Is Arithmetic Embodied? Differential Interference of Sequential Finger Tapping on Addition during a Dual Task Paradigm

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Abstract

We propose that the unique ability of humans to have separate mental representations for each finger and to move them in different sequential orders were redeployed for arithmetic. We tested our hypothesis with a behavioral dual-task experiment, where subjects (N=46) solved addition problems (primary task) and performed a sentence comprehension task (control task), while concurrently tapping their fingers (secondary task). We examined two sequential finger tapping tasks: one that was more automatic and followed the anatomical finger order (simple) and one that relied heavily on sequence processing (complex). The results revealed that both simple and complex finger tapping differentially interfered with addition compared to sentence comprehension. These results provide support for a finger-based representation of numbers and shared use of sequence processing resources for finger movements and addition.

Keywords: fingers; embodied cognition; mathematical cognition; arithmetic; number processing; dual task; sequence processing

The Relationship Between Fingers and Number Processing

A relation between fingers and number processing was first formulated in 1924 when Josef Gerstmann diagnosed a condition, now named Gerstmann's syndrome, with four co-occurring symptoms: finger agnosia (loss of finger sense), acalculia (inability to carry out simple mathematical calculations), left-right disorientation and agraphia (inability to write). Gerstmann found that the condition was most commonly due to a lesion in the left angular gyrus (Gerstmann, 1940). He believed that the main symptom was finger agnosia, a specific type of body schema impairment (autopagnosia) affecting the mental representation of hands and fingers. He proposed that the loss of finger sense combined with the left-right disorientation caused acalculia,(Butterworth, 1999, p. 219). There have been a number of studies reporting data to support Gerstmann's theory. For example, a study examining patients with tumors in and around the angular gyrus found that these patients had impairments in writing, calculating, and finger recognition (Roux, Boetto, Sacko, Chollet, & Tremoulet, 2003). Also, in an rTMS study of healthy subjects it was found that disruption of the left angular gyrus impaired access to the finger schema and number magnitude processing (Rusconi, Walsh, & Butterworth, 2005). Additionally, a series of behavioral studies have consistently shown that finger gnosia in younger children is a predictor of numerical abilities; pointing to a functional relation between finger representation and number processing (Noel, 2005; Penner-Wilger et al., 2007).

While there is evidence to support Gerstmann's theory, an opposing theory suggests that acalculia in Gerstmann's syndrome is due to an impairment in mental manipulation of images and not to a deficit in the representation of hands and fingers (Mayer et al., 1999). In a study with healthy patients rTMS to the angular gyrus disrupted both a visual search and a number comparison task (Gobel, Walsh, & Rushworth, 2001). However, this finding only partially supports the opposing theory because the effects of rTMS on finger schema representation were not tested.

The question of whether acalculia in Gerstmann syndrome is due to finger representation or visuo-spatial processing impairments characterizes a general discussion: To what extent is number representation body-based?

Fischer (2008) explored whether finger-counting habits interact with the SNARC (Spatial-Numerical Association of Response Codes) effect, which is an association of small numbers with the left visual field and big numbers with the right visual field (Dehaene, Bossini, & Giraux, 1993). The results revealed that subjects who are left-starters show a SNARC effect significantly more than right-starters. Di Luca, Grana, Semenza, Seron and Pesenti (2006) asked subjects to identify Arabic digits by pressing one of 10 keys with all 10 fingers. The configuration of response buttons varied both in terms of the global direction of the hand-digit mapping and the direction of the finger-digit mapping within each hand, from small to large digits or vice versa. The results showed that subjects performed better when there was a congruency between the reported finger-counting strategy of the subject and the mapping of the response buttons. Both studies (Di Luca, et al., 2006; Fischer, 2008) provide evidence for the dominance of a finger-based number representation compared to a spatial one.

Although arithmetic, and more generally number processing, involves sequential manipulation of numbers the role of sequence processing in number processing is not well understood. Neuroimaging evidence suggests a relation based on the neural overlap between visual-motor sequencing (Buhusi & Meck, 2005) and number processing (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999), particularly in cerebellum and IPS (Intra-parietal sulcus) (Sakai, Ramnani, & Passingham, 2002). Both visuo-spatial and motor simulation strategies used in calculation require sequencing under conditions with time constraints and this might explain the cerebellar activity in calculation tasks (Arsalidou & Taylor, 2010).

