Trends in Neuroscience and Education 8–9 (2017) 1–9

Contents lists available at ScienceDirect

Trends in Neuroscience and Education

journal homepage: www.elsevier.com/locate/tine

Number line estimation under working memory load: Dissociations between working memory subsystems

Sarit Ashkenazi*, Shir Shapira

Learning Disabilities, Seymour Fox School of Education, The Hebrew University of Jerusalem, Israel

ARTICLE INFO

Keywords:
Number line estimation
Spatial working memory
Visual working memory
Phonological working memory
Dual task

ABSTRACT

The preverbal representation of quantity has been shown to associate with space, as quantities are spatially mapped on a mental number line. One traditional method to test this association is the number line estimation task that asks participants to locate a number on a number line. However, current approaches suggest that number line estimation task performance involves verbally mediated strategies such as reliance on reference points, questioning the nature of the task as a measurement of pure quantitative or spatial skills. To resolve this conflict, in the current study participants performed the number line estimation task in three dual task conditions under phonological, spatial or visual working memory (WM) loads. We found that phonological WM load and spatial WM load affected performance, while visual WM load did not. Model fits indicated that number line estimation task performance was based on the usage of reference points, and involved phonological WM and spatial WM which are required for the understanding of symbols and the spatial relation between them.

1. Introduction

Converging evidence from infants, preschool children and adults, as well as non-human primates, has consistently found an inherent and neurologically based ability for quantity approximation [1–5]. The representation of approximate quantities is a preverbal, intuitive understanding of discrete quantities, and the relationship between quantities. There is evidence in both human and non-human primates that the cognitive representation of quantities is spatial in the form of the mental number line that has a left to right orientation and logarithmic scale [6,7]. Over the course of development and experience with symbolic numbers, the spatial representation of number shifts from logarithmic to linear [8,9].

Siegler and Opfer [9] designed the number line estimation task to examine the relationship between quantity representation and space (for opposing views see [10,11]). In the number line estimation task participants are presented with a number line ranging from 1 to 100 or 1 to 1000 and a symbolic number appears above the line, and s/he has to spatially place the number on the line. Siegler and Opfer [9] found that most preschoolers produced estimates consistent with a logarithmic function (overestimates of small numbers and underestimates of large numbers) in the 1–100 range [9], whereas the majority of second graders produced estimates consistent with a linear function in the 1–100 range and logarithmic distribution of estimates in the 1–1000 range, and the majority of sixth graders produced linear distributions even in the 1–1000 range [9]. Altogether, these results suggest a developmental, representational shift from a logarithmic to linear representation of the mental number line.

This shift occurs over the course of formal education, and positive relation can be found between number line estimation and mathematical performances [12], but logarithmic tendencies can reappear even in adults under conditions of high attentional load. For example, Anobile, Cicchini [13] examined number line estimation task performance using non-symbolic stimuli (dot patterns) with number lines ranging between 1 and 10 or 1–30 dots, with and without an additional attention task. They found that the use of the linear scale was dependent on attentional resources. Namely, in the single task condition, they found participants used a linear scale, while in the dual task condition, participants used a logarithmic-like scale.

However, there is a debate regarding the nature of the number line estimation task. Siegler & others [8,9,14] view the number line estimation task as a measure of pure estimation, while others argue that performance is a reflection of employed strategies, such as use of reference points. For example, Barth and Paladino [11] argued that number line estimation task performance relies on proportion estimation strategies, and recent developmental studies have found that this approach can explain the estimation data from children better than the logarithmic to linear shift explanation [15,16]. Proportion estimation strategies involve a focus on a part of the line, such as the reference points, which produces a bias in estimation that is reflected in more

* Correspondence to: Seymour Fox School of Education, The Hebrew University of Jerusalem, Mount Scopus, Room 469, Jerusalem 91905.
E-mail address: sarit.ashkenazi@mail.huji.ac.il (S. Ashkenazi).

http://dx.doi.org/10.1016/j.tine.2017.09.001
Received 6 October 2016; Received in revised form 15 August 2017; Accepted 10 September 2017
Available online 12 September 2017
2211-9493/

precise estimations closer to the reference point compared to further away from it. Barth and Paladino proposed that the developmental shift from logarithmic to linear representation [8,9,14] can be better explained by the improvement in using the reference points strategy, which advance over the course of development. They suggest that 1st graders used the beginning of the line as a single reference point, while 2nd graders used both endpoints, and typically by 3rd grade children's strategy was similar to adults and they used multiple reference points, including both endpoints and the midpoint. The tendency of using multiple reference points improves number line estimations [12]. Familiarity of numbers and understanding of the base-ten structure can serve as an explanation of the improvement in the usage of multiple reference points in the number line estimation task during development [17].

In addition to estimation and proportion estimation strategies, multiple cognitive skills can be involved in number line estimation task performance. In a longitudinal, developmental study, LeFevre, Fast [18] examined number line estimation task performance along with a comprehensive battery of math and cognitive tasks. They found that quantity comparison, linguistic skills and spatial working memory (WM) measured in preschool each independently predicted number line estimation performance during elementary school. Therefore, the question whether the number line estimation task reflects pure numerical estimation, strategies employed, or other cognitive skills is still largely open.

This question is also reflected in the hybrid of cognitive skills required for math tasks, which can require WM, quantitative understanding and linguistic skills [18–20]. WM is one of the most studied domain general processes examined in numerical cognition research [20–27]. The multicomponent view of WM makes a distinction between WM, which is responsible for the short-term storage of verbal or visuospatial information, and the central executive, which is responsible for the manipulation of information and high-level monitoring and control [28–30]. Studies have examined the relationship between the components of WM and math performance [24,31]. In accordance with the multicomponent view, verbally mediated math, such as retrieval of well-learned arithmetical facts, relies on verbal WM, while estimation tasks require spatial-numerical representations and rely on visuospatial WM [24,31].

More up-to-date theoretical views further break down the components of WM and differentiate between spatial and visual WM [32,33]. Visual WM includes storage of object properties such as shape, color or identity, while spatial WM includes storage of location or movement [34,35]. Several studies, based on the dual task paradigm, have found dissociations between visual and spatial WM. The dual-task paradigm is a frequently used approach for studying WM subsystems; a participant engages in two tasks simultaneously, one is the primary task of interest and the other is a secondary task designed to create a strain on WM. The goal of this approach is to understand underlying cognitive skills required of the primary task; if simultaneous performance of the secondary task decreases performance in the primary task then it is concluded that they share a common resource.

To contribute to the debate on the nature of the number line estimation task, the current study employed a dual task paradigm, while participants engaged in the number line estimation task they simultaneously performed a WM task. The main goal was to examine which WM component relates to number line estimation task performance, and therefore, we compared the single task condition with three dual task conditions, one for each WM subsystem: phonological WM, visual WM and spatial WM.

According to the proportion estimation view, phonological WM load would influence number line estimation task performance due to the proposed importance of symbolic representation of numbers and place value that influences usage of reference points [11]. While, according to the more traditional approach [8,9,14], spatial WM load would create interference with number line estimation performance, as seen in previous studies and based on the relationship between number representation and space. Furthermore, since spatial and visual processing are two different aspects of visual processing resulting in two distinct WM systems, we expected to find divergent effects of these loads on the task. Weakness in spatial and not visual WM can be found in children with developmental dyscalculia [26]. Hence, we expected to find greater interference in number line estimation task performance under spatial WM load compared to visual WM load.

2. Methods

2.1. Participants

The participants were 22 undergraduate students (19 women and 3 men) from the Seymour Fox School of Education at the Hebrew University of Jerusalem (mean age = 24.23, SD = 2.39). The participants received course credit for their participation. All the participants performed all four experimental conditions (described below). The number line used in the experiment had a left to right orientation, and therefore, only participants whose mother tongue language writes numbers from left to right were included (languages such as Arabic use the Hindu-Arabic numeral system which writes numbers from right to left). We also restricted the experiment to participants without color blindness, due to required color recognition and differentiation in the visual WM task.

2.2. Stimuli and procedure

We built the experiment using E-Prime software. The experiment included 4 tasks: a single task condition entitled no load, which was the task of interest, the number line estimation task, and 3 dual task conditions, which in addition to the number line estimation task included a WM task with either a spatial, visual or phonological load. Prior to each of the dual tasks conditions individual WM span (spatial, phonological or visual) was assessed for each participant. The experimenter counterbalanced the condition order between participants, such that they all performed each of the dual task conditions, and were divided into 4 groups based on task order: group 1: 1. No load, 2. spatial span and WM load, 3. visual span and WM load, 4. phonological span and WM load. Group 2: 1. Spatial span and WM load, 2. Visual span and WM load, 3. Phonological span and WM load, 4. No load. Group 3: 1. Visual span and WM load, 2. Phonological span and WM load, 3. No load, 4. Spatial span and WM load. Group 4: 1. Phonological span and WM load, 2. No load, 3. Spatial span and WM load, 4. Visual span and WM load.

2.2.1. Number line estimation task: single task condition

Each trial included a picture of a number line, with the values "1" and "1000" on the endpoints and a target number was presented on the top of the screen, above the middle of the number line (see Fig. 1). The participant had to select the correct spatial location of the target number on the number line using the forced choice method of two choices marked on the line. Participants were instructed to select the correct location as fast and accurately as possible. Based on evidence that the mental number line is arranged logarithmically, in accordance with the Weber-Fechner law [38], we generated distracter locations proportionate to the target location. Based on 16 different targets, we constructed 4 trials per target, each with a different type of distracter. The distracters were characterized by value, which was greater or less than the target, and distance, which was close (10% greater or less than the target), or far (20% greater or less than the target). For example, for the target "640", the distracter that was 10% greater was "704". The task included 64 different trials, which we randomized and divided into 8 blocks of 8 trials to match the paradigm to the dual task conditions. At the end of each block participants were instructed to take a break and then press the space bar to continue; in most cases they continued immediately to the next block.