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Do Do Do, The The The: Interactivity and Articulatory Suppression in Mental Arithmetic

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Abstract

Doing long sums in the absence of complementary actions or artefacts is a multi-step procedure that quickly taxes working memory; congesting the phonological loop further handicaps performance. In the experiment reported here, participants completed long sums either with hands down—the low interactivity condition—or by moving numbered tokens—the high interactivity condition—while they repeated 'the' continuously, loading the phonological loop, or not. As expected, articulatory suppression substantially affected performance, but more so in the low interactivity condition. Independent measures of basic arithmetic skill and mathematics anxiety moderated the impact of articulatory suppression on performance in the low but not in the high interactivity condition. These findings suggest that working memory resources are augmented with interactivity, underscoring the importance of characterizing the properties of the system as it is configured by the dynamic agent-environment coupling.

Keywords: Interactivity, Mental Arithmetic, Articulatory Suppression, Working Memory, Systemic Cognition

Introduction

Different components of working memory are engaged in doing long sums without external aids or complementary actions (Raghubar, Barnes, & Hecht, 2010). The exact involvement of these components depends on the complexity of the arithmetic task, the presentation format and modality of presentation, as well as the agent's level of mathematical competence (DeStefano & LeFevre, 2004). Take the task of adding a long series of single-digit numbers presented visually all at once in a random pattern. The requisite arithmetic skills to compute the correct total are certainly mastered by numerate young adults. However, calculating the correct answer in a multi-step procedure requires temporary storage and executive skills: interim totals are calculated and rehearsed, numbers tagged as having been added, others tagged as not, attention allocated to certain areas of the visual presentation or switched to others to identify what number or the easiest number to add next, arithmetic knowledge retrieved from long term memory to facilitate the identification of congenial sub-totals. Some of these processes rely on the sub-vocal rehearsal of cumulative interim sums. It is no surprise that loading the phonological loop in dual-task paradigms interferes with mental arithmetic that requires counting (Fürst & Hitch, 2000; Logie, Gilhooly, & Wynn, 1994).

Complementary Actions and Interactivity

The role of working memory in mental arithmetic is traditionally established with an experimental procedure that limits or prevents participants from modifying the problem presentation in working out an answer. These research efforts reflect a commitment to a representational and internalist model of cognitive processing. In order to create an unadulterated window onto the processes implicated in mental arithmetic and to permit the clinical precision of their segmentation, simple problems devoid of content are presented in a manner that cannot be modified by the agent. However, once released from the confines of the cognitive psychologist's laboratory, mental arithmetic is often situated (Lave, 1988) and naturally supported by a range of complementary actions, such as pointing, to guide attention and bind elements in a functional sequence (Kirsh, 1995, Carlson, Avraamides, Cary, & Strasberg, 2007). Gesturing can also lighten the cognitive load: individuals who were not allowed to gesture while explaining how they solved a mathematical problem also exhibited poorer recall on an interfering memory task compared to individuals who were allowed to gesture (Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001).

Interacting with an external representation of the problem can modify its physical presentation and the agent's "mental" computations are reflected in the dynamic changes in the problem's appearance. Imagine, again, adding a long series of single digit numbers, however, this time, the numbers do not configure a static visual presentation, but rather adorn the face of wooden tokens creating a malleable physical configuration which participants can modify as they work on the problem. The calculation unfolds along a spatio-temporal itinerary wrought by the agent's actions. These actions modify the problem presentation and in doing so the problem is restructured, added numbers can be physically demarcated, no longer exerting attentional pull, congenial interim totals (e.g., 8+7) are identified and physically segregated, shifting the affordances of what to do next, guiding the agent to identify complementary sub-totals (e.g., 9+6), that inter-lock to create easy-to-remember provisional sums (e.g., 30), improving efficiency and reducing error. Thus, the dynamic reconfiguration of the problem guides, in part, the allocation of attentional resources and strategy selection (Vallée-Tourangeau, 2013).

