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Brief article

Arithmetic operation and working memory: differential suppression in dual tasks

Kyoung-Min Lee[a,b,c,*], So-Young Kang[a,c]

[a]Cognitive Science Program, Seoul National University, Seoul, South Korea
[b]Department of Neurology, Seoul National University, Seoul, South Korea
[c]BK 21 HLS Division, Seoul National University, Seoul, South Korea

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Abstract

The relationship between arithmetic function and working memory was examined using a dual-task paradigm for either phonological or visuo-spatial suppression. Simultaneous phonological rehearsal significantly delayed the performance of multiplication but not subtraction, whereas holding an image in the mind delayed subtraction but not multiplication. This result indicates that arithmetic function is related to working memory in a subsystem-specific manner: multiplication is more closely linked to phonological loop and subtraction to visuo-spatial sketchpad. Whereas this is not compatible with the notion that arithmetic is done on a unitary, amodal representation of numbers, it provides support for the triple-code and/or the modular processing models on human numerical cognition in which number representations are specific for input/output modality and arithmetic types. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Arithmetic involves various cognitive processes and strategies depending on the types of operation, numerical symbol used, and so on, as evidenced by double dissociations found in brain-damaged patients with impairment of function (Anderson, Damasio, & Damasio, 1990; Ashcraft, 1992; Cohen & Dehaene, 1995, 1996; McCloskey, 1992; McCloskey, Sokol, & Goodman, 1986). Such neuropsychological data have led to a few models on how human brains represent and process numbers. First of all, McCloskey (1992) has proposed that arithmetic operation per se is separable from input and/or output

* Corresponding author. Department of Neurology, Seoul National University Hospital, 28 Yongon-Dong, Chongno-Gu, Seoul, 110-744, South Korea. Tel.: +82-2-760-2985; fax: +82-2-3672-7553.
E-mail address: kminlee@snu.ac.kr (K.-M. Lee).

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processing of numerical symbols and that the former is performed on a unitary representation of quantity regardless of the code in which the input is presented (for example, Arabic or verbal number forms). In his model, the abstract quantity representation serves as a mental platform upon which all numerical operations such as arithmetic fact retrieval, mental calculation, etc. are performed. Dehaene and his colleagues, in contrast, have put forth the idea that there are three kinds of number codes in human brain, namely, visual-Arabic, auditory-verbal, and analog magnitude codes, which are differentially involved in various kinds of arithmetic operations and number processing, with no need to rely on a unitary number representation (Cohen & Dehaene, 1996; Dehaene, 1992; Dehaene, Dehaene-Lambertz, & Cohen, 1998). Multiplication, for example, is regarded as a rote verbal memory task that utilizes the auditory verbal number code, whereas subtraction is performed using analog magnitude code.

According to Baddeley (1998), the working memory system consists of the central executive and subsidiary slave systems. Two slave subsystems thus far identified are the articulatory-phonological loop for handling verbally coded information, and the visuo-spatial sketchpad for processing image-based information. Although the role of working memory in arithmetic was the focus of many previous studies, for example those by Logie, Gilhooly, and Wynn (1994) which showed that the central executive and subvocal rehearsal components played a role in maintaining accuracy in mental arithmetic and by Furst and Hitch (2000) which demonstrated that the carrying component of mental arithmetic placed substantial demands on executive processes whereas the need to retain problem information was met by the phonological loop, how the two subsystems of working memory are related to the various kinds of numerical codes mentioned above has not been examined. While it seems intuitively certain that the phonological loop is involved in reading and reciting numbers during arithmetic of any kind, it is not so clear whether the visuo-spatial sketchpad is involved in a similar manner as well. Thus, in the current study, we aimed at examining whether and how working memory is related to arithmetic function. More specifically, we compared the performance of multiplication vs. subtraction in dual-task suppression conditions with phonological vs. visuo-spatial tasks, in order to determine whether the arithmetic type and dual-task type interact and whether such interaction, or the lack thereof, is compatible with the models described above on human numerical function.

2. Materials and methods

Ten undergraduate and graduate students aged between 24 and 30 years participated in this study. Each subject performed an arithmetic task in three sessions: one without a dual task (i.e. arithmetic task only), and the others with a dual task for either phonological or visuo-spatial suppression. The order of sessions was randomized across subjects. Each arithmetic trial of a session began by the presentation of a problem set on a computer monitor located at approximately 50 cm in front of a subject. The display was about 5 degrees of visual angle in height and 10 degrees in width. Problem sets were shown until the subjects typed in the answers using the number keypad of a keyboard. The reaction time was measured on each trial from the display onset of a problem to the first keystroke made with an answer. Only those trials with the correct answer were included for further analysis. Both the first and second operands of arithmetic problems were single digit numbers used in the same frequency for multiplication and subtraction, and were different from each other so that there was no same-number arithmetic, such as $7 - 7$, 3×3, etc. The arithmetic trials were grouped into three-trial sets by operation type, and groups of either multiplication or subtraction were randomly intermixed within a session. Each session was comprised of 80 arithmetic trials, i.e. 40 trials (12 three-trial groups plus one last four-trial group) each for multiplication and subtraction.

In a session with phonological suppression subjects repetitively whispered a non-word string while solving arithmetic problems, and in the visuo-spatial dual-task session they remembered for a match-to-sample test both the shape of an abstract decorative figure and its location among the four quadrants of visual field while doing an arithmetic task. The non-word strings or the figures were displayed on the same monitor between three-arithmetic-trial groups. The event sequence in a phonological suppression session was therefore an alternation between a non-word string display and three arithmetic trials, whereas that in a visual suppression session was the following: a one-figure display → three arithmetic trials → a sample display with four figures for checking subjects' memory response (see below) → another one-figure display → three arithmetic trials, and so on. Thus, the material for phonological rehearsal or maintenance in the visuo-spatial sketchpad was changed approximately every 5 s, i.e. the sum of reaction times and inter-trial intervals of three arithmetic trials. Whereas the performance of phonological rehearsal was auditorily monitored by one of the authors for consistency across sessions and across subjects, subjects' answers to the visuo-spatial dual task were recorded as a key-press. The correct answer in this task was '1' if the shape and the location of the target figure in a one-figure display were exactly replicated in the next four-figure display (the target and three non-targets, one in each quadrant), or '0' otherwise, i.e. if either the shape or the location of the target figure was different.

3. Results

The error rate in the arithmetic tasks was 2% (multiplication) and 1.75% (subtraction) in sessions without suppression, 2.75% (multiplication) and 1.5% (subtraction) in sessions with the phonological dual task, and 1.75% (multiplication) and 2.25% (subtraction) in sessions with the visuo-spatial dual task. There was no significant difference ($P > 0.05$) across sessions and between multiplication and subtraction.

The average reaction times of the arithmetic tasks are depicted in Fig. 1. The reaction times ($\pm$standard error) in sessions without suppression were 992.8 ($\pm$20.1) and 996.0 ($\pm$20.3) ms for multiplication and subtraction, respectively. Those in phonological suppression sessions were 1169.5 ($\pm$26.2) and 993.0 ($\pm$20.1) ms, and those in visuo-spatial suppression sessions were 995.9 ($\pm$18.4) and 1271.2 ($\pm$31.8) ms for multiplication and subtraction trials, respectively. As illustrated in Fig. 1, there was a significant difference between multiplication and subtraction in both suppression conditions, but in an opposite direction: only multiplication was delayed in the phonological suppression condition and only subtraction was delayed in visuo-spatial suppression.

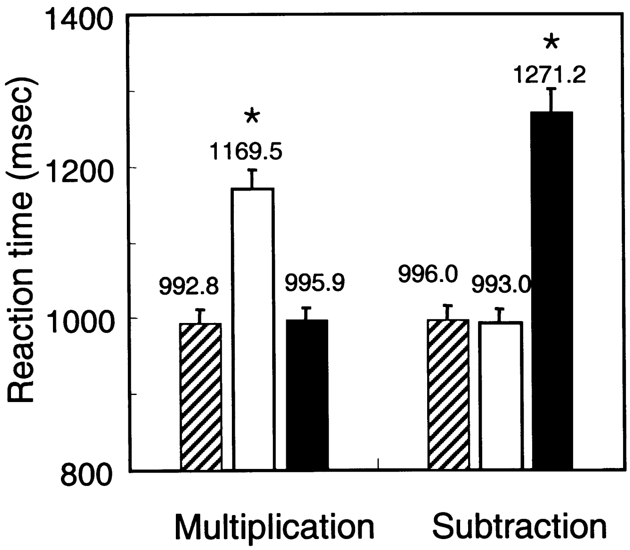

Fig. 1. The mean and standard error of reaction times are shown for multiplication and subtraction without suppression (hatched bar) and with either a phonological (open bar) or a visuo-spatial (filled bar) dual task. Multiplication with phonological rehearsal and subtraction with holding a visual image in the mind were significantly delayed when compared to the arithmetic alone (* $P < 0.0001$ in two-tailed t-test, and otherwise $P > 0.1$ for all pair-wise comparisons in each arithmetic type).

While the performance of the phonological dual task was grossly consistent across the arithmetic types and across subjects, the percent correct of the visuo-spatial task in subtraction trials (89.2 ± 4.0, mean ± standard deviation) was significantly worse than in multiplication trials (98.5 ± 3.2%) (two-tailed t-test, $P < 0.0001$).

4. Discussion

The focus of the current study was on the relationship between the types of simple arithmetic operations and working memory subsystems. We found that dual tasks involving different subsystems of working memory had a double-dissociative effect on multiplication and subtraction. The phonological dual task had a suppressive effect on the performance of multiplication, but not on subtraction, whereas the visuo-spatial dual task had a negative influence on subtraction, but not on multiplication. At the same time, the performance of the visual task was impaired only with subtraction. Therefore, we conclude that arithmetic function and working memory subsystems are related in an operation type-specific manner.

Only if we assume that the suppressive effect occurred at either encoding of arithmetic problems or at the articulatory output stage of the result may the current findings be explained by McCloskey's model. The model precludes the possibility that the observed differential suppression effect occurred at the "core stage" of number processing, because it is assumed to be amodal and independent of the type of arithmetic operation (McCloskey, 1992). However, it is very unlikely that encoding or output stages were where the differential suppression occurred, because both multiplication and subtraction were performed using the same modality.

Our results fit better with the triple-code model (Dehaene, 1996, 1997) or modular processing model (Campbell, 1994, 1997; Campbell & Clark, 1992), which propose different forms of number representation for various types of arithmetic operation. According to such models, auditory-verbal code may be used for multiplication, which was therefore differentially suppressed by a phonological dual task. In contrast, analog magnitude code may be preferentially accessed for subtraction, which seems to involve the use of the mental number line (Dehaene, 1997), and thus more suppressed by a visuo-spatial dual task. This notion that different arithmetic types may involve dissociable number representations has also been supported by a recent functional neuroimaging study (Lee, 2000): a blood-oxygen-level dependent magnetic resonance signal was significantly higher during multiplication than subtraction at the border between the angular and supramarginal gyri of the left hemisphere, suggesting more involvement of the verbal system, while the signal was higher during subtraction than multiplication, most notably, at the intra-parietal sulci of both hemispheres frequently implicated in visuo-spatial functions. Our finding that phonological and visuo-spatial tasks differentially suppress multiplication and subtraction, respectively, provides further behavioral evidence for the arithmetic type-specific representation for human numerical function.

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