



## Processing ordinality and quantity: ERP evidence of separate mechanisms

Orly Rubinsten<sup>a,c,\*</sup>, Sury Dana<sup>a,c</sup>, Dmitri Lavro<sup>b,c</sup>, Andrea Berger<sup>b,c</sup>

<sup>a</sup> Edmond J. Safra Brain Research Center for the Study of Learning Disabilities, Department of Learning Disabilities, University of Haifa, Israel

<sup>b</sup> Department of Psychology and Zlotowski Center for Neuroscience, Ben-Gurion University of the Negev, Beer-Sheva, Israel

<sup>c</sup> Center for the Neurocognitive Basis of Numerical Cognition, Israel Science Foundation, Israel

### ARTICLE INFO

#### Article history:

Accepted 15 April 2013

Available online 14 May 2013

#### Keywords:

ERP

Ordinality

### ABSTRACT

We report an event-related potential (ERP) experiment of ordinal processing exploring the relationship between ordinal and numerical information.

ERPs were recorded from healthy adults while making *ordered/non-ordered* judgments on 3 non-symbolic numerical stimuli (arrays of dots). Three main variables were manipulated: (1) **Ordinality** (ordered vs. non-ordered groups of dots), tapping the quick “gist” estimation of ordinality. (2) **Direction** (ascending vs. descending order), tapping the symbolic, culturally influenced aspect of ordinality, and (3) **Ratio** between the group of dots, tapping the processing of the basic numerosity information. Behavioral results showed independent effects for each variable, replicating our previous findings with this paradigm. ERP effects differentiated between three cognitive processes for estimating ordinality, processing numerosity, and direction. This differentiation was found both in terms of timing and topography: Order estimation was associated with early scalp parietal and lateral occipital positivity (80–130 ms) originating in the left Middle Temporal Gyrus; numerical ratio was associated with a later scalp medial posterior positivity (130–200 ms); and direction was associated with a late and widespread scalp right frontal and scalp right parietotemporal positivity and a corresponding scalp left frontal and scalp left parietotemporal negativity (300–600 ms).

A theoretical model is suggested, stressing an early and basic ordinal-specific mechanism.

© 2013 Elsevier Inc. All rights reserved.

### 1. Introduction

In the last two decades the field of numerical cognition has developed immensely and major strides have been made toward understanding the brain and cognitive mechanisms involved in arithmetic reasoning. Nevertheless, the research community is still struggling to define and conceptualize numerical cognition, especially with respect to understanding the building blocks of numerical cognition such as processing quantity and ordinality. Ordinality refers to the relative position in a sequence (for full discussion of definitions of ordinality see [Sury & Rubinsten, 2012](#)) and is a multidimensional construct involved in numerical processing (e.g., [Jacob & Nieder, 2008](#); [Nieder, 2005](#)), reading (e.g., [Davis, 2010](#)), planning, and learning (e.g., [Gobel, Parrish, & Reber, 2011](#)). In the current study, we focus on the numerical dimension of ordinality and argue that it is a basic perceptual cognitive construct. A simple example from daily life may help us demonstrate different aspects of numerical processing. Let's take the example of looking for a specific seat in a concert hall. The numbers on the last seat

indicate numerical quantity or numerosity (e.g. there are 250 seats in the room), namely the cardinal aspect of this number; secondly, the number on the seat indicates the position of the item in a sequence (e.g. the two hundred and fiftieth seat), which is the ordinal aspect of the number ([Jacob & Nieder, 2008](#); [Nieder, 2005](#)). The processing of cardinal quantity, or numerosity, has been extensively investigated, and findings consistently show that the ability to process quantities is part of a “cognitive core knowledge” associated with evolutionarily ancient and specialized cerebral subsystems ([Cantlon, Platt, & Brannon, 2009](#); [Dehaene, 1992, 1997](#); [Feigenson, Dehaene, & Spelke, 2004](#); [Spelke, 2000](#)). In contrast, the nature of ordinality has received scant research attention, despite the fact that both quantity and ordinality are embodied in numerical information. Also, the theoretical and functional structure of ordinality remains under debate. For example, whereas one model argues for a single cognitive and biological resource for storing and manipulating ordinal and quantitative information (e.g., [Fias, Lammertyn, Caessens, & Orban, 2007](#); [Fulbright, Manson, Skurdlasky, Ladadie, & Gore, 2003](#); [Ischebeck et al., 2008](#); [Kaufmann, Vogel, Starke, & Schocke, 2009](#)), another proposes two separate pools of ordinality and quantity representations (e.g., [Delazer & Butterworth, 1997](#); [Zorzi, Di Bono, & Fias, 2011](#); single case study: [Turconi & Seron, 2002](#);). Specifically, several recent papers ([Fias et al., 2007](#); [Ischebeck et al., 2008](#); [Kaufmann et al.,](#)

\* Corresponding author at: Edmond J. Safra Brain Research Center for the Study of Learning Disabilities, Department of Learning Disabilities, University of Haifa, Israel. Fax: +972 (0)4 8240911.

E-mail address: [orly.rubinsten@gmail.com](mailto:orly.rubinsten@gmail.com) (O. Rubinsten).

2009) compared the neural bases of symbolic ordinality and numerical processing by using functional magnetic resonance imaging (fMRI) and contrasting brain activation during symbolic numerical comparisons (e.g., which comes first – 3 or 9) with brain activation during comparisons of non-numerical stimuli carrying ordinal information (letters and months). These studies found that the anterior Intraparietal Sulcus (IPS) responds equally to both numerical and non-numerical ordinal information. These findings suggest that the anterior region of the IPS may be involved in abstract representation of ordinal information that is not number-specific. Hence, domain-general representations of ordinal information are involved in any type of stimulus that embodies ordinal information, such as numerical, magnitude, and alphabetical stimuli. Kaufmann et al. (2009) also found that when presented with three written numbers or three abstract symbols of different size, the IPS is involved in processing numerical and non-numerical ordinal information not only in adults but also in children. These findings suggest that ordinal judging is not an ‘adult ability’ but rather might develop early in life. However, Zorzi et al. (2011) used support vector machines to reanalyze the data of Fias et al. (2007). They found a clear behavioral dissociation between processing numerical vs. alphabetical orders in bilateral horizontal IPS. These findings support previous neuropsychological studies with brain damaged patients (e.g., Delazer & Butterworth, 1997; Turconi & Seron, 2002). Specifically, Delazer and Butterworth (1997) introduced SE, an acalculic patient with impaired processing of cardinal meaning but a preserved ability to process the ordinal meaning of numbers. SE, who suffered from a left frontal infarct, was unable to access the cardinal meaning of numbers (i.e., deficiencies in calculation tasks and an inverse distance effect in number comparison), yet was able to answer correctly “which number comes next?” questions. Turconi and Seron (2002) reported a reverse dissociation. They described a patient with right parietal lesion whose processing of the order of words that denote ordinal information (i.e., numbers, letters, days and months) in various tasks was impaired, while showing better performance in processing quantity information.

Together with Fias et al.’s finding these single case studies suggest that ordinal and quantity processing dissociate at both the behavioral and biological levels.

Here, and based on previous findings (Rubinsten & Sury, 2011), we propose three distinct components of numerical processing: (a) ordinal processing; (b) quantity/numerosity processing; (c) processing of acquired linguistic information (e.g., direction of reading and writing). To be able to separate these three components we use not only the Event-Related Potentials (ERPs) methodology, which is capable of distinguishing between different temporal stages of processing, rather we also use a novel cognitive computerized task that enables us to separate cognitive representations of order, quantity, and direction. Indeed, a major obstacle to the study of cognitive and neural correlates of ordinality lies in the difficulty of teasing apart, at the cognitive level of analysis, processes that vary in their involvement with either ordinal or quantity processes. Under normal conditions, these processes are inseparably bound together; i.e., when viewing numbers people process both quantity and order. To better separate ordinal processing from quantity processing (Sury & Rubinsten, 2012) we developed a task in which Hebrew speaking participants were asked to decide if a series of three briefly presented groups of dots (in one slide) are organized in an ordinal fashion or not (without considering whether they are ascending or descending). No symbolic information is given and counting is not possible due to the brief presentation time. Moreover, low visual features, such as the density of the dots or the area they occupy, may be used to estimate order since they correspond with the quantity of dots in the stimuli. Hence, we operationally manipulated these two variables to control for any cognitive process other than order processing. As will be discussed below, within this task,

systematic and controlled manipulation of the ratio between two adjacent groups of dots can affect quantity processing, systematic manipulation of order (ordered vs. non-ordered group of dots) should affect ordinal processing as well, and finally, manipulation of the direction in which the three groups of dots are presented (ascending vs. descending) is related to acquired linguistic abilities.