The Present Experiment

The present experiment employed a dual-task procedure to explore the impact of articulatory suppression in a mental arithmetic task. The task involved adding 11 single-digit numbers presented either as a static configuration (a low interactivity condition) or as a set of number tokens that could be manipulated in calculating the answer (a high interactivity condition). Participants completed the task either with articulatory suppression—by repeating aloud 'the' continuously— or without. Thus the experiment employed a 2(Interactivity: Low, High) × 2(Articulatory Suppression: Without, With) design with both factors as repeated measures. Past research findings led us to expect poorer performance with articulatory suppression, but better performance with interactivity. If interactivity augments an agent's working memory capacity, the impact of articulatory suppression on performance should be mitigated in the high interactivity condition, such as to result in an interaction between the two factors: The performance advantage conferred by a high degree of interactivity should be greater with articulatory suppression than without.

We also profiled participants in terms of their (i) basic arithmetic skills, (ii) level of mathematics anxiety, and (iii) executive function with an attention-switching task. We used these concomitant variables to determine whether they were moderators of the impact of suppression on mental arithmetic, and whether the moderation was the same in the low and high interactivity condition. We expected all three variables to moderate the impact of suppression primarily in the low interactivity condition; if a higher degree of interactivity augments working memory resources, then participants' performance would be more resilient and the moderating properties of these factors might be attenuated.

Method

Participants

Fifty-two Kingston University psychology undergraduate and postgraduate students (45 females) participated in the experiment in exchange for course credits (M_{age} = 21.8, *SD* = 4.0).

Materials and Measures

Arithmetic Task. Participants were invited to add series of 11 single digits. For each sum the digits were arrayed in a random cloud pattern, and were presented either on a sheet of A4 or as identically-arranged wooden tokens. Participants were instructed to calculate the sum as quickly as they could and announce their answer to an experimenter. They did so either with their hands flat on the table top in front of them and were not allowed to use their fingers to count or point (low interactivity) or by moving the tokens about as they saw fit in producing an answer (high interactivity). Performance on this arithmetic task was measured in terms of accuracy—percentage correct and absolute calculation error—solution latencies and efficiency. Participants' efficiency at calculating the sums was measured as the ratio of their accuracy—percentage correct—over the resources invested in arriving at the answer. The later was operationalized as the proportion of time taken to announce an answer out of the maximum of time to do so as indexed by the average latency of the slowest quartile. Thus, if a participant's accuracy was 80%, taking an average of 60 seconds to announce an answer, and that the average latency for the slowest quartile was 80 seconds, that participant's efficiency ratio would be 80%/(60/80) or 80%/75%, hence 1.067. A ratio of 1 or greater indicates efficient performance, whereas a ratio below 1 indicates inefficient performance.

Mathematics Anxiety Scale. Participants completed a 25-item Mathematics Anxiety Scale-UK (MAS-UK; Hunt, Clark-Carter & Sheffield, 2011). The questionnaire invited participants to imagine how anxious they would feel in certain situations (1 = "not at all" and 5 = "very much"), such as "Working out how much your shopping bill comes to" or "Taking a maths exam".

Basic Arithmetic Skill. Basic arithmetic skill was measured by having participants complete as many of 45 simple expressions (such as 11-9 = ?) in a 60-second period.

Executive Function: Shifting. The plus-minus task reported in Miyake, Friedman, Emerson, Witzki and Howerter (2000) was employed to measure attention switching skills. With three different series of 30 double-digit numbers, participants were instructed to add 3 to each in the first series, subtract 3 to each in the second series, and alternate between adding and subtracting 3 with the third series. The switching cost, measured in seconds, was the difference in completion time for the third series minus the average completion time for the first two. Larger differences indicated poorer switching skills.