In this study we test claims about a finger-based representation of numbers from a performance based perspective. If numbers are grounded in a system that is originally used for finger processing, than we hypothesize that movement of fingers should interfere with number processing differentially compared to a non-numerical control task, since finger movement would demand more overlapping resources with number processing. Arithmetic often requires representation and manipulation of different numbers. Similarly, finger tapping with multiple fingers require activation of finger representations in different sequences. Therefore, arithmetic and sequential finger tapping might use a shared sequence processing system. Our second hypothesis is that manipulation of the complexity of the finger tapping sequence should differentially modulate the interference with arithmetic compared to a sentence comprehension control task. We used a dual-task design to test these two hypotheses.

We manipulated the task difficulty for addition to investigate the differential effect of finger processing on the retrieval of arithmetic facts (easy) and calculation (hard). The comparison of single conditions with dual conditions involving simple tapping (dual-simple) allowed us to determine whether finger processing resources are shared with number processing. The manipulation of the complexity of finger tapping allowed us to determine whether sequence processing resources are shared between addition and finger tapping.

We predicted that addition would be differentially affected by both simple tapping and complex tapping compared to sentence comprehension, due to: first, a finger-based representation of numbers and, second, involvement of sequence processing both in addition and finger tapping. We also predicted the finger tapping interference on easy and hard addition questions to be comparable for the simple tapping condition, and higher for hard addition questions for the complex tapping. Previous research shows that arithmetic questions answered from rote memory use fundamentally different brain networks compared to questions requiring calculation (Dehaene & Cohen, 1997; Lee, 2000) therefore we expect rote memory operations to be less affected by sequential finger tapping compared to calculation.

Methods

Participants

46 adults (age 18-28, M=19.90, 35 females, all right handed) were recruited from the Indiana University community. None of the subjects reported any neuropsychological conditions except one with dyslexia. Data from four subjects were excluded due to low (lower than 3 standard deviations below the mean) finger tapping or arithmetic performance.

Stimuli

The experiment utilized a dual-task paradigm. The primary task was addition. The addition problem was presented at the top of the screen with 4 possible answers at the bottom. There were two levels of difficulty. Easy questions involved addition of three numbers between 1 and 4, and hard questions involved the addition of two numbers between 11 and 99, excluding multiplies of 5. The secondary task was finger tapping involving the four fingers of the right hand (no little finger), with two levels of complexity. The simple sequence followed the anatomical order of fingers (ring, middle, index and thumb), and the complex sequence followed the “ring, thumb, middle and index” order. It was previously shown that learning to tap sequentially at a given rhythm allocates additional resources compared to sequential tapping with an uncontrolled rhythm. Therefore, the subjects were told to tap rhythmically at a self-controlled and comfortable pace (Sakai, et al., 2002). We had a control language task; a sentence comprehension task. In the comprehension task subjects were presented with a sentence at the top of the screen, and a true/false comprehension probe at the bottom. The comprehension task also had two levels of difficulty, with active sentences used in the easy condition and passive sentences in the hard condition.

Finger tapping complexity was presented in two separate blocks such that the dual task condition in one block involved tapping with the simple sequence while the other block involved the complex sequence. The order of the blocks was counterbalanced across subjects. Each block consisted of 20 trials of single addition, single comprehension, dual addition-tapping and dual comprehension-tapping conditions. In addition, single finger tapping trials were included which consisted of 15 secs of tapping while a fixation crosshair was presented on the screen.

While finger tapping was performed with the right hand, subjects responded to the addition and comprehension trials with their left hands. Subjects responded to the addition trials by pressing the “a”, ”s”, ”d”, and “f” buttons on the keyboard (matching with A,B,C,D choices), using their little, ring, middle and index fingers respectively. They used “a” (true) and “s” (false) keyboard buttons, matching with middle and index fingers respectively, to respond to the comprehension probe.

We designed a task to test if having four response buttons for addition and two response buttons for comprehension is a confound in terms of the interaction between the left hand finger movement to give a response and the right hand finger tapping. We thought that using one of four fingers to respond might interfere more with finger tapping than using two. During the task the subjects (N=5) were presented with either four ("A) B) C) D)") or two ("T) F)") choices. After choices stayed on the screen for 3 secs one of them turned yellow and the subject clicked on the button for that choice. Subjects were also asked to tap their fingers both with the simple and complex finger tapping sequences in two separate blocks. There were 30 trials per condition with a total of 120 trials. The results showed that there were no significant differences between four and two choice conditions in terms of RT, response accuracy, and tapping performance, across both tapping complexities (Table 1). Based on the results we concluded that having different response settings for the two task conditions had little impact on the results.

	Simple				Complex			
	ABCD		True/False		ABCD		True/False	
	M	SD	M	SD	M	SD	M	SD
RT	3.62	0.58	3.65	0.56	3.76	0.73	3.89	0.48
Accuracy	0.93	0.26	0.90	0.30	0.93	0.25	0.91	0.29
Tap Perf.	4.77	1.82	4.66	2.44	2.83	0.87	2.82	0.76

Table 1. Results from the confound task

Procedure

After subjects were given general information about the experiment they went through a training session where they were presented with a shortened version of the experiment. The finger tapping combination used during the training was different than the two tapping combinations used in the experiment. After the training the subjects completed a finger tapping training where they finger tapped at a rhythmic and comfortable pace using the sequence for block 1. A blinking green ellipse, was presented when they completed a sequence correctly. They were to complete 25 consecutive tapping sequences successfully before the training ended.

Before the experiment started the subjects were told to tap their fingers as rhythmically as possible in a comfortable pace. They were also reminded that there were no time constraints and accuracy was more important than speed. They were instructed that during the dual trials they were to continuously tap, even when responding to the addition and comprehension trials.

Results

We use the terms "simple" and "complex" to refer to the complexity of the tapping sequence, and "easy" and "hard" to indicate the task difficulty for addition and comprehension. For example dual-complex refers to the dual conditions where the subject answers addition or comprehension questions while tapping the complex sequence.

Filtering

All trials with RT values outside the M ±2 SD range were filtered from the results (6%). The range was calculated separately for each subject/block. Dual trials in which the subject did not tap fingers were also filtered out (1.4%). Finally, trials with incorrect responses were filtered out from analysis of RT and tapping performance (9.7%).

Reaction Time

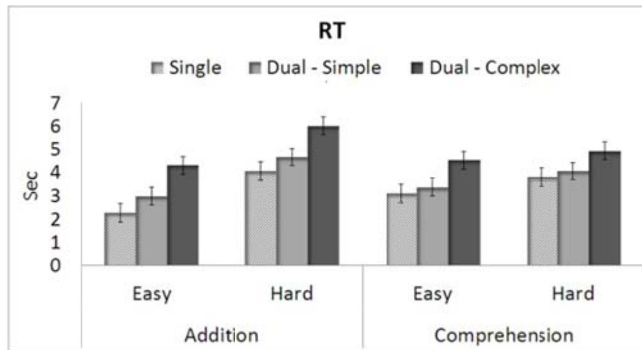

Figure 1. Average RT (seconds)

For the simple tapping condition, we performed a 2 (single vs. dual-simple) x 2 (addition vs. comprehension) x 2 (easy vs. hard) within subjects ANOVA on reaction time (RT) (Fig. 1). Analysis revealed a main effect of single/dual such that RT was higher for dual compared to the single conditions [$F(1,45) = 20.67$, $p<0.0001$]. There was also a main effect of difficulty, hard questions taking longer than easy questions: [$F(1,45)=310.28$, $p<0.0001$].A significant interaction between single/dual-simple and task [$F(2,45)=13.51$, $p<0.001$] was found. Post-hoc analysis revealed that the difficulty-collapsed single and dual-simple RT values were significantly different both for addition [(M=3.15, SD=0.75), (M=3.76, SD=0.97)] and comprehension [(M=3.41, SD=0.78), (M=3.70, SD=0.99)]. The effect size was bigger for addition (0.85) compared to comprehension (0.38), showing that, based on RT, the dual-task demands of simple tapping interfered more with addition more than comprehension. There was also a significant interaction between task and difficulty [$F(2,45)=80.59$, $p<0.0001$]. According to the post-hoc analysis the single/dual-simple collapsed averages were significantly different between easy (M=2.63, SD=0.54), and hard (M=4.35, SD=1.14) addition, and easy (M=3.24, SD=0.72) and hard (M=3.90, SD=0.91) comprehension. The effects size for addition (2.29) was bigger than it is for comprehension (1.08) showing that the interaction was due to a bigger difference between easy and hard conditions for addition.