### 1.1. Manipulating numerical ratios between stimuli to indicate numerical representation

Although numbers can be written in multiple notations, such as words or Arabic numerals, the parietal lobes are thought to comprise a notation-independent representation of quantities (e.g., Cohen Kadosh, Cohen Kadosh, Kaas, Henik, & Goebel, 2007; Roggeman, Santens, Fias, & Verguts, 2011). This imprecise cognitive and biological system is shared across development stages and across species and is dedicated to representations of the approximate cardinal value of a group (Cantlon et al., 2009; Feigenson et al., 2004; Piazza, 2010). One major signature of this non-symbolic core numerical representation is that comparisons are subject to a ratio limit: accuracy declines and reaction time (RT) increases as the ratio of the numbers compared approaches one (i.e., the ratio effect. e.g., Barth, La Mont, Lipton, & Spelke, 2005; Barth et al., 2006; Cantlon & Brannon, 2006; Dehaene, 1997; van Oeffelen & Vos, 1982). Similarly, the larger the distance between two numbers to be compared the quicker the response (i.e., the Distance Effect. E.g., Ansari, 2008).

A positive component at around 200–250 ms (ms) post stimulus onset has been shown in ERP studies to respond to numerical ratio or distance in both symbolic number comparison tasks and nonsymbolic passive viewing tasks (Dehaene, 1996; Hyde & Spelke, 2009, 2012; Libertus, Woldorff, & Brannon, 2007; Pinel, Dehaene, Rivière, & LeBihan, 2001; Szűcs & Csépe, 2004; Szűcs, Soltész, Jármi, & Csépe, 2007; Temple & Posner, 1998). We tested the ratio effect by analyzing the ERP during this time window of interest (around 200 ms post stimulus onset), identifying significant differences between small and large numerical ratios.

### 1.2. Dissociating ordinal and quantity processing

Turconi, Campbell, and Seron (2006) compared a number comparison task (4–9; which is larger) with an ordinal judging task (4–9; ascending or descending order) and found (1) a reverse distance effect (the smaller the distance between numbers the quicker the response) in the order task and (2) a reduced distance effect in the number comparison task when the numbers were presented in an ascending order (4–9). Turconi et al. suggested that the reverse distance effect may reflect specific ordinal related processes such as serial search or direct recognition of order for sequential numbers. They also suggested that the reduced distance effect for ascending pairs in the number comparison task may reflect an ordinal related process that involves number comparison and may be one of the processes underpinning the distance effect in addition to magnitude representation. This is compatible with recent findings suggesting that there might be a specific brain area that is dedicated to general processing of ordinal information (in this case, the brain area is the left inferior frontal gyrus; Van Opstal, Fias, Peigneux, & Verguts, 2009). For example, in the study by Turconi, Jemel, Rossion, and Seron (2004), participants performed a quantity task (judging whether a number is larger or smaller than a target number) and an ordinal task on the same type of stimuli (judging whether a number comes before or after the target number) and similarly with letters. Despite similar behavioral effects of ordinality and quantity, they were found to be associated with different spatio-temporal courses in parietal and

prefrontal cortices. These findings suggest that the two processes, quantity and ordinality, are dissociated.

Accordingly, it might be interesting to ask whether humans are able to implicitly and selectively estimate order (as part of their core abilities) without needing to extract any additional information, such as quantity. Estimation of numbers or quantities relates to the strategy employed when a stimulus configuration is comprised of a large number of items and is presented briefly (Pavese & Umiltà, 1998). It is an intuition available to humans regardless of language and education and, hence, estimation is considered to be part of the core numerical system (Dehaene, 2009) and innately available to humans and non-human beings (i.e., animals; Cantlon et al., 2009). But can we estimate order as well? Do we automatically or unconsciously analyze and perceive visual, auditory, or any other scene of daily life based on order? If we do, one might expect to find a very early perceptual component, such as the early visual P1 component, to be involved with ordinal estimation. P1 is a positive component that typically begins around 70–90 ms with a peak at around 80–130 ms (Mangun, 1995), which has been traditionally identified primarily (although not exclusively) as an early sensory/perceptual response (e.g., Anllo-Vento & Hillyard, 1996; Luck, Heinze, Mangun, & Hillyard, 1990; Nikolaev, Gepshtein, Kubovy, & van Leeuwen, 2008). To the best of our knowledge, to date, no study has tested ordinal estimation, presenting a large quantity of non-symbolic numerical information and requiring extraction of ordinal information. Accordingly, in order to study the effect of ordinality we focus here on the P1 timetable as an optional and hypothesized component of ordinality.

### 1.3. Manipulation of ascending vs. descending order to indicate symbolic order representations

A wide range of work has shown that small-magnitude values are associated with the left side and larger values with the right side of space (for a recent meta-analysis, see Dehaene, Bossini, & Giroux, 1993; Wood, Nuerk, Willmes, & Fischer, 2008). Accordingly, it seems that people also place smaller numbers further to the left of a mental number line than larger numbers when enumerating objects or processing magnitudes. Such findings have been interpreted as reflecting the effect of directional reading or writing habits. For example, a reverse mental number line was found among Iranian participants, who habitually read Arabic script from right to left but were only recently immersed in a left-to-right reading culture (Dehaene et al., 1993, experiment 7). Another example is the reverse mental number line found when Palestinian participants read Arabic words and Arabic–Indic numbers from right to left (Shaki, Fischer, & Petrusic, 2009) (for similar findings among Hebrew vs. English native speakers see Fischer, Mills, & Shaki, 2010). This may suggest that processing ordered information in general may also be influenced by reading direction and is subject to cultural and educational influences (i.e., related to the symbolic system). Indeed, Suanda, Tompson, and Brannon (2008) have shown that ascending vs. descending directions have an influence on order processing only from the age of 11 months but not at 9 months of age.

From an electrophysiological perspective, Paulsen, Woldorff, and Brannon (2010) presented different quantities of dots (non-symbolic) one after the other, and asked participants to make the same/different judgments. They found a direction effect between 320 and 440 ms (greater negativity for decreasing direction) compatible with the behavioral results of the task (quicker response to numbers presented in the ascending left to right direction). Importantly, direction effect did not interact with numerical distance, suggesting that the two types of information (distance and direction) are processed independently.

Accordingly, in order to study symbolic or acquired linguistic processing of ordinal information, we manipulated the stimuli in our non-symbolic ordinal task such that half the ordered stimuli were presented in an ascending order and the other half in a descending order. Participants were native Hebrew speakers who read and write the Hebrew language from right to left but read and write numbers from left to right. Following previous findings we hypothesized that direction would only have an effect at a late stage of processing (around 300–500 ms post stimulus onset, Paulsen et al., 2010).

### 1.4. The present study

We manipulated the ratios between the groups of non-symbolic numerical stimuli (groups of dots). In previous work, participants were presented with pairs of items (e.g., numbers, letters, months, etc.) and were asked to decide whether these pairs are presented in an ascending or descending order (e.g., Fias et al., 2007; Turconi et al., 2006) or which of the items appears earlier/later in a sequence (e.g., Brannon & Terrace, 1998; Brannon & Van de Walle, 2001). These tasks require manipulation of quantity, cardinal meaning, magnitude, or semantic information, before extracting order information and arriving at a decision. For example, in order for one to know that 4 and 8 are presented in an ascending and not a descending order, it must be initially clear that 8 is larger than 4 (i.e., a numerical comparison, extracting magnitude information), or in order for one to know that D and G are presented in an ascending and not a descending order, it must be initially clear that D appears before G in the alphabet (i.e., retrieving semantic information). We argue that in contrast to previous work, in the current task the brief presentation time and the large number of dots do not allow for serial search or for performance of three separate numerical comparisons before reaching a decision. A good way to decide if the three stimuli are ordered or not, would be to estimate ordinality (as if using intuition of order) as when estimating a large number of stimuli.