Procedure

Ten different sums of 11 single-digits were created: none of the sums were the same and totals ranged from 57 to 80. From these, five were randomly selected and allocated to the low interactivity condition, and the other five to the high interactivity condition for each participant. Participants completed these five sums twice within each level of interactivity: Once with articulatory suppression, once without. Thus the design employed was a 2 (Interactivity: Low, High) × 2 (Articulatory Suppression: Without, With) repeated measures. The order of the four conditions for each participant was constructed as follows: One of the four conditions was randomly selected to be the first condition experienced by the participant. Once that first condition was identified, the order of the other three was determined by the following constraint: conditions with the same level of interactivity could not be presented in succession (e.g., the two high interactivity conditions experienced consecutively). For example, if the condition with low interactivity and with articulatory suppression was the first condition experienced by a participant then the remaining conditions could be presented in the following order: (ii) high interactivity without articulatory suppression; (iii) low interactivity without articulatory suppression; (iv) high interactivity with articulatory suppression. As a result, participants never calculated the same set of five sums in succession. The first presentation of a condition with articulatory suppression was always preceded by a training task during which participants were asked to write successive subtractions of 3 starting from 100 for one minute while continuously repeating 'the'. The instructions read: "You will be presented with 5 addition problems involving single digit numbers. For each of the problems, you must add the digits as quickly and as accurately as you can". The low interactivity instructions then read "During this task you will be required to keep your hands flat on the table and must not move them for the duration of this task" while the high interactivity instructions read: "During this task you will be able to manipulate the tokens as you see fit for this task". Participants experienced each interactivity condition twice, once with articulatory suppression, once without. The articulatory suppression instructions read: "You will also be required to repeat the word "the" throughout the duration of the task as you did in the practice task. You can start repeating the sound and calculating the sums when prompted". Participants were instructed to announce their answer to the experimenter once completed. In the articulatory suppression conditions if more than two seconds elapsed without participants engaging in the secondary task, they were prompted to comply with the task. Finally, the presentation of each condition was separated by the completion of either the Basic Arithmetic Skill test, the Mathematics Anxiety Scale, or the Attention Switching task; the order of these three tasks was counterbalanced across participants.

Results

Mental Arithmetic Performance

Participants' performance was measured in terms of the percentage of sums correctly solved (out of five), the average absolute calculation error, the average latency to solution, and the efficiency ratio in each of the four conditions.

Percentage Correct. The mean percentage of correct additions in the four experimental conditions are reported in the top portion of Table 1. As expected, participants were better at providing correct answers in the absence of articulatory suppression; however performance was always better in the high interactivity condition. In addition, the decline in performance with articulatory suppression appeared steeper in the low interactivity condition. A 2×2 repeated measures analysis of variance (ANOVA) confirms these impressions: The main effect of suppression was significant, $F(1, 51) = 60.1$, $p < .001$, $\eta_p^2 = .54$, as was the main effect of interactivity, $F(1, 51) = 13.6$, $p = .001$, $\eta_p^2 = .21$; the interaction was also significant, $F(1, 51) = 4.06$, $p = .049$, $\eta_p^2 = .07$.

Absolute Calculation Error. The mean absolute calculation error in the four conditions are plotted in Figure 1. These data illustrate a substantial effect of suppression, with larger deviations from the correct answers recorded with suppression than without. Errors were generally smaller in the high interactivity condition, and more important, articulatory suppression appeared not to have as dramatic an impact on calculation accuracy in the high interactivity condition. In a 2×2 repeated measures ANOVA the main effects of suppression, $F(1, 51) = 36.2$, $p < .001$, $\eta_p^2 = .42$ and interactivity, $F(1, 51) = 9.69$, $p = .003$, $\eta_p^2 = .16$, were significant, as was the interaction, $F(1, 51) = 6.02$, $p = .018$, $\eta_p^2 = .11$.

Solution Latency. The mean solution latencies are reported in the middle portion of Table 1. In the absence of articulatory suppression, solution latencies were similar in the low and high interactivity conditions. And while participants were generally slower with articulatory suppression, they were slowest in the high interactivity condition. The 2×2 repeated measures ANOVA revealed a significant main effect of suppression, $F(1, 51) = 16.4$, $p < .001$, $\eta_p^2 = .25$, a significant main effect of interactivity, $F(1, 51) = 11.5$, $p < .001$, $\eta_p^2 = .19$, as well as a significant interaction, $F(1, 51) = 18.6$, $p < .001$, $\eta_p^2 = .27$.

Table 1: Mean and standard deviation for the percentage correct, latency (measured in seconds), and efficiency ratio for the five sums in the low and high interactivity condition without and with articulatory suppression.

	Articulatory Suppression			
	Without		With	
	Percentage Correct			
Interactivity	*M*	*SD*	*M*	*SD*
Low	56.0%	27.7%	26.9%	31.7%
High	63.5%	28.2%	44.6%	29.5%
	Latencies			
	M	*SD*	*M*	*SD*
Low	38.1	16.4	41.5	21.2
High	37.4	14.8	51.2	27.2
	Efficiency Ratio			
	M	*SD*	*M*	*SD*
Low	1.20	0.99	0.68	0.95
High	1.16	0.70	0.99	0.84

Efficiency Ratio. The mean efficiency ratios are reported in the bottom portion of Table 1: Participants were much more efficient in the absence of articulatory suppression, and efficiency declined sharply with suppression. However, in the high interactivity condition, participants' efficiency ratio remained good even with articulatory suppression. A 2×2 repeated measures ANOVA supported these impressions: The main effect of suppression was significant, $F(1, 51) = 32.8$, $p < .001$, $\eta_p^2 = .39$, but the main effect of interactivity was not, $F(1, 51) = 2.61$, $p = .113$, $\eta_p^2 = .05$; however, the interaction between suppression and level of interactivity was significant, $F(1, 51) = 7.47$, $p = .009$, $\eta_p^2 = .13$.

