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Mental Number Line and Simple Addition Task: Experimental Study with Native Russian Speakers

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Abstract

This article presents the results of an experiment whose purpose was to investigate the mechanisms of simple addition among native speakers of Russian. The means of storage and retrieval of numerical data in and from the mind and the concrete mechanisms used to perform arithmetic operations are highly cultural specific, and to a great extent dependent on a concrete language, as has been shown in many works previously. The link between number concepts and some cultural features, like reading direction or educational methods, is now being researched intensively. Our experiment tested the hypothesis that the mechanism of simple addition is based on a mental number line, at least for Russian native speakers, so far as Russian is read from left to right and a number line is a widely used method to visualize number relationships in Russian schools. The results of the experiment showed that the proposed hypothesis was not correct, and that arithmetic processing is rather more complicated than linear. Many new questions have arisen because of this and possible directions for future investigations are discussed here.

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Keywords: Mental number line; simple addition task; cultural specificity; reading direction.

1. Introduction

Many current studies show that some operations of abstract thinking which have been studied previously as absolutely independent are actually connected strongly not only with each other, but also with a wide range of

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phenomena of cultural and social life. This understanding has involved many new factors in modern cognitive studies and has led these studies to utilize true interdisciplinary approaches.

Mathematical abilities are highly important in a modern technology-oriented society for individual success as well as for the prosperity of a nation. But the present educational system shows how little we know about what mathematical ability is and how it should be developed with the most efficiency. A series of studies is intended to find answers to these questions (Kovas et al., 2013).

It seems that one of the most interesting and important findings at the present time is that mathematical abilities are not separate at all, and that they might be connected with many other factors, such as cultural specificity and social life, national language features, individual language and spatial abilities, educational methods, genetic factors and many others. This particular study is focused on interrelationships between language features, spatial representations of numbers, and mechanisms of simple arithmetic calculations.

In 1993 S. Dehaene, S. Bossini and P. Giraux demonstrated the SNARC effect (Spatial Numerical Association of Response Codes) – an association of small numbers (e.g. 1, 2) with left side and large numbers (e.g. 8, 9) with right side of the visual field. It was then proposed that numbers are organized in mind through spatial representations as a mental number line, directed from left to right. A series of experimental studies were performed which demonstrated a strong link between the character of the counting process (like finger counting) and the way a numerical system in child's or adult's mind is stored (Domahs, Kaufmann, Fischer, 2012); the participation of spatial information in the processing of number concepts (Wood & Fischer, 2008); and simulation of number concepts as a line in our mental space (Nuerk et al., 2011). A detailed model was described (Fischer, 2012), which includes grounded, embodied and situated levels of numerical cognition.

The interrelationship between the number line in the human mental space and a person's culture also was investigated: reading directions in different cultures are different, and the standard way to read texts in each culture influences the direction of the number line in the culture bearer's mind accordingly, so for Hebrew or Arabic languages the mental number line is directed from right to left and large numbers are associated with the left side, whereas small are with the right. It was even discovered that second language acquisition can influence individual spatial and mathematical abilities depending on the type of language (Rodic et al., 2015). There is no doubt, moreover, that language semantics is also associated with spatial locations, as has been shown previously (Pecher et al., 2010; Janyan et al., 2015). It seems, even excluding other factors, that spatial, linguistic and mathematical abilities are connected with each other and they can influence each other in a complicated way during an individual's developmental process.

But there are some questions that should be answered. One of them is how arithmetic tasks are performed, that is, which cognitive mechanisms underlie such tasks as addition or subtraction? Are these mechanisms also cultural specific? If yes, which cultural (in particular – spatial and linguistic) features influence these mechanisms?

In order to answer some of these questions the hypothesis was proposed that simple arithmetic operations (i.e. addition and subtraction) are based on a mental number line mechanism: addition and subtraction are performed by moving attention in mental space from one point (the first number of sum/difference) to another point (the result) through a particular number of positions (the second number, see Fig.1).

Fig.1. Simple addition (mental number line-based model).

If the hypothesis is correct, the mechanism of these arithmetic operations should vary between different cultures in the same way as the mental number line does. Particularly, for the Russian language simple arithmetic operations should be performed by shifting to the right during addition and to the left during subtraction, as far as Russian writing is directed from left to right. Another possible piece of evidence of this mechanism is that a number line is widely used in Russian secondary schools in order to help children to visualize relationships between numbers and as a part of a coordinate plane. Thus, it might be that this tool becomes automatic in the course of time, and people continue to use it unconsciously.

2. Methodology

2.1. Design and procedure

If the mechanism of simple arithmetic operations is as described above, that is, if simple addition and subtraction are performed by shifts in mental space, it would be logical to expect that the more distance is covered, the more time is needed for this action. In this context the distance is marked by the second number in the sum/difference, which reflects the number of positions between the first and the last point.

To examine whether this model can properly explain arithmetic operations, 19 digital simple arithmetical problems were generated, for example 0+9, 1+8, 7+2 and so forth. Each trial started with a fixation cross (500 ms), then one of the exercises appeared at the center of the screen for 2000 ms. If the participant did not answer, the exercise disappeared. There were only two possible answers, 8 or 9, and the participant's task was to press the corresponding key on a standard keyboard. So there was only 1 independent variable (symbolic distance on a mental number line, marked by the second number in each task) with 10 levels (from 0 to 9).

Exercises appeared on the screen randomly. Each exercise repeated 10 times, thus each participant gave 19*10 = 190 responses. Stimuli were demonstrated in black on a white background. Reaction time for each answer was recorded. The experiment was run using E-Prime 2.0.

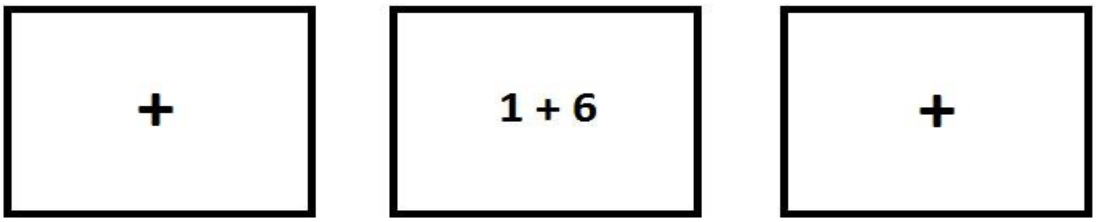

Fig.2. Procedure of the experiment.

2.2. Participants

All the participants were native Russian speakers, mostly university students, aged 18 to 25 (and one participant 41, whose results did not show any significant differences). 33 people participated, 14 men and 19 women.

2.3. Results

Data of 4 participants were excluded from the analysis due to low accuracy (<91%), although the task was quite easy. The analysis was based on the data of 32 participants (13 males, mean age = 20.8, SD = 4.1). Erroneous responses (3.3%) and response times lying more than ±2SD from the reaction time mean for each independent variable value (4,7%) were excluded as well. The data were aggregated within subjects in order to provide repeated analysis of the measurements. Table 1. shows the means and standard deviations for each of the levels.

Table 1. Means and standard deviations per variable levels, in ms.

Distance	Mean	SD
0	585	48
1	686	60
2	748	93
3	742	84
4	638	44
5	725	72
6	762	92
7	734	77
8	668	52
9	545	43

Repeated analysis of the measurements showed a significant effect of the symbolic distance on a mental number line (F(9, 279)=88.54, p=0.00, partial eta-squared = 0.74): some exercises were performed faster than others. There is, however, no linear regularity as might be seen at the graph below (Fig.3).

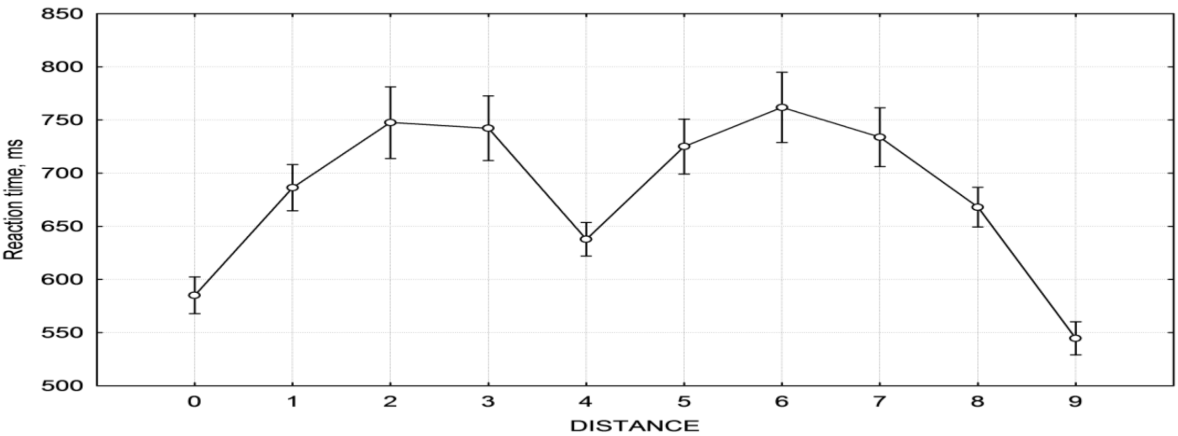

Fig.3. The results (X-axis represents the symbolic distance on a mental number line, Y-axis represents the average reaction time; vertical bars denote 95% confidence interval).

As a Bonferroni post-hoc test showed, most of the means differ from each other significantly (see Table 2).

Table 2.The results of the Bonferroni post-hoc analysis (all the significant results are in bold and marked with a star).

Distance	0 (mean = 585)	1 (mean = 686)	2 (mean = 748)	3 (mean = 742)	4 (mean = 638)	5 (mean = 725)	6 (mean = 762)	7 (mean = 734)	8 (mean = 668)	9 (mean = 545)
0		**0,00***	**0,00***	**0,00***	**0,00***	**0,00***	**0,00***	**0,00***	**0,00***	**0,01***
1			**0,00***	**0,00***	**0,00***	**0,03***	**0,00***	**0,00***	1,00	**0,00***
2				1,00	**0,00***	1,00	1,00	1,00	**0,00***	**0,00***
3					**0,00***	1,00	1,00	1,00	**0,00***	**0,00***
4						**0,00***	**0,00***	**0,00***	0,31	**0,00***
5							**0,05***	1,00	**0,00***	**0,00***
6								0,56	**0,00***	**0,00***
7									**0,00***	**0,00***
8										**0,00***

If the proposed model did underlie addition operations, the graph should represent one straight line and reaction time should rise together with the rising of the second number in each task. Instead, the line is not straight, but has a complicate contour with two peaks, which means that there likely exists another mechanism of performing addition operations.

4. Discussion

The mechanism is not linear, as might be seen from the results of the experiment above, and the initial hypothesis should be negated. Nevertheless, the results indicate that some unidentified regularity exists and new possible explanations should be explored. One is that number processing might be mediated by verbal processing and the pattern above reflects not the influence of number features on addition operations, but rather the influence of Russian numerals (their surface word forms or content and specific features of this language category). One possible direction for future research is to investigate numerical systems and the category of number itself in different national languages by cognitive methods. Modern cognitive linguistics as an interdisciplinary field of research makes it possible to highlight new sides of supposedly well-known language phenomena by including them in the wider context of cognitive functions and social practices (Rezanova, 2010). It is already shown that language categories might be studied in connection with cognitive categories in a fruitful way (Rezanova et al., 2014), and the category of number might be one of them.

A quick glance reveals the diversity of number representation forms in language. For example, in German it would be right to say *Dreiundzwanzig* (three and twenty, literally), but the standard way in English to say this number is *twenty three*, that is, another order of lexical units. Whether or not it influences the arithmetic problem-solving of German speakers, whether Hebrew or Arabic speakers would have the same RT-pattern as above, though their mental number line goes in the opposite direction – questions like these might be investigated in future. It has already been shown that people with different languages use different brain areas to perform arithmetic tasks (Tang et al., 2006), and research of numerical systems in different languages might explain these findings.

5. Conclusion

The hypothesis of a linear mechanism of simple arithmetic operations was tested and negated. Findings suggest that arithmetic processing is more complicated than linear. One possible explanation is the involvement of verbal processing in arithmetic operations, which needs to be proved by future research.

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