We conducted a 2 (single vs. dual-complex) x 2 (addition vs. comprehension) x 2 (easy vs. hard) within subjects ANOVA to investigate the effects of complex tapping. The analysis revealed a main effect of single/dual-complex [F(1,43)=72.75, p<0.0001] with single conditions showing higher accuracy; and of difficulty [F(1,45)=110.29, p<0.0001] with easy trials having a higher accuracy. A significant interaction between single/dual-simple and task [F(2,45)=21.57, p<0.0001] was found. Post-hoc analysis revealed that the difficulty-collapsed single and dual-complex RT values were significantly different both for addition [(M=3.15, SD=0.75), (M=5.17, SD=1.62)] and comprehension [(M=3.41, SD=0.78), (M=4.72, SD=1.49)]. The effect size was bigger for addition (1.50) compared to comprehension (0.94), showing that, based on RT, the dual-task demands of complex tapping interfered more with addition than comprehension. There was also a significant interaction between task and difficulty [F(2,45)=37.65, p<0.0001] due to a bigger difference between easy and hard conditions for addition.

A 2 (dual-simple vs. dual-complex) x 2 (addition vs. comprehension) x 2 (easy vs. hard) within subjects ANOVA was used to investigate the effects of sequence processing load on RT (Fig. 1). Main effects of complexity [F(1,43) = 73.22, p<0.0001] and difficulty [F(1,43) = 91.88, p<0.0001] were found, hard and dual-complex conditions having higher RT than easy and dual-simple conditions respectively. An interaction between complexity and task was found [F(1,43) = 2.401, p=0.043]. Post-hoc analysis showed that the difficulty-collapsed dual-simple and dual-complex RT values were significantly different both for addition [(M=3.76, SD=0.97), (M=5.17, SD=1.62)] and comprehension [(M=3.70, SD=0.99), (M=4.71, SD=1.49)]. However, the effect size was bigger for addition (1.33) compared to comprehension (0.92), showing that, in terms of RT, the additional sequence processing demand in complex tapping interfered more with addition than comprehension. Additionally, there was an interaction between task and difficulty [F(1,43) = 34.22, p>0.0001] due to the bigger RT difference between easy and hard for addition compared to comprehension.

Task Accuracy

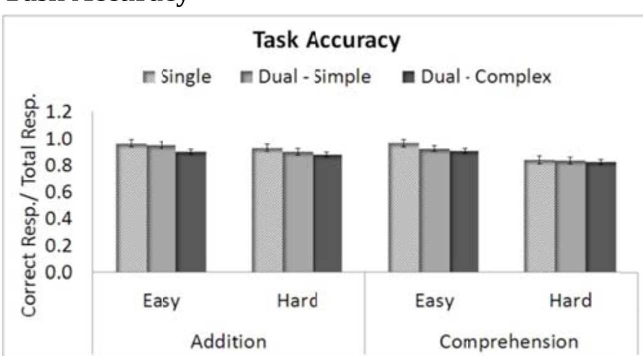

Figure 2. Average task accuracy (correct / total responses)

We performed a 2 (single vs. dual-simple) x 2 (addition vs. comprehension) x 2 (easy vs. hard) within subjects ANOVA on task accuracy to investigate the effects of simple finger tapping on accuracy (Fig. 2). The analysis revealed a main effect of single/dual-simple[F(1,45)=7.46, p=0.009]with single conditions showing higher accuracy; of task [F(1,45)=18.40, p<0.0001] with addition having higher accuracy; and of difficulty [F(1,45)=48.82, p<0.0001] with easy trials having a higher accuracy. There was a significant interaction between task and difficulty [F(2,45)=18.40, p<0.0001]. According to the post-hoc analysis while there was no significant difference between single-dual collapsed averages of easy (M=0.96, SD=0.04) and hard (M=0.95, SD=0.05) addition, the difference was significant for easy (M=0.92, SD=0.07) and hard (M=0.84, SD=0.12) comprehension. Notably there was no interaction between single/dual and task [F(2,45)=0.006, p=0.941] showing that both addition and comprehension accuracy were affected similarly from simple finger tapping compared to single conditions.

We conducted a 2 (single vs. dual-complex) x 2 (addition vs. comprehension) x 2 (easy vs. hard) within subjects ANOVA to investigate the effects of complex tapping on accuracy (Fig. 2). We found a main effect of single/dual-complex [F(1,43)=30.207, p=<0.0001] with single conditions having higher accuracy; of task [F(1,45)=7.02, p=0.011] with addition showing greater accuracy; and of difficulty [F(1,45)=30.68, p=0.009] due to easy conditions having higher accuracy. The only significant interaction was between task and difficulty [F(1,45)=9.18, p=0.004] due to larger accuracy difference between easy and difficulty comprehension conditions compared to addition.

A 2 (dual-simple vs. dual-complex) x 2 (addition vs. comprehension) x 2 (easy vs. hard) within subjects ANOVA was conducted to investigate the effects of sequence processing load on accuracy (Fig. 2).The results revealed main effects of complexity [F(1,43)=12.99, p=0.001], task [F(1,43)=8.05, p=0.007], and difficulty [F(1,43)=40.23, p<0.0001].There was an interaction between task and difficulty [F(2,45)=4.593, p=0.038]. Notably, there was no interaction between complexity and task [F(1,43)=0.62, p=0.436], showing that the sequence processing load affected addition and comprehension accuracy similarly.

Tapping Performance

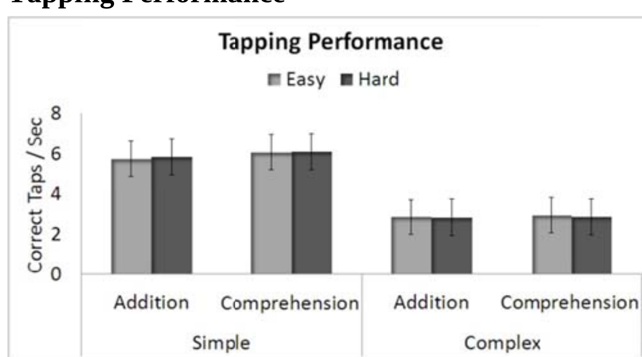

Figure 3. Tapping performance (corrects taps/sec)

The tapping performance measure was the number of correct taps per second. A correct tap is one that follows the order of the assigned tapping sequence. This measure

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combines both the speed of tapping and accuracy. We performed a 2 (simple vs. complex tapping) x 2 (addition vs. comprehension) x 2 (easy vs. hard) within subjects ANOVA on tapping performance to investigate the effects of sequential processing load on tapping performance. The analysis revealed a main effect of complexity [$F(1,45)=123.99$, $p<0.0001$] and task [$F(1,45)=12.28$, $p=0.001$] (Fig. 3).

There was an interaction between complexity and task [$F(2,45)=0.320$, $p=0.574$].The post-hoc analysis revealed that while there was a significant difference between difficulty collapsed tapping performance averages for simple tapping addition (M=5.76, SD=2.24) and comprehension (M=6.06, SD=2.20) values, there were no significant differences between addition (M=2.82, SD=0.87) and comprehension (M=2.87, SD=0.84) for complex tapping conditions. Therefore the interaction is due to the relatively bigger interference of addition on simple-finger tapping compared to comprehension.

Discussion

Our overall motivation in this study was to explore the embodiment of number processing. We aimed to determine whether arithmetic shares resources with finger movement processes from a performance based perspective. Within a dual-task paradigm we compared addition to a control, sentence comprehension task.

Task accuracy for addition and comprehension failed to show interference effects. However, tapping performance results(for the simple sequence) showed that addition affected simple tapping and revealed differential effects in that performance was lower when solving addition problems than during sentence comprehension. There was no differential effect for the complex sequence.

Finger tapping interference was observed for both tasks when examining RT. Participants were told to answer all questions as accurately as possible and not to sacrifice from tapping performance or task accuracy during the dual-trials but to weigh accuracy higher. Therefore results are compatible with the instructions given to the participants and the discussion will focus on the RT results.

One of the predictions was that addition would be differentially affected by both simple tapping and complex tapping compared to sentence comprehension. This was observed here. For both the simple tapping and complex tapping a significant interaction between dual/single and task was observed which indicated that addition performance was more affected by tapping. We argue that one reason for this increased interference is that both finger tapping and addition rely on a finger-based representation. The participants in this study were all adult, college students therefore it is not likely that they used finger counting strategies to solve the addition problems. Instead, we argue that the finger representation is tied to and facilitates processing of number and this is seen in the results presented.

Second, we predicted that when the demand on sequence processing increases in the finger tapping task the interference with addition would also increase. This was also observed here. Sequence processing is an important aspect of arithmetic. This includes finger counting to the algorithms typically used in adding two or more digits. However unexpectedly, both easy and hard addition were affected by the additional sequencing load. This might be because although the majority of the operations taking place in easy addition involve rote memory retrieval, the solution still involves taking multiple executive steps, which might require sequence processing resources.

It should also be noted that aspects of sentence processing also involves sequence processing, particularly syntactic processing. For example, Pulvermuller (2003) suggests that syntax is built on serial-order mechanisms. As a result, it was expected that the complex finger tapping sequence would affect comprehension more so than the simple sequence and the data presented does hint at this.

The increase in process overlap between finger tapping and addition compared to comprehension implies that these two tasks may also share neural resources. Previous neuroimaging research showing shared neural resource allocation for finger representation and number processing supports this interpretation (Sato, Cattaneo, Rizzolatti, & Gallese, 2007; Zago et al., 2001). From a functional standpoint the results provide support for the previously established relation between the mental representation of fingers and numerical quantity (Noel, 2005; Penner-Wilger, et al., 2007). In addition we propose that sequence processing resources are also shared between finger motor processes and number processing.

Limitations & Future Directions

An alternative interpretation for the results would be that addition is more prone to dual-task interference compared to sentence comprehension, independent of the nature of the secondary task. Therefore future experiments should focus on testing if other motor tasks (e.g. jumping) would also show differential interference for addition. Based on our hypotheses we would predict that a non-hand or finger related secondary motor task not cause differential interference for addition. Additionally a double dissociation of addition and comprehension can be established by finding a motor task that differentially interferes with comprehension, which would provide further support for our claims. Nevertheless, there are practical limitations about capturing non-hand related motor movements. Also due to lack of previous research on motor task interference in mathematics or sentence comprehension it is challenging to narrow down the secondary task possibilities.

Previous research shows that the motor system is involved in semantic language processing (Buccino et al., 2005; Kemmerer & Gonzalez-Castillo, 2008), therefore it is possible that finger tapping interference is modulated by the relevance of sentence semantic content to hand/finger related movements. Although we did not control for the semantic content, none of the sentences involved hand/finger related verbs (e.g. grasp, tap, squeeze).

We are currently conducting an fMRI adaptation of the same experiment to investigate the neural dynamics of the finger tapping and addition relation. This study will allow for the assessment of the neural overlap between these two tasks which would provide strong evidence to support the embodiment of arithmetic.

Conclusion

Mathematics is a representation hungry knowledge domain presenting challenges for the idea of embodied cognition. In this study we explored the embodiment of arithmetic by investigating the shared resource usage between addition and finger tapping. We found evidence for shared use of resources between addition and finger tapping at different levels of complexity. This study is unique in two aspects: First, we focused on the role of sequence processing in the interaction between finger movements and arithmetic, which has not been studied before. Second, by studying dual task interference we adopted a performance based approach to explore the interaction between motor and arithmetic processes.

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