Moderators of the Impact of Suppression on Calculation Error

Participants were profiled in terms of their basic arithmetic skills, level of math anxiety and executive function using an attention switching task. To test our moderation hypotheses we conducted a moderation analysis for within-subject design using ordinary least square regression with difference scores, as proposed and formalized by Judd, Kenny and McClelland (2001). This was a preferred solution for the current experiment with a sample size that is not optimal for a multilevel modelling. Judd et al. suggested that the moderation in within-subject designs occurs when a concomitant variable (e.g., basic arithmetic skill, or math anxiety level) predicts differences in performance between two conditions. Thus we determined how these variables moderated the difference in performance with and without articulatory suppression (within each level of interactivity, and then by collapsing level of interactivity). Table 2 reports the correlations between each of the concomitant variables and the difference in absolute calculation errors between the condition with articulatory suppression and the condition without, when interactivity level is low, high, and when collapsing over the two levels of interactivity ($df = 50$ for all correlation coefficients).

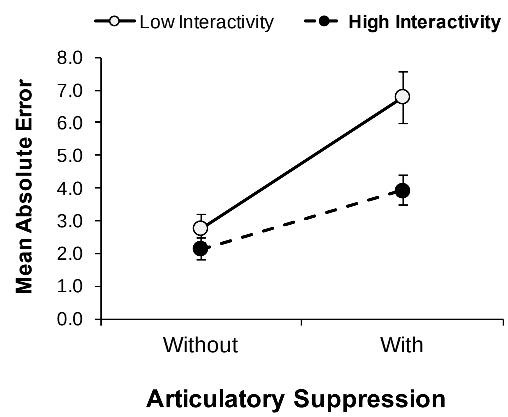

Figure 1: Mean absolute deviation (with standard errors) in the low and high interactivity condition as a function of the absence and presence of articulatory suppression.

Basic Arithmetic Skill. Overall, the increase in absolute calculation error when collapsing across interactivity conditions was moderated by basic arithmetic skills, $r = -.37$, $p = .007$, that is the higher was participants' arithmetic skill, the smaller the increase in calculation error with articulatory suppression. This relationship was also observed in the low interactivity condition, $r = -.28$, $p = .042$ but less so in the high interactivity condition, $r = -.27$, $p = .056$.

Math Anxiety. When collapsing the data over both interactivity conditions, levels of mathematic anxiety moderated the impact of articulatory suppression, $r = .34$, $p = .014$; that is, the higher the level of math anxiety, the higher the increase in calculation error with articulatory suppression. However, this overall pattern obscures a more interesting pattern across levels of interactivity. Thus in the low interactivity condition math anxiety was a significant moderator of the increase in error with suppression, $r = .41$, $p = .003$, but not in the high interactivity condition, $r = .01$, $p = .951$.

Attention Switching. As the correlation coefficients reported in the bottom row of Table 2 indicate, scores on the attention switching test did not moderate the increase in calculation error with articulatory suppression.

Table 2: Correlation between increase in absolute calculation error as a function of articulatory suppression and Basic Arithmetic Skill (BAS), Math Anxiety Score (MAS), and Attention Switching Score (SWITCH) in the low and high interactivity condition, and overall (*df* = 50).

	Interactivity Condition		
	Low	High	Overall
BAS	-.28 *	-.27	-.37 **
MAS	.41 **	.01	.34 *
SWICH	-.01	.04	.01

Note. * $p < .05$, ** $p < .01$

Discussion

This experiment explored how interactivity could mitigate the impact on mental arithmetic performance of a reduction in working memory resources through articulatory suppression. We predicted that performance overall would be influenced by both articulatory suppression and interactivity, and more important, that these two factors would interact such that the impact of articulatory suppression would be more pronounced in the condition with low interactivity. This is what we observed: While mental arithmetic performance was always poorer with articulatory suppression, the deterioration of accuracy was always significantly greater when participants completed the sums with their hands palm down on the table top. The repeated-measures design ensured that differences across conditions were not in themselves a reflection of differences in arithmetic skills or working memory capacity across participants.

The data reported here on the effect of articulatory suppression on counting performance corroborate previous findings (see Raghubar et al., 2010). However, interactivity attenuated the impact of a secondary task that taxed the phonological loop which reduced participants' ability to rehearse interim totals or plan counting strategies sub-vocally. The possibility of restructuring the physical problem presentation over the course of the calculation ensured that the participants could reconfigure the environment in a manner that compensated for the reduction in internal working memory capacity. This is not to say that working memory was augmented such as to soak up completely the resources depletion caused by articulatory suppression since performance was affected by the secondary task, but nonetheless it was sufficiently robust to ensure efficient calculations, as reflected by the efficiency ratio measure that did not dip substantially below 1 as it did in the low interactivity condition with articulatory suppression.

Accuracy in the high interactivity conditions dropped by 20% with articulatory suppression, and latency increased by nearly 14 seconds on average (a 37% increase in latency). In contrast, the latency across the low interactivity conditions increased by 3.4 seconds on average with articulatory suppression (a 9% increase in latency). At first, the latency data might suggest participants did not fully engage with the secondary task in the low interactivity condition, yet accuracy was down by 30% and absolute calculation error were four times as large with articulatory suppression in the low interactivity condition (see Fig. 1). Rather, what these relatively short latencies indicate was that the task was very hard in the low interactivity condition with articulatory suppression: participants abandoned more quickly than in the high interactivity condition and were more likely to guess the answer. It is interesting to note that participants' level of mathematics anxiety was a significant moderator of the impact of suppression on calculation error, but only in the low interactivity condition. This suggests that math anxious participants might have guessed more in low interactivity condition, reducing problem latency but also increasing error. This pattern has been previously reported in the math anxiety literature (e.g., Ashcraft & Klause, 2007). Thus, in this simple arithmetic task, the reduction of internal working memory capacity through articulatory suppression had its most deleterious effect on participants with higher levels of math anxiety.

Participants' basic arithmetic skills moderated the impact of articulatory suppression. This pattern was marginally more pronounced in the low than in the high interactivity condition. Along with the moderating influence of math anxiety on the impact of suppression across levels of interactivity, these data suggest that a higher degree of interactivity produced more resilient performance irrespective of differences in skills and anxiety. Finally, the attention switching scores did not moderate the impact of suppression on performance either in the low or high interactivity condition. This finding is a little puzzling. To the extent that this task gauges participants' ability to switch their attention, we expected these scores to correlate positively with changes in performance as a function of suppression; they did not. A more precise measure of attention switching, perhaps using an automated task, or a composite score from different attention switching tasks, might offer a more informative window on how switching skills might moderate the influence of articulatory suppression on mental arithmetic.

Overall, these moderation patterns are interesting. Psychometric efforts to unveil the cognitive capacities and dispositions subserving performance in a domain must be interpreted relative to a context of reasoning. In the experiment reported here, the context varied in terms of the degree of interactivity it afforded and the cognitive resources that could be deployed on the primary task. Math anxiety may be an important moderator of mental arithmetic performance (Ashcraft, 2002), but allowing participants to interact with a malleable problem presentation attenuates the impact of math anxiety on performance. Similarly, a high interactivity context elevates performance such that participants with poorer arithmetic skills perform in a manner similar to participants with stronger skills.

The data presented here validate a systemic perspective on cognition, one that seeks to describe cognitive products and processes of a system configured by the dynamic coupling of an agent and his or her physical environment (Vallée-Tourangeau & Vallée-Tourangeau, 2014; Vallée-Tourangeau, Abadie, & Vallée-Tourangeau., 2015). In the present mental arithmetic task, interacting with the physical problem presentation transformed an agent's ability to solve these problems. The resulting performance invites a characterization of the cognitive capacities of the system rather than of the agent. Profiling an agent's cognitive resources—such as working memory capacity—with tasks that eliminate interactivity with a physical problem presentation will paint an inaccurate and perhaps distorted picture of how these resources are deployed, augmented and transformed once the agent is released from the psychologist's laboratory and is embedded in the physical world.

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