Our research questions were: (1) Is there an ordinal-specific mechanism and if so, is it associated with an early ERP component that is sensitive to estimation of ordered information? (2) Are quantity and ordinal information processed independently and are they reflected in distinct ERP components, and (3) Is the process of directional identification reflected in an identifiable scalp ERP component? To answer these questions we systematically manipulated 3 different variables: (1) ordinality (ordered vs. non-ordered groups of dots) to study estimation of order, (2) ratio (large or small ratios between the different groups of dots) to study core numerical knowledge, and (3) direction (ascending vs. descending order) to study symbolic or culturally influenced order. ERPs that are sensitive to the timing of processes may show that distinct temporal windows are affected by each of these factors.

It was hypothesized that we would find not only the typical ratio effect (suggesting numerical processing) but also a main effect of ordinality (i.e., the difference between ordered and non-ordered stimuli) independent of ratio. This would suggest a general estimation of order independent of core numerical information. Electrophysiologically, we hypothesized that separate ERP differences would be found between ordinality, quantity, and direction over the first 600 ms. We expected to find an early component (such as P1) of order vs. non-ordered stimuli (regardless of ratio or ascending/descending direction) which may suggest an automatic perceptual component of order. We also focused our analysis on an additional temporally distinct component, the P2 (around 200 ms), identified in previous studies as related to number processing and specifically to the ratio and distance effects (Dehaene, 1996; Hyde & Spelke, 2009, 2012; Libertus et al., 2007; Temple & Posner, 1998). Finally, we focused on a timetable of 300–600 ms post stimulus onset to study the effect of direction (based on Paulsen et al., 2010).

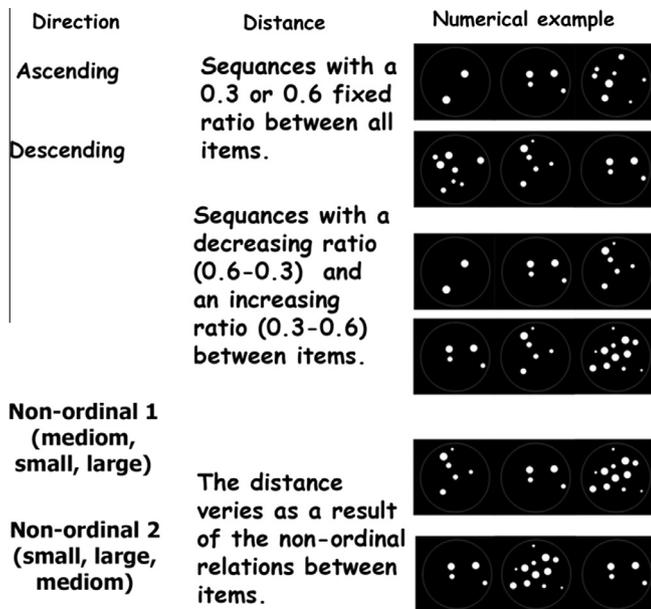


Fig. 1. Example of distance and direction manipulation.

## 2. Material and method

### 2.1. Participants

Undergraduate students at the Ben-Gurion University of the Negev participated in the experiment. All participants were native Hebrew speakers and reported to be right-handed. They were all healthy with no history of neurological illness and had normal or corrected-to-normal vision. Participants gave informed consent and participated in the study as partial fulfillment of course requirements. Data for 20 of the 25 participants were retained for analysis, while data for the other 5 participants were discarded due to poor data quality or insufficient artifact-free error trials for signal averaging. The age of the remaining sample ranged from 21.90 to 27.75 (60% female).

### 2.2. Task and design

Participants were presented with 768 stimuli composed of three groups of dots and were asked to decide, based on the number of dots in each group, if these items were presented in an ordinal fashion (whether ascending or descending) or not (no ordinal relation between all three items). The three groups of dots were ordered in an ascending direction (i.e., small, medium, large), a descending direction (i.e., large, medium, small) or in a mixed fashion that included two possible presentations: (1) medium, small, large (2) small, large, medium (see Fig. 1 for illustration). The central group of dots appeared in the center of the screen and both additional stimuli appeared on its left and right.

We also manipulated the ratio of the gaps between items in the sequence presented. The ratio between items was either constant (a ratio of 0.6 or 0.3 between each pair within the 3 items) or varied. The varied gaps included sequences with decreasing gaps (a ratio of 0.6 between first and second item and a ratio of 0.3 between second and third item in the sequence) and increasing gaps (a ratio of 0.3 between first and second item and a ratio of 0.6 between second and third item in the sequence) (see Fig. 1 for an example). In every block there were 96 sequences (which appeared twice and resulted in 192 stimuli per block). Thus, a total of 768 stimuli per task were presented.

### 2.2.1. Stimuli

Non-symbolic numerical stimuli consisted of multiple-dot patterns ranging from 1 to 20 dots per stimuli. To ensure that the ordinal task was solved by judging the order of quantities, low-level visual features were excluded by randomly manipulating area and density (for detailed description of stimuli see Appendix A).

**Procedure:** Participants were seated at a distance of 135 cm facing a 17" standard LCD computer monitor and asked to relax as much as possible in order to reduce muscle tension. They were asked to decide if the 3 groups of dots presented were ordered or not by pressing a corresponding key on the E-prime serial response box which had four keys numbered "one" through "four". If the sequence on the screen was presented in an ordinal fashion, subjects were supposed to press "one", otherwise they were supposed to press "two". Participants were informed that the sequences could appear in both directions (ascending or descending) and that both should be considered an "ordered" answer. Participants were asked to respond only when they were certain of their decision and to take their time.

Each trial began with a central fixation point presented for 500 ms (ms). 200/300/400 ms after elimination of the fixation point, the stimuli appeared, remaining in view until the participant pressed a key or for 3000 ms. The next trial started 600/700/800 ms after response onset. A block of 16 practice trials was presented first, followed by eight experimental blocks of 96 trials each: 2 directions<sup>1</sup> (ascending, descending)  $\times$  4 ratios (0.3, 0.6, 0.6–0.3, 0.3–0.6)  $\times$  2 orders (ordered and non-ordered). The sequences within the block appeared in a random order.

### 2.3. Behavioral analysis

The initial  $2 \times 4 \times 2$  design was reduced to 2 directions (ascending, descending)  $\times$  2 ratios (0.3, 0.6)  $\times$  2 orders (ordered and non-ordered) design. Increasing and decreasing ratios were only used as fillers to maintain stimuli variability, and to prevent subjects from applying unwanted strategies while performing the task. Therefore these conditions had no theoretical significance and were discarded from the analysis. We used a repeated measures analysis of variance (ANOVA) on reaction times and accuracy values. The *Ordinality* and *Ratio* processing were assessed by the corresponding main effects, while *Direction* processing was tested by planned comparison of the ascending vs. descending condition (as non-ordinal conditions have no apparent direction).

### 2.4. Electroencephalogram (EEG) recording

The EEG was recorded from 128 scalp sites using the EGI Geodesic Sensor net and system (Tucker, 1993). Electrode impedances were kept below 40 k $\Omega$ , an acceptable level for this system (Ferree, Luu, Russell, & Tucker, 2001). During EEG acquisition all channels were referenced to the VREF (Cz) channel and a 100 Hz hardware lowpass filter was used. Signals were collected at 250 samples per second and digitized with a 24-bit A/D converter.

EEG data from trials included in the behavioral analysis were processed in Netstation v4.3 (Electrical Geodesics, Oregon, USA). A 0.1–40 Hz digital band-pass filter was applied, with the output being segmented to 200 ms prior to stimulus presentation and 600 ms post stimulus. Resulting segments were subjected to an automatic bad channels and eye blink or movement detection procedure followed by visual verification. The procedure marks channels with a Max–Min difference higher than 100  $\mu$ V as bad, and segments with this difference being higher than 100  $\mu$ V or 85  $\mu$ V

<sup>1</sup> Since non ordinal sequences had no clear direction, they were assigned as ascending or descending based on the relation between the left and middle quantity in each sequence.

as containing an eye blink or an eye movement, respectively. Segments containing 10 or more bad channels, or those in which any eye activity was detected, were discarded. The minimum number of trials remaining per condition was 72. In remaining segments bad channels were interpolated and the artifact-free trials were then averaged for each subject. In order to compensate for the polar average reference effect (PARE) (Junghoefer, Elbert, Tucker, & Braun, 1999), which is caused by uneven surface sample, we referenced all channels to a PARE-corrected overall average. Using this estimation method, spherical spline interpolation is performed in order to estimate the voltages of the surface not covered by electrodes. Only then is the value of the average reference computed for the entire surface of the head, resulting in a more accurate reference. The averages were then baseline corrected, with 200 ms pre-stimulus period serving as a baseline. Finally, a grand average (average of all subjects for each experimental condition) was created. Visual inspection of grand average ERP waveforms and topographical maps, guided by previous ERP literature, led to selection of the following ERP components: For *Ordinality*, a group of parietal and lateral occipital electrodes were selected over the right and left hemisphere, in a time window of 80–130 ms after stimulus presentation. This group was located within the P4, P8, O2 (right) and P3, P7, O1 (left) of the 10–20 international standard system (Mangun, 1995). For the *Ratio* effect a bilateral group of medial posterior electrodes were selected, in a time window of 130–200 ms after stimulus presentation. This group was located within the P3, P4, P7, O1, O2, P8 of the 10–20 mapping, closely overlapping with groups of electrodes from previous ERP studies dealing with numeral processing (Dehaene, 1996; Hyde & Spelke, 2009, 2012; Pinel et al., 2001; Temple & Posner, 1998). Although Paulsen et al. (2010) found a direction effect using measurements from sites spanning the entire scalp, inspection of scalp topography and waveforms suggested that the effect was longer-latency, and less evident at posterior regions. Therefore, for the *Direction* effect a widespread group of bilateral frontal and parietotemporal electrodes were defined within the Fp1, F7, T7, C3, Fz (left) and Fp2, F8, T8, C4, Fz (right) of the 10–20 mapping, in the 300–600 ms time window.

To verify the validity of the visual inspection, the chosen components were analyzed using sample-by-sample parametric statistics (e.g., Paulsen et al., 2010; Pinel et al., 2001; Szűcs et al., 2007; Temple & Posner, 1998). Paired *t*-tests were used to compare between experimental conditions (e.g., ordinal vs. non-ordinal) at each electrode, separately for each type of processing (i.e., Ordinality, Ratio, and Direction). To reduce the probability of Type I error resulting from multiple testing, consistent differences between experimental conditions were only considered when *t* values corresponding to an alpha of 0.01, across at least 5 consecutive samples (20 ms) and 5 adjacent electrodes, were found. The results of this procedure were in line with all three components chosen. Moreover, this analysis supports the expected stream of processing, with each of the different effects becoming significant in a sequential manner, one after the other: order, ratio, direction.

As a result of artifact free segments and the inability to extend the length of the experiment without causing subjects a greater level of discomfort, we did not perform a three-way ANOVA analysis on ERP data. Alternately, each subject's adaptive<sup>2</sup> mean amplitude of *Ordinality* and mean amplitudes of *Ratio* and *Direction* components were processed using separate repeated measures ANOVAs. Due to

<sup>2</sup> We used the adaptive mean procedure that returned the mean amplitude of 6 samples (24 ms) around the positive peak defined within the 80–130 ms time window. Since the *Ordinality* component was a short latency peak component that might be highly sensitive to inter-subject latency variability and averaging across time, we used the adaptive mean method to retain a reliable measure of the component.

differences in hemispheric voltage distribution, the *Ordinality* and *Direction* components were analyzed with laterality factor (Left or Right locations on the scalp) added to the design as a within-group variable. For the *Ratio* component, no differences in hemispheric distribution were evident.

Standardized low-resolution brain electromagnetic tomography (sLORETA; Fuchs, Kastner, Wagner, Hawes, & Ebersole, 2002; Jurcak, Tsuzuki, & Dan, 2007, p. 20; Pascual-Marqui, 2002) was used to compute images of electrical neuronal activity in order to estimate the electrical neuronal generators involved in the different components. To determine regions of interest (ROIs) for the analysis, a bootstrap method with 10,000 randomized samples was used. This randomization method gives exact significance thresholds (corrected for multiple comparisons), regardless of non-normality. The localization of differences between conditions is computed by voxel-by-voxel *t*-tests for dependent measures of the average sLORETA images over the relevant time window. The ROI was chosen as a single centroid voxel at the Brodmann area showing the local maxima resulting from the randomization test. Accordingly, sLORETA values for each ROI and the relevant time frame were analyzed using a repeated-measures ANOVA with type of processing (i.e., Order, Ratio, and Direction) as within-subject variable.

### 3. Results

#### 3.1. Behavioral results

Mean error rates were low, detailed analysis was performed only on RT data of correct responses. Specifically, the mean error rate was 6% ( $SD = 2.3$ ). For all analysis of RTs, means for each participant were calculated using only the correct trials whose RTs were below 2500 ms (a total of 65 trials were excluded).

There was a significant main effect for ratio [ $F(1, 19) = 294.254$ ,  $p < .0001$ ] as a result of a lower RT for the 0.6 ratio (mean = 1002 ms,  $SD = 39$ ) than for the 0.3 ratio (mean = 1201 ms,  $SD = 47$ ). Additionally, there was an interaction between order and direction [ $F(1, 19) = 19.044$ ,  $p < .0001$ ] and a marginal interaction between ratio and ordinality [ $F(1, 19) = 4.107$ ,  $p = .057$ ] (see Fig. 2).

##### 3.1.1. Ordinality X ratio

We further analyzed the interaction between ordinality and ratio and compared ordinal to non-ordinal sequences in each ratio separately. Ordinality was significant in the 0.6 ratio [ $F(1, 19) = 4.769$ ,  $p < .05$ ] where the response to ordinal sequences was quicker (mean = 978 ms,  $SD = 40$ ) than the response to non-ordinal sequences (mean = 1026 ms,  $SD = 41$ , see Fig. 2).

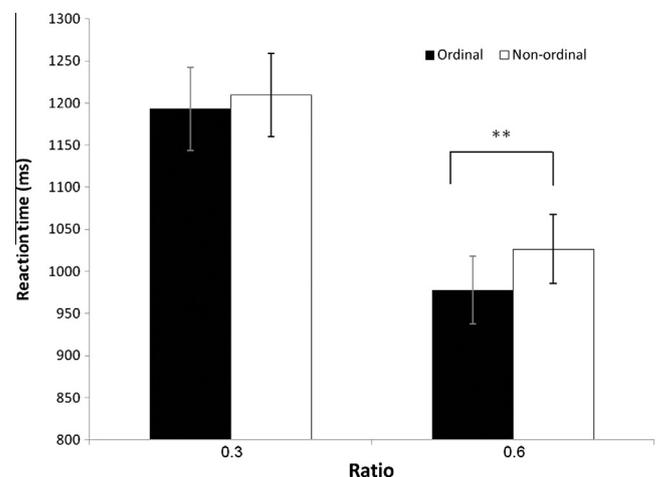


Fig. 2. Mean RT for ordinal and non-ordinal sequences in different directions.

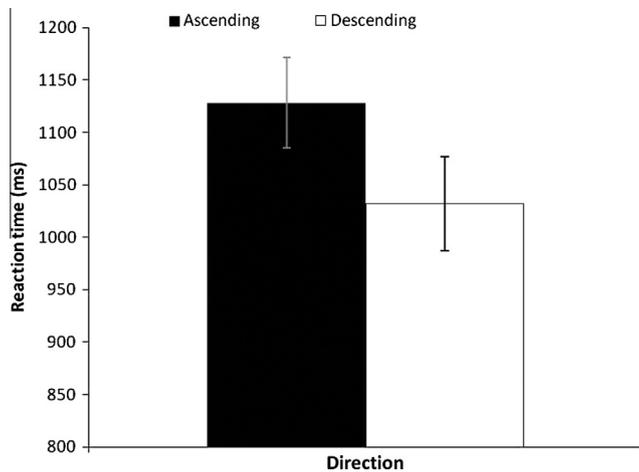


Fig. 3. Mean RT for ascending and descending sequences in different ratios.

3.1.2. Ordinality X direction

Due to the interaction between ordinality and direction we further analyzed each direction separately for the ordinal sequences and found that the response to descending sequences was significantly quicker (mean = 1041, SD = 45) than the response to ascend-

ing sequences (mean = 1129, SD = 45) [ $F(1, 19) = 27.719, p < .0001$ ] (see Fig. 3).

3.2. ERP results

3.2.1. Ordinality

Repeated measures ANOVAs on adaptive mean amplitudes of parietal and lateral occipital electrode group in the 80–130 ms post stimulus time window, with the order and laterality conditions as within-subject variables, revealed a significant order effect [ $F(1, 19) = 9.587, p < .01$ ] indicating larger positive amplitude for the ordinal sequences compared to the non-ordinal sequences. Although there was no interaction between order and laterality [ $F(1, 19) = 1.99, p = .17$ ], planned comparisons of order (i.e. ordinal vs. non-ordinal) on each scalp location (i.e. left or right) revealed a significant order effect over the right electrode group [ $F(1, 19) = 7.93, p < .05$ ], but failed to reach significance over the left electrode group [ $F(1, 19) = 1.99, p = .109$ ] (see Fig. 4a–c).

Source localization of this effect indicated that the difference between the ordered vs. non-ordered conditions seems to be localized to the left Middle Temporal Gyrus (Brodmann area 37; MNI coordinates  $X = -50, Y = -65, Z = 5$ ). Repeated measures ANOVA on sLORETA values, with order as the within-subject variable, revealed a significant order effect [ $F(1, 19) = 4.96, p < .05$ ] indicating greater activity associated with ordinal sequences compared to non-ordinal sequences (see Fig. 4d).

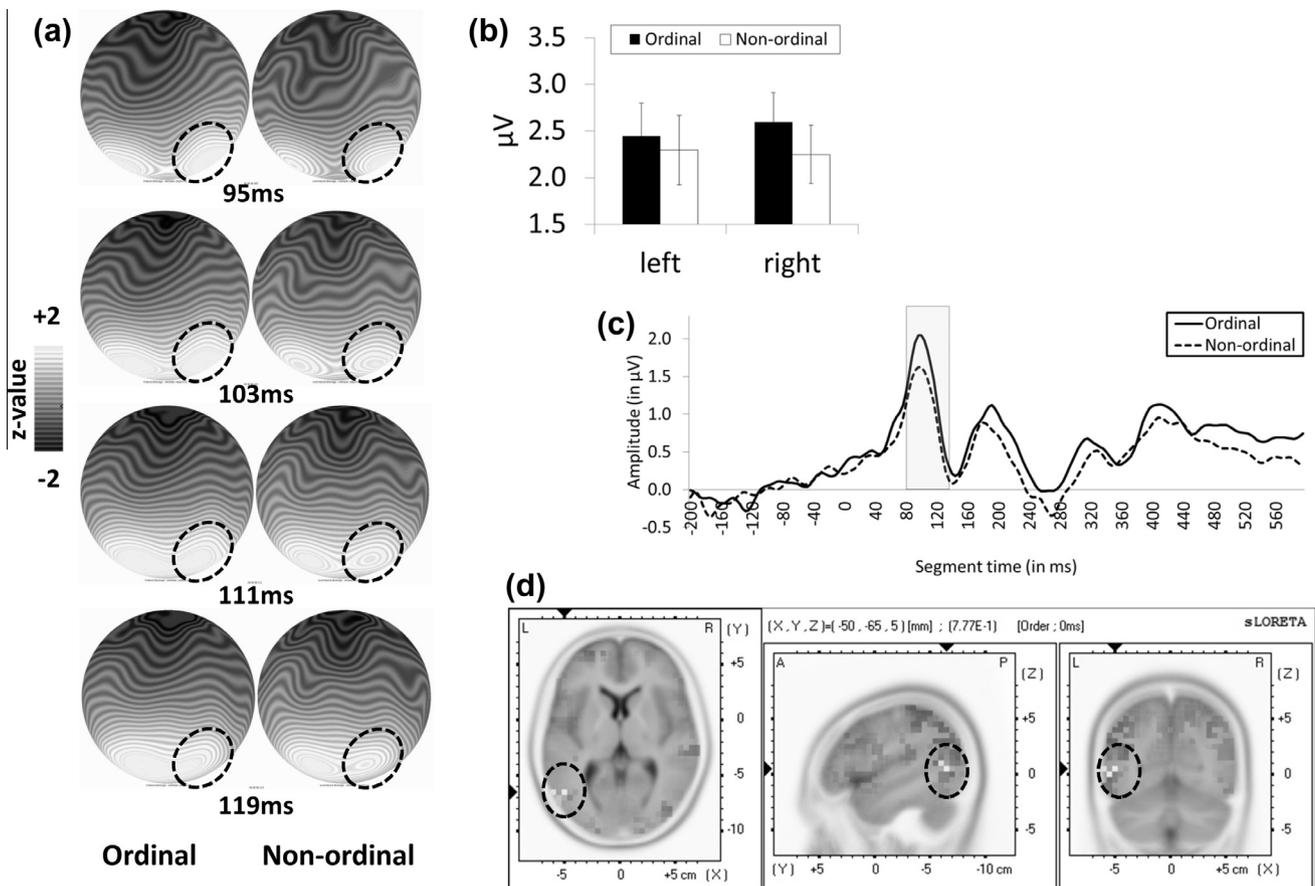


Fig. 4. (a) Grand-averaged voltage distribution in two-dimensional scalp topographic maps at 95 ms, 103 ms, 111 ms, and 119 ms post stimulus presentation. In the ordinal condition, a greater positive voltage distribution is seen over the right parietal and right lateral occipital sites. (b) Adaptive mean amplitudes and the standard error of ordinal and non-ordinal conditions by laterality. (c) Waveforms of the ordinality effect in the 80–130 ms time frame as observed over right parietal and right lateral occipital sites. (d) Graphical representation of the sLORETA *t* statistics comparing the current density estimates extracted from ERPs of the conditions. The light yellow color indicates local maxima of increased electrical activity for ordered vs. non-ordered conditions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

### 3.2.2. Ratio

Repeated measures ANOVAs on mean amplitudes of the medial posterior electrode group in the 130–200 ms post stimulus time window, with the ratio condition as the within-subject variable, revealed a significant ratio effect [ $F(1, 19) = 4.393, p < .05$ ] indicating larger positive amplitude for the 0.6 ratio compared to the 0.3 ratio (see Figs. 5a–c).

Source localization of this effect indicated that the difference between the 0.3 vs. 0.6 ratio conditions seems to be localized to the left Postcentral Gyrus of the Parietal Lobe (Brodmann area 5). However, repeated measures ANOVA on sLORETA values, with the ratio condition as the within-subject variable, failed to reach significance [ $F(1, 19) < 1$ ] (see Fig. 5d).

### 3.2.3. Direction

Repeated measures ANOVAs on mean amplitudes of frontal and parietotemporal electrode groups in the 300–600 ms post stimulus time window, with the direction and laterality conditions as within-subject variables, revealed a significant interaction between direction and laterality [ $F(1, 19) = 36.079, p < .0001$ ] (see Fig. 6a and b). This interaction effect was further analyzed by conducting planned comparisons of direction (i.e. ascending vs. descending) on each scalp location (i.e. left or right). The analysis revealed significant direction effect over the left electrode group [ $F(1, 19) = 32.346, p < .0001$ ], indicating larger negative amplitude for descending compared to ascending sequences. This in addition to a significant direction effect over the right electrode group [ $F(1, 19) = 8.118,$

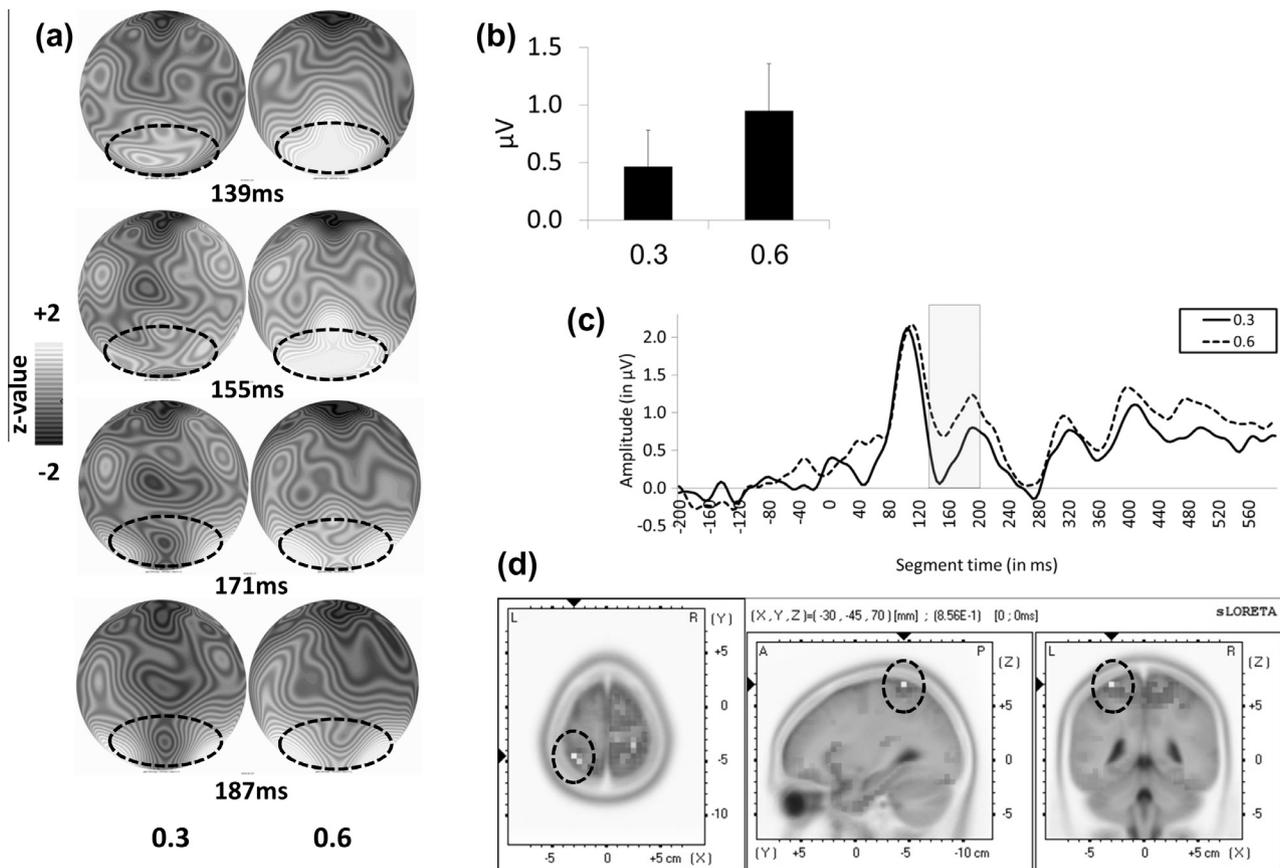
$p < .05$ ], indicating larger positive amplitude for descending compared to ascending sequences (see Fig. 6c).

The sLORETA analysis of this effect showed very diffuse activity and no specific and reliable ROI could be chosen for source localization.

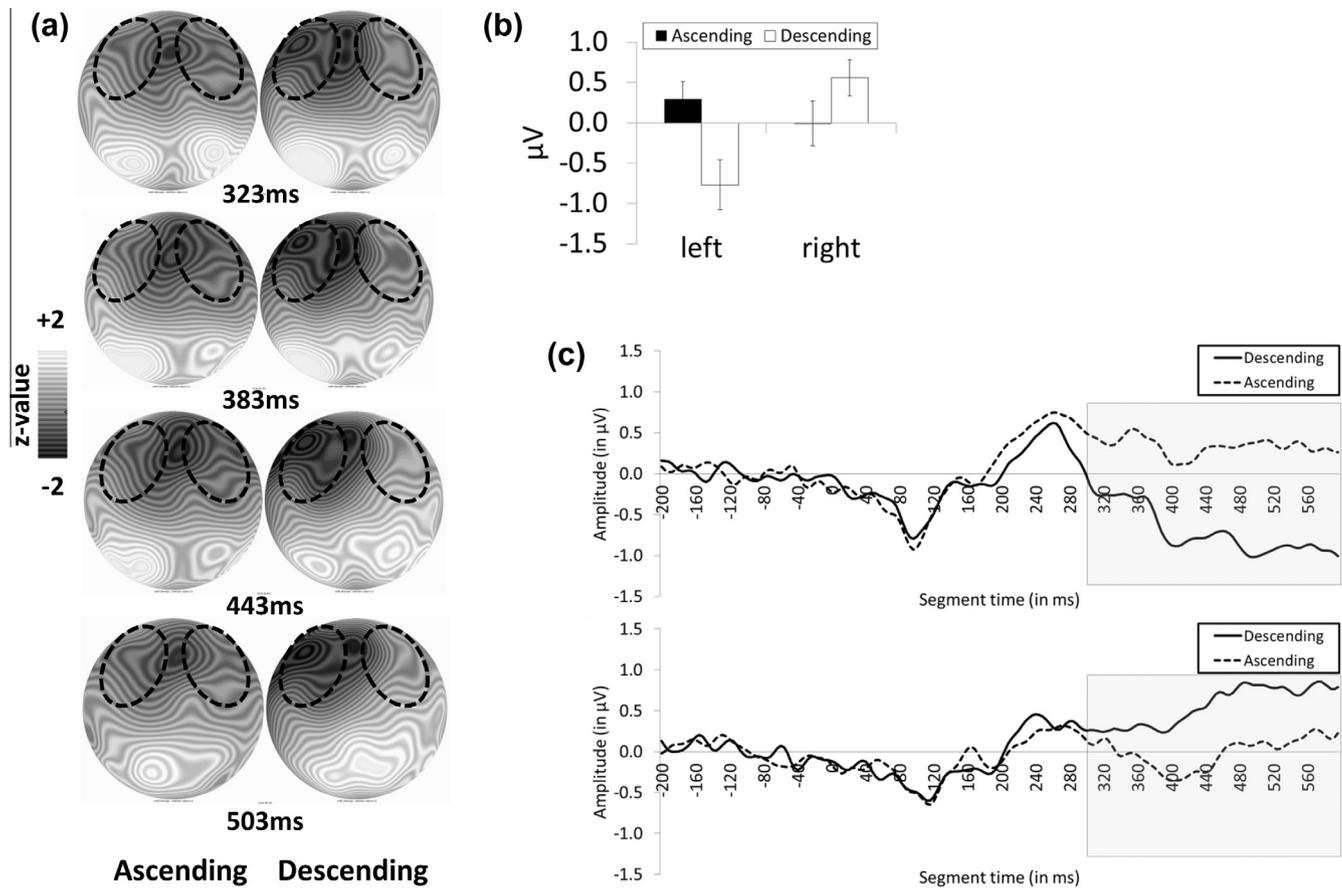
## 4. Discussion

The present study was designed to explore the process of ordinal information as reflected by the behavioral level in reaction times and at the brain activity level in ERPs. More specifically, our questions were: (1) Can **order**, **quantity**, and **direction** be differentiated at the behavioral level? Do these processes have independent effects? (2) Can these processes be differentiated at the ERP level? What is their timeline? and (3) Is the direction of ordered sequences processed at a different stage? In general we wanted to learn about the timing within the timeline of these processes. The results seem to have provided interesting answers to these questions.

Behaviorally, the current findings are similar to our previous study (Rubinsten & Sury, 2011). We show here that intact developing adults are able to process ordinal information. Additionally within the ordered sequences, it seems that acquired linguistic skills (such as direction) may act as a medium which facilitates the processing of core representations such as ordinal information. Hence, our behavior findings show an interaction between order and direction (which, as indicated in the Introduction, is influenced by learned direction of reading and writing). However, and



**Fig. 5.** (a) Grand-averaged voltage distribution in two-dimensional scalp topographic maps at 139 ms, 155 ms, 171 ms, and 187 ms post stimulus presentation. In the 0.6 condition, a greater positive voltage distribution is seen over the medial posterior sites. (b) Mean amplitudes and the standard error of 0.3 and 0.6 conditions. (c) Waveforms of the ratio effect in the 130–200 ms time frame as observed over the medial posterior sites. (d) Graphical representation of the sLORETA  $t$  statistics comparing the current density estimates extracted from ERPs of the conditions. The light yellow color indicates local maxima of increased electrical activity for 0.6 vs. 0.3 conditions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 6.** (a) Grand-averaged voltage distribution in two-dimensional scalp topographic maps at 323 ms, 383 ms, 443 ms, and 503 ms post stimulus presentation. In the descending condition, a widespread negative voltage distribution is seen over the left frontal and parietotemporal sites, in addition to a positive voltage distribution over the right frontal and parietotemporal sites. (b) Mean amplitudes and the standard error of ascending and descending conditions by laterality. (c) Waveforms of the direction effect in the 300–600 ms time frame as observed over left (top) and right (bottom) electrode sites.

contrary to our ERP data, from a behavioral perspective ordinality was significant only for a large ratio between items within the sequences (i.e. a ratio of 0.6). Several other studies have clearly shown that effects that are not evident or clearly evident behaviorally do exist biologically (e.g., Price, Holloway, Vesterinen, Rasanen, & Ansari, 2007, who found only accuracy but no RT differences between Developmental Dyscalculia (DD) and control in contrast to significant differences in IPS activation). This supports our claim that ordinality may be a core system for implicitly processing ordered representation. The fact that it is implicit and automatic may hamper the ability to note such implicit core functions behaviorally but not necessarily biologically.

Electrophysiologically, regardless of the ratio between the three groups of dots, the amplitude of the ERP wave between 80–130 ms after stimulus onset was modulated by the ordinal information (i.e., ordered vs. non-ordered stimuli) and showed a restricted parietal and lateral occipital distribution. Such timing and scalp distribution lead us to suggest that this early positive component is an ordinal related activation of P1 (Spehlmann, 1965). P1 is typically elicited by external stimuli that are strongly influenced by stimulus parameters, such as luminance, spatial frequency (e.g., Hansen, Jacques, Johnson, & Ellemberg, 2011) or depth (i.e., 2 vs. 3 dimensional stimuli; e.g., Omoto et al., 2010). It should be noted that the current ordinal effect has been found to resist extensive manipulation of the non-numerical parameters of the display, thus evading simple explanations in terms of density or area. In contrast to the P1 and consistent with previous findings, a later positive component, ranging roughly from 130–200 ms, was modulated by the ratio between the different numerosities presented. That is, as can be

seen in the topography, the absolute amplitude size is larger for larger ratios compared to smaller ones. In line with former studies (e.g., Piazza, Pinel, Le Bihan, & Dehaene, 2007, who showed a stimulus-independent coding of numerical magnitude in the bilateral IPS), the current ERP “distance effect” was salient bilaterally. The timing of the numerical (ratio) effect is in line with prior observations demonstrating parietal distance effects of between 124 and 300 ms (Dehaene, 1996; D.C. Hyde & Spelke, 2009, 2012; Libertus et al., 2007; Pinel et al., 2001; Szűcs & Csépe, 2004; Szűcs et al., 2007; Temple & Posner, 1998). Finally, direction (ascending vs. descending order) was associated with a widespread, late right frontal and right parietotemporal (300–600 ms) positivity as well as left frontal and left parietotemporal negativity. We elaborate on theoretical and practical implications below.

#### 4.1. Estimating order: Do we count or do we in fact estimate order?

Behaviorally, our data indicates that participants were not verbally counting in the ordinal task. Specifically, participants’ response times to the 4, 8, 16 stimulus, for example, were on average only 200 ms longer than to the 2, 4, 8 stimulus. If participants had been covertly counting, they should have taken at least twice as long to enumerate 28 (4, 8, 16) as opposed to 14 (2, 4, 8) elements, assuming an equal counting time per object and a linear increase in RT from one quantity to the other (e.g., Schleifer & Landerl, 2011). Hence, it is unlikely that participants were verbally counting. It seems likely that they relied on the analog nonverbal system for representing order, hypothesized here to underlie ordinal numerical processes.

The ERP evidence is also consistent with the claim that order is perceived at an early stage. As mentioned, the “order” manipulation effect was found in the P1 time window and scalp distribution. P1 is recorded at around 100 ms at occipital sites, and is probably generated by the extrastriate cortex (Bentin & Deouell, 2000; Mangun, 1995). The current result indicates that differences in visual features across stimuli affected the P1 component. These visual features are interpreted here as variation in the ordinal aspect of the stimulus. This early component is particularly interesting, as it has been shown in healthy participants that complex visual analysis can be carried out within the first 100 ms; for example, visual evoked potentials differentiate previously seen faces from novel faces as early as 50 ms after stimulus onset (Braeutigam & Switkenby, 2003; Seeck et al., 1997). Here, any visual analysis (e.g., density or area) is statistically averaged to zero because it was randomly presented. Accordingly, and taking the behavioral as well as the ERP data together, we argue that P1 is also associated with an early visual mechanism dedicated to analyzing ordinal information and providing a sensory representation of order to higher-level perceptual systems (e.g., systems that process quantity or direction). More specifically, we argue that P1 here reflects implicit estimation of ordinal information. The source localization of the effect is certainly consistent with the idea that the order information was processed within the dorsal “what” visual cortical pathway extensively studied in monkeys (e.g., Ungeleider & Mishkin, 1982) and humans (e.g., Goodale & Milner, 2004).

#### 4.2. Processing quantity information

The current results accurately replicate previous ERP findings dealing with distance or ratio effects. Hyde and Spelke (2009), for example, found that large numbers modulate a mid-latency ERP component at around 200 ms post stimulus onset (P2p) by a ratio of change irrespective of cardinal value. Also, Dehaene (1996) reported an ERP component associated with the distance effect for both Arabic numerals and written number words at electrodes at the parieto-occipito-temporal junction from 174 to 230 ms after stimulus onset. We tested the ratio effect by analyzing the ERP during this time window of interest (around 200 ms post stimulus onset), and indeed found significant medial posterior differences between small and large numerical ratios at 130–200 ms post stimulus onset.

One potential explanation for the above pattern of findings may be that there are two separate representations of ordinal and quantity information. When considering this suggestion, our findings may contribute a novel argument to the literature, namely, that the specific requirement for intact development of arithmetical skills is not necessarily quantity processing, or at least not only quantity processing, but ordinality as well. In particular, in our study, the noticeable separation between ERP components of quantity and ordinality provides support for invoking two systems; both, together or separately, may underlie arithmetical knowledge. Such an argument contrasts with a major alternative view, which assumes that the cognitive deficit of people with math learning disabilities results from a core deficit of quantity processing (and not ordinality) (e.g., Wilson & Dehaene, 2007). Moreover, it is theoretically assumed that non-symbolic, preverbal quantitative knowledge acts as building blocks for higher numerical knowledge (Butterworth, 2005). Both arguments regarding the cognitive and biological source of DD and higher arithmetical abilities (which involve quantity but not ordinal processing) may require further investigation. Indeed, systematic investigation of the issue of quantity processing as the building blocks of arithmetic, shows that this is not always the case. For example, Holloway and Ansari (2009) showed that only the symbolic, but not the non-symbolic distance effect (i.e., the inverse relationship between numerical distance

and reaction time in number comparison tasks) seems to be a predictor of later math performance. This finding challenges the notion that non-symbolic number processing may be a building block for (symbolic) arithmetic skills and may suggest that other non-symbolic constructs such as ordinality form the basis of arithmetic. Future studies might better investigate relationships between ordinality and arithmetic.

Although the Loreta results for the ratio effect were not significant, their plausible localization was found at the postcentral gyrus of the Parietal Lobe. A recent coordinate-based meta-analysis (Kaufmann, Wood, Rubinsten, & Henik, 2011) tried to identify brain regions that are commonly activated in fMRI studies investigating number processing and calculation in children vs. adults. Results of this meta-analysis proposed that children activate more anterior intraparietal regions (specifically, intraparietal activation foci in response to non-symbolic number processing are found adjacent to the anterior IPS – TC 40, –36, 46, and extending to the postcentral gyrus – TC 48, –26, 54). Our findings, despite being marginal, are consistent with these findings. Kaufmann and colleagues suggested that activations in postcentral gyrus and neighboring anterior IPS may reflect a link between fingers and number processing (Butterworth, 2005; Gracia-Bafalluy & Noël, 2008; Kaufmann et al., 2008). Similar to Kaufmann’s suggestion and together with our previous argument, a potential explanation of the current findings is that non-symbolic ordinal tasks may elicit numerical finger-based solution strategies. These finger based strategies may result from initial counting habits which are based on **both** quantity and ordinal information (e.g., Gallistel & Gelman, 1992), again, supporting our two separate core systems – quantity and ordinality.

#### 4.3. Direction

The ordinality effect appeared, both behaviorally and electrophysiologically (i.e., amplitude size), to be stronger in the descending direction. This is compatible with the Hebrew writing system, in which words and sentences are written from right to left. Indeed, ordinal processing is associated with well-documented activation in high-order processes such as direction (Fischer et al., 2010; Shaki et al., 2009). Specifically, direction is a product of experience-dependent, neuroplastic development that requires more than just the availability of intact core-systems, and takes place during preschool and elementary school years. Indeed, in contrast to Paulsen et al. (2010), findings show that for English speakers (who read and write from left to right), numerical pairs of increasing magnitude (from left to right) are more easily discriminated than pairs of decreasing magnitude; we found that our native Hebrew speaking participants (who read and write from right to left) are quicker with the descending (left to right) sequences than with the ascending ones. Accordingly, we wish to suggest quantity and ordinal representation as two potential core numerical systems, and direction as a later acquired linguistic representation. Such an argument is compatible with the hypothesis put forth by Spelke and colleagues (e.g., Carey, 2009; Hermer-Vazquez, Moffet, & Munkholm, 2001; Platt & Spelke, 2009; Spelke, 2003) who claimed that human cognition begins with a set of core systems of knowledge. Nevertheless, new representations may emerge when children learn language, because language provides a bridge between these distinct systems and hence combines information. With this in mind, it seems plausible to argue that, if early processing could be evidenced in ordinal information, these primary visual activations may underlie the appearance of “higher-level” later processing (such as directional or semantic processes). We suggest that for this reason, the effect at the ERP level associated with processing direction (ascending vs. descending order) was found later (300–600 ms). Note that this time window is in line with previous find-

ings showing a direction effect of between 320 and 440 ms (Paulsen et al., 2010). Interestingly, this effect was widespread, including right frontal and right parietotemporal positivity as well as left frontal and left parietotemporal negativity, and seems to have multiple sources, suggesting that the direction effect may indeed be related to widespread higher level cognitive functions such as language, perception, and attention, as suggested by Han and Northhoff (2008). However, this conclusion should be carefully extracted from our findings due to some methodological limitations. As mentioned, the participants in our study responded using only the right hand during the experiment. In addition, significantly shorter RTs were observed in the descending condition, as opposed to the ascending condition. This could suggest that the widespread inter-hemispheric activity observed in the Direction component, is merely a reflection of motor related activity in the shorter descending condition. Based on this logic, we attempted to test the alternative explanation by measuring the correlation between RT and the ERP inter-hemispheric difference in the 300–600 ms timeframe. We predicted that if motor related activity is the cause of the Direction ERP effect, we should find an association between shorter RTs and larger ERP inter-hemispheric difference. This negative correlation was not found [ $r = .225, p = .34$ ]. Moreover, looking specifically at RT differences, we can see that participants responded approximately 90 ms quicker in the descending condition as opposed to the ascending condition. Thus, if the inter-hemispheric difference at 300 ms post stimulus time window was response related, and reflected descending condition responses, we would expect to observe such activity in the ascending condition approximately 390 ms post stimulus. As we can see from Fig. 6a, there was no evidence for this type of activity. Therefore, the data does not support this alternative explanation, although we cannot fully reject the idea that there is some motor related activity involved in the Direction component. Further research and replication is needed to establish this effect.

#### 4.4. Conclusions: Tentative model

Summarizing our results, an overall theoretical neurodevelopmental model of the processes involved in ordinality is presented in Fig. 7. The first aspect of this model emanates from our results, which are consistent with the idea that ordinal and numerical processing are serially organized. Specifically, we suggest that it is possible to differentiate between three processes: an early perceptual ordinal process that takes place even before the process of quantity information. Then a second process is elicited by the numerical information, as indicated by the ratio effect. Then a later, third process, is related to the direction of the ordered stimuli.

Furthermore, a second aspect included in the model relates to the developmental timeline of the different processes. This aspect

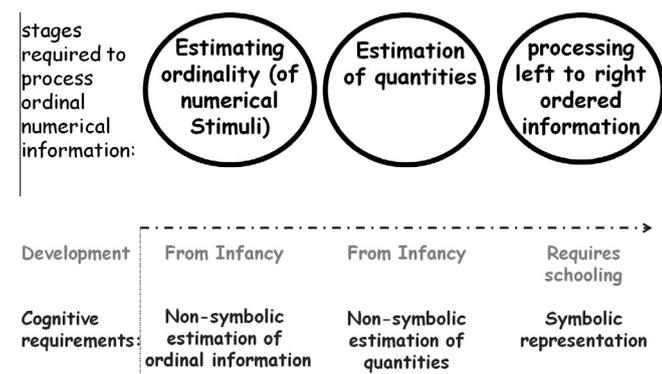


Fig. 7. Suggested theoretical model.

of the model is at this point more speculative and based on integration of the suggested timeline of ordinal and quantity processing, together with previous developmental data suggesting that ordinal processing is a very initial cognitive ability (e.g., Brannon, 2002; Cantlon & Brannon, 2006). This hypothetical neurodevelopmental aspect of the model of number representation postulates that the core-system representation of ordinality and accompanying functions (such as approximation), is not only early and basic in the processing timeline, but also early and basic in the developmental line, and probably a necessary precondition for children to cognitively represent the mental number line which has a spatial orientation (for review see Ansari, 2008).

Our findings have a number of implications for the study of ordinality. First of all, our work shows that quantities and ordinal information, at least at a certain stage of cognitive processing, are distinct and are not necessarily “two sides of the same coin” (Jacob & Neider, 2008). Accordingly, we expect that our work will not only provide important data but will also encourage discussions of the effects of ordinal and quantity processes and their mutual effects. Secondly, if human beings are indeed able to estimate order as part of their core cognitive system, it will mean that among some, such as those with developmental dyscalculia, this ability might be deficient. In such a case, those people would be partially “blind” to ordinal information and not only to quantity. This may have a huge effect on the scientific community, which mainly argues for quantity (rather than order) deficits in dyscalculia (Rubinsten & Sury, 2011), and on the clinical and pedagogical community, which shall need to consider relevant intervention tools.

#### Acknowledgments

Work by O. Rubinsten and A. Berger was conducted under the auspices of the Center for the Study of the Neurocognitive Basis of Numerical Cognition, supported by the Israel Science Foundation (Grant Number 1664/08) as part of their Centers of Excellence.

#### Appendix A. Appendix. Detailed description of stimuli used in the task

Stimuli were generated using a custom-written software programmed in the C# (pronounced as c sharp) language above Microsoft .NET 2 Framework™ using Visual Studio 2005 IDE. This software provided the control of parameters of the dot patterns. We used a  $1280 \times 1024$  resolution to create the images. Dot locations in each stimulus were randomized.

White dots appeared on a black background and were positioned within the bounds of a white circle of a 3 visual angle (VA; VA was calculated using the following formula:  $\theta = 2 \tan^{-1}(\frac{s}{2d})$  where  $d$  is the distance between the subject's eye and the screen and  $s$  is the size of the object on the screen). Each dot size was randomly varied between 0.17–0.28 VA. Each dot position was determined by placing it on a randomized arc of an inner circle with a randomized radius using the following formula:  $d(x, y) = [r \sin(\alpha), r \cos(\alpha)]$  where  $d(x, y)$  is the dot position on  $x, y$  space,  $r$  is a randomized radius from the center of the invisible circle, and  $\alpha$  is a randomized arc (0–360°) on a circle created with this radius. The randomization method is based on the System's Random library, which provides a pseudo random numbers generation method. Each dot was smoothed using the advanced anti-aliasing algorithm provided with the Microsoft.Graphics2D code library.

In addition, the dots never touched each other and were no closer than 0.1 visual angles. This was achieved by randomly selecting a dot location (see randomizing dot location) and comparing the distance of this dot to all the others. If the dot was no closer to

the other dots than a fixed minimum (1 degree visual angle), the dot was marked. Otherwise, a new dot was randomly selected. A maximum number of iterations (5000) were determined as a stop criterion. When the criterion was met, the stimuli were omitted and the program wrote an error message for not being able to create a suitable dot array for this numerosity.

To ensure that the ordinal task was solved by judging the order of quantities, low-level visual features were excluded by randomly manipulating area and density.

**Randomizing area:** While creating the numeral array, the software calculated the total amount of pixels occupied by the numerals. All stimuli/slides were drawn with a randomized range of  $n$ -pixel surface.

**Randomizing density:** The density of a numeral array was defined as the ratio of the bounding circle surface and the quantity. Therefore, to randomize density, the software was given different ratios (500), which were translated into the diameter of the invisible circle in which the dots were positioned.

Note – eventually all stimuli in all 3 conditions were presented with a visible circle of 3° visual angle (so participants saw the same circle size around all stimuli).

## References

- Anillo-Vento, L., & Hillyard, S. A. (1996). Selective attention to the color and direction of moving stimuli: Electrophysiological correlates of hierarchical feature selection. *Psychophysiology*, *58*, 191–206.
- Ansari, D. (2008). Effects of development and enculturation on number representation in the brain. *Nature Reviews Neuroscience*, *9*, 278–291.
- Barth, H., