the two conditions identical (number + number + number, etc.). Therefore, if we observe a super-additive interaction between the two tasks when the complexity of both tasks is high, then we may infer that the verbal WM resources that are involved in performing the arithmetic task overlap with those that are involved in syntactic integration processes. In contrast, if language processing relies on an independent verbal WM resource pool, there should be no such interaction.

### Methods

**Participants** Forty participants from MIT and the surrounding community were paid for their participation. All were native speakers of English and were naive as to the purposes of the study.

**Design and materials** The experiment had a 2x2 design, crossing syntactic complexity (subject-extracted relative clauses (RCs), object-extracted RCs) with arithmetic complexity (simple additions (low initial addend, consequent addends between 1 and 3) vs. complex additions (higher initial addend, consequent addends between 4 and 6)).

The language materials consisted of 32 sets of sentences, having four different versions as in (1):

(1) a. *Subject-extracted, version 1*:
The janitor | who frustrated the plumber | lost the key | on the street.
b. *Subject-extracted, version 2*:
The plumber | who frustrated the janitor | lost the key | on the street.
c. *Object-extracted, version 1*:
The janitor | who the plumber frustrated | lost the key | on the street.
d. *Object-extracted, version 2*:
The plumber | who the janitor frustrated | lost the key | on the street.

As described above, there were only two levels of syntactic complexity – subject- and object-extractions – but there were four versions of each sentence in order to control for potential plausibility differences between the subject- and object-extracted versions of each sentence. As a result, no independent plausibility control is needed in this design. Each participant saw only one version of each sentence, following a Latin-Square design.

The numbers for the addition task were randomly generated online for each participant with the following constraints: (1) the value of the initial addend in the easy-math condition varied from 1 to 10, whereas the value of the initial addend in the hard-math condition varied from 11 to 20, and (2) the addends varied from 1 to 3 in the easy-math condition and from 4 to 6 in the hard-math condition.

In addition to the target sentences, 40 filler sentences with various syntactic structures other than relative clauses were included. The length and syntactic complexity of the filler sentences was similar to that of the target sentences. The stimuli were pseudo-randomized separately for each participant, with at least one filler separating the target sentences.

**Procedure** The task was self-paced phrase-by-phrase reading with a moving-window display (Just, Carpenter & Woolley, 1982). The experiment was run using the Linger 2.85 software by Doug Rohde. Each experimental sentence had four regions (as shown in (1a)-(1d)): (1) a noun phrase, (2) an RC (subject-/object-extracted), (3) a main verb with a direct object (an inanimate noun phrase) and (4) an adjunct prepositional phrase. The addends for the addition task were presented simultaneously with the sentence fragments, above and aligned with the second character of each fragment. The first sentence region had a number above it (e.g. "12") and all the consequent regions had a plus sign followed by a number (e.g. "+4"), as shown in Figure 1.

| | | | | |
|---|---|---|---|---|
| Time 1: | 12<br>The janitor | --- ---------- --- ------- | ---- --- --- | -- --- ------. |
| Time 2: | --- ------- | +4<br>who frustrated the plumber | ---- --- --- | -- --- ------. |
| Time 3: | --- ------- | --- ---------- --- ------- | +5<br>lost the key | -- --- ------. |
| Time 4: | --- ------- | --- ---------- --- ------- | ---- --- --- | +4<br>on the street. |

Figure 1: Sample frame-by-frame presentation of an item.

Each trial began with a series of dashes marking the length and position of the words in the sentence. Participants pressed the spacebar to reveal each region of the sentence. As each new region appeared, the preceding region disappeared along with the number above it. The amount of time the participant spent reading each region and performing the accompanying arithmetic task, was recorded as the time between key-presses.

To make sure the participants performed the arithmetic task, a window appeared at the center of the screen at the end of each sentence and the participants were asked to type in the sum of their calculations. If the answer was correct, the word "CORRECT" flashed briefly on the screen, if the answer differed by up to 2 from the correct sum, the word "CLOSE" flashed briefly, and if the answer was off by more than 2, the word "INCORRECT" flashed briefly on the screen. To assure that the participants read the sentences for meaning, two true-or-false statements were presented sequentially after the sum question, asking about the propositional content of the sentence they just read. Participants pressed one of two keys to respond "true" or "false" to the statements. After a correct answer, the word "CORRECT" flashed briefly on the screen, and after an incorrect answer, the word "INCORRECT" flashed briefly.

Participants were instructed not to concentrate on one task (reading or additions) more than the other. They were asked to read sentences silently at a natural pace and to be sure that they understood what they read. They were also told to answer the math and sentence questions as quickly and accurately as they could, and to take wrong answers as an indication to be more careful.

Before the experiment started, a short list of practice items and questions was presented in order to familiarize the participants with the task. Participants took approximately 35 minutes to complete the experiment.

## Results

**Arithmetic accuracy** Participants answered the arithmetic sum correctly 88.7% of the time. A two-factor ANOVA crossing arithmetic complexity (easy, hard) and syntactic complexity (easy, hard) on these question-answering data revealed a main effect of arithmetic complexity ($F1(1,39)=9.45$; $MSe=0.120$; $p < .005$; $F2(1,31)=7.21$; $MSe=0.087$; $p < .02$), but no other significant effects.

**Comprehension question performance** There were two comprehension questions following each experimental trial. Participants answered the first question correctly 80.2% of the time, and the second question 78.1% of the time. The percentages of correct answers by condition were very similar for the two questions, so we collapsed the results in our analyses. A two-factor ANOVA crossing arithmetic complexity (easy, hard) and syntactic complexity (easy, hard) on the responses to the two comprehension questions revealed a main effect of syntactic complexity ($F1(1,39)=9.8$; $MS=0.1$; $p < .005$; $F2(1,31)=4.04$; $MS=0.074$; $p=.05$) and a main effect of arithmetic complexity in the participants analysis ($F1(1,39)=4.31$; $MS=0.047$; $p <.05$; $F2(1,31)=2.9$; $MS=0.042$; $p =.10$), but no significant interaction ($Fs < 1$).

**Reaction times** Because participants had to answer three questions (one math, two language) for each sentence, the odds of getting all three correct were not very high overall (55.6%). As a result, we analyzed all trials, regardless of how the comprehension questions were answered. The data patterns were very similar in analyses of smaller amounts of data, in which we analyzed (1) trials in which one or both of the language comprehension questions were answered correctly, or (2) trials in which the math question was answered correctly. To adjust for differences in word length as well as overall differences in participants' reading rates, a regression equation predicting reading times from word length was derived for each participant, using all filler and target items (Ferreira & Clifton, 1986; see Trueswell, Tanenhaus & Garnsey, 1994, for discussion). At each word position, the reaction time predicted by the participant's regression equation was subtracted from the actual measured reaction time to obtain a residual reaction time. The statistical analyses gave the same numerical patterns for analyses of raw reaction times. Reaction time data points that were less than 100 msec in the raw data (indicating erroneous key presses) or more than 2.5 standard deviations away from the mean residual RT for a position within a condition were excluded from the analysis, affecting 3.3% of the data. Figure 2 presents the mean residual RTs per region across the four conditions of the experiment.

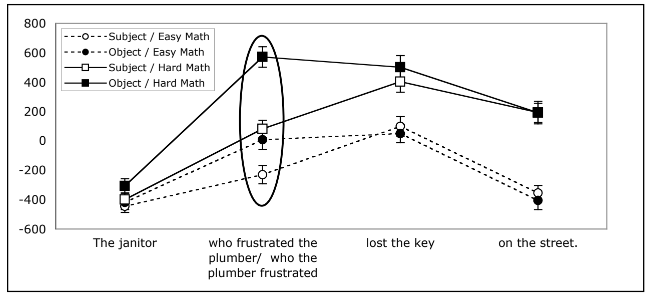


Figure 2: Reaction times per region in the four conditions of Experiment 1. The critical region is circled.

We present the analysis of the critical region (Region 2) first, followed by the analyses of the other regions. The critical region included the RC ("who frustrated the plumber" / "who the plumber frustrated"). A 2x2 ANOVA (easy-math / hard-math, subject-extracted RC / object-extracted RC) in this region revealed two significant main effects and a significant interaction. First, the hard-math conditions were read significantly slower than the easy-math conditions ($F1(1,39)=47.26$; $MSe=7641827$; $p < .001$; $F2(1,31)=42.58$; $MSe=5880083$; $p < .001$). Second, the syntactically more complex object-extracted RC conditions were read significantly slower than the subject-extracted conditions ($F1(1,39)=38.74$; $MSe=5283587$; $p < .001$; $F2(1,31)=33.4$; $MSe=4072481$; $p < .001$). Third, and most interestingly, there was a significant interaction, such that in the hard math conditions, the difference between subject- and object-extracted RCs was larger than in the easy math conditions ($F1(1,39)=4.74$; $MSe=623599$; $p < .05$; $F2(1,31)=7.15$; $MSe=526415$; $p < .02$). This interaction is predicted by the hypothesis whereby sentence processing and arithmetic processing rely on overlapping pools of resources, but not by the hypothesis that the pools of resources are independent.

In Region 1, consisting of the main clause subject (e.g., "The janitor") together with the initial addend, a 2x2 ANOVA revealed a main effect of arithmetic complexity (marginal in the items analysis), but no other significant effects. The hard-math conditions were read slower than the easy-math conditions ($F1(1,39)=5.08$; $MSe=245326$; $p < .05$; $F2(1,31)=3.62$; $MSe=149836$; $p = .067$). In Region 3, the top-level verb and its object ("lost the key"), a 2x2 ANOVA revealed a main effect of arithmetic complexity ($F1(1,39)=30.21$; $MSe=5726294$; $p < .001$; $F2(1,31)=33.32$; $MSe=3978352$; $p < .001$), but no other effects. Finally, in

Region 4, the sentence-final prepositional phrase ("on the street"), there was again an effect of arithmetic complexity ($F1(1,39)=72.58$; $MSe=13066602$; $p < .001$; $F2(1,31)= 105.06$; $MSe=10545386$; $p < .001$), but no other effects.

## Discussion

The results of Experiment 1 are consistent with a WM framework where online sentence comprehension and arithmetic processing rely on overlapping resource pools. Most importantly, there was an interaction between syntactic complexity and arithmetic complexity in the critical region of the linguistic materials, where syntactic complexity was manipulated between subject-extracted RCs (low complexity) and object-extracted RCs (high complexity). There was no evidence of any interaction of this kind in any of the other three regions. Critically, linguistic complexity was not varied in the arithmetic task, so the observed interaction is not due to an overlap in the linguistic processes that are involved in the two tasks.

It should be noted, however, that there is an alternative explanation for the observed pattern of results in terms of attentional resources required for the simultaneous performance of the two tasks. In dual-task paradigms, resources are needed in order to direct attention to one task or another. It is possible that in the difficult conditions, more attention switches are required, or the switches between tasks are more costly. The observed interaction could therefore be a result of additional task-switching costs in the high syntactic complexity / high arithmetic complexity condition. Experiment 2 was designed to address this issue.

# Experiment 2

This experiment used a similar dual-task paradigm as the first experiment. In contrast to Experiment 1, however, the secondary task was a spatial-rotation task matched for difficulty with the addition task used in Experiment 1. In this task, participants were instructed to visually imagine adding different-size sectors of a circle and to keep track of the angle subtended by the combined segments. The most natural way to solve this task is to mentally rotate each incoming sector until it abuts the estimated sum of the previous sectors. The on-line spatial-rotation task is similar to the addition task in that an incoming element – a sector – must be integrated into, or added to, the representation constructed thus far. Critically though, the spatial-rotation task does not rely on verbal WM resources, and should not therefore interact with the sentence-processing task if the cause for the observed interaction in Experiment 1 is an overlap in the use of verbal WM resources. However, if the attentional costs are responsible for the interaction, we should observe a similar interaction, regardless of the nature of the secondary task.

## Methods

**Participants** Twenty-four participants from MIT and the surrounding community were paid for their participation. All were native speakers of English and were naive as to the purposes of the study. None of the participants took part in Experiment 1.

**Design and materials** The experiment had a 2x2 design, crossing syntactic complexity (subject-/ object-extracted RCs) with the complexity of the spatial-rotation task (simple rotations with small-angle sectors/ complex rotations with larger-angle sectors). The language materials were exactly the same as those used in Experiment 1.

The sectors for the spatial-rotation task were randomly generated online for each participant in the following way: the size of the sectors for the easy condition varied from 5 to 90 degrees, whereas the size of the sectors for the hard condition varied from 30 to 180 degrees. As a result, it was more likely in the hard condition for the sum of sectors to be more than 360 degrees, thus "wrapping around" the circle. Pilot testing of the pie task by itself suggested that the task is easier to perform with smaller sectors.

As in Experiment 1, 40 filler sentences with various syntactic structures other than relative clauses were included, and the stimuli were pseudo-randomized separately for each participant, with at least one filler separating the target sentences.

**Procedure** The procedure was identical to that of Experiment 1, except for substituting the spatial-rotation task for the arithmetic task. Above each sentence fragment, participants saw a small circle. They were instructed to think of it as a plate for a pie. On each "plate", there was a "pie-slice" shown in blue. The size of the "pie-slices" varied (as described in Materials and Design above), but they all started at the 12:00 position, as shown in Figure 3.

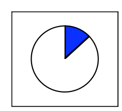

Figure 3: Sample figure of the spatial-rotation task.

Participants were instructed to visually imagine adding each new "pie-slice" to the previous one(s) by mentally "putting" them next to each other. To assure that the participants performed the task, at the end of each trial a large blank circle appeared at the center of the screen with a vertically-pointing radius. Participants were instructed to drag this radius (by using the mouse) to the end-point where all the "pie-slices" they just saw would come to when placed next to each other. If the answer was within 10 degrees of the correct answer, the words "Very Close!" flashed briefly on the screen; if the answer was within 35 degrees, the words "Pretty Good" flashed briefly; if the answer was within 90 degrees, the words "In The Ballpark" flashed briefly; finally, if the answer was not within 90 degrees, the words "Not Very Good" flashed briefly on the screen. The participants were warned that sometimes the "pie-slices", when added together, would form more than a complete pie. In such cases, they were told to assume that the slices "wrapped around" and to ignore the complete portion of the pie.

As in Experiment 1, this task was followed by two comprehension questions about the content of the sentences.

## Results

**Spatial-rotation task accuracy** On average, participants' estimates were 30.3 degrees off of the correct answer. A two-factor ANOVA crossing spatial-rotation task complexity (easy, hard) and syntactic complexity (easy, hard) revealed a main effect of complexity of the spatial-rotation task ($F1(1,23)=18.36$; $MSe=2676$; $p < .0005$; $F2(1,31)=22.28$; $MSe=3568$; $p < .0005$), but no other significant effects. It is worth noting that this pattern of results for the spatial-rotation task accuracy is parallel to that of the results for the arithmetic task accuracy in Experiment 1.

**Comprehension question performance** There were two comprehension questions following each experimental trial. The percentages of correct answers by condition were very similar for the two questions, so we collapsed the results in our analyses. Across conditions, participants answered the questions correctly 83% of the time. A 2x2 ANOVA crossing spatial-rotation task complexity (easy, hard) and syntactic complexity (easy, hard) on the responses to the comprehension questions revealed no significant effects or interactions ($Fs<1$). This pattern of results differs slightly from that in Experiment 1 in that there was no effect of syntactic complexity in Experiment 2. Note, however, that overall, subjects performed better on comprehension questions in Experiment 2 (83% across conditions), compared with Experiment 1 (79% across conditions). This accuracy difference across the experiments may have resulted from greater interference of the secondary task in Experiment 1 with subjects' memory of the propositional content of the sentences, due to its verbal nature. The lack of syntactic complexity effect in Experiment 2 could then be explained by a possible ceiling effect in the comprehension performance: without a verbally interfering task, people perform well on both the subject- and object-extracted relative clause sentence types.

**Reaction times** As in Experiment 1, we analyzed all trials, regardless of how the comprehension questions were answered. Also, as in Experiment 1, reaction time data points that were more than 2.5 standard deviations away from the mean residual RT for a position within a condition or less than 100 msec in the raw data were excluded from the analyses, affecting 3.7% of the data. Figure 4 presents the mean reaction times per region across the four conditions in the experiment.

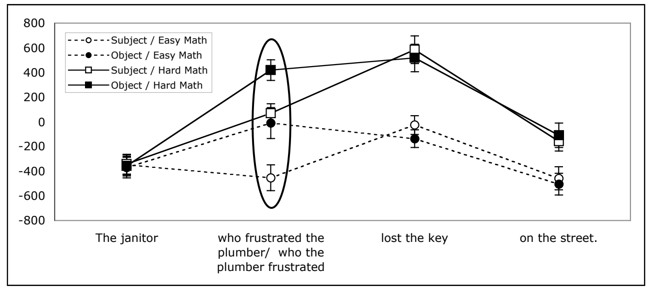


Figure 4: Reaction times per region in the four conditions of Experiment 2. The critical region is circled.

We first present the analysis of the critical region, Region 2, which included the RC ("who frustrated the plumber" / "who the plumber frustrated"). A 2x2 ANOVA conducted on this region revealed two significant main effects. First, the hard-spatial-task conditions were read significantly slower than the easy-spatial-task conditions ($F1(1,23)=22.98$; $MSe=5451605$; $p < .001$; $F2(1,31)=40.08$; $MSe=6428277$; $p < .001$). Second, the syntactically more complex object-extracted RC conditions were read significantly slower than the subject-extracted RC conditions ($F1(1,23)=15.59$; $MSe=3791349$; $p < .001$; $F2(1,31)=22.94$; $MSe=4675397$; $p < .001$). Critically, there was no trace of an interaction between syntactic complexity and the complexity of the spatial task ($Fs<1$). Moreover, the effect of syntactic complexity in the hard-spatial-task conditions was numerically *smaller* than that in the easy-spatial-task conditions. This result rules out the attentional explanation of the interaction that was observed in Experiment 1.

In Region 1, consisting of the main clause subject (e.g., "The janitor") together with the initial "pie-slice", a 2x2 ANOVA revealed no significant effects. In Region 3, the top-level verb and its object ("lost the key"), a 2x2 ANOVA revealed a main effect of spatial task complexity ($F1(1,23)=39.36$; $MSe=9601145$; $p < .001$; $F2(1,31)=62.5$; $MSe=12710598$; $p < .001$), but no other effects. Finally, in Region 4, the sentence-final prepositional phrase ("on the street"), there was again an effect of spatial task complexity ($F1(1,23)=16.1$; $MSe=2925378$; $p < .001$; $F2(1,31)=45.2$; $MSe=4061993$; $p < .001$), but no other effects.

## Discussion

The attentional account of the interaction between syntactic and arithmetic complexity that was observed in Experiment 1 predicted a similar interaction between syntactic and spatial-rotation complexity in Experiment 2. No such interaction was observed. In fact, the numerical trend was in the reverse direction. The lack of such an interaction therefore argues against the attentional account of the interaction observed in Experiment 1.

In general, the lack of an interaction between the complexity of two tasks could arise for at least two different reasons: (1) independent resource pools required for each task; or (2) ceiling or floor effects on one or both of the tasks, such that resources are either abundant or insufficient. Hence, in order to argue that the results of Experiment 2 are due to independent resource pools for the two tasks, we need to be confident that the secondary task is neither too complex nor too simple. It is unlikely that the spatial-rotation task is too simple, because we observed a highly significant complexity effect for this task. Neither is it likely that the spatial-rotation task is too complex for the following reasons. First, the performance on the spatial-rotation task was extremely good, averaging only 30.3 degrees off from the target position. Second, the range of the reaction times across conditions for the two experiments was almost identical, suggesting that the arithmetic and spatial-rotation tasks were comparable in difficulty.

## Conclusions

In summary, using a dual-task paradigm, we have demonstrated an on-line interaction between syntactic complexity and arithmetic complexity in Experiment 1 suggesting that these two cognitive functions rely on overlapping pools of verbal WM resources. Furthermore, in Experiment 2, we have ruled out an attentional account of the observed interaction by showing that a spatial task, which does not rely on verbal WM resources, does not interact with on-line sentence comprehension. These results therefore support a WM framework in which sentence processing and arithmetic processing overlap in the use of verbal WM resources. The results are not consistent with the hypothesis whereby sentence processing relies on an independent pool of verbal WM resources (Caplan & Waters, 1999).

An open question that we have not yet addressed is the exact nature of the overlap in verbal working memory resources for sentence and arithmetic processing. One possibility is that both syntactic and arithmetic processes involve a subservant mechanism for integrating verbal symbolic information units. In this mechanism, the difficulty of integrating linguistic elements depends on the distance between elements to be connected. Relatedly, the difficulty of adding numbers depends on the distance between the initial addend and the resulting sum in the computation on the number line. We leave it to future work to distinguish this hypothesis from other possibilities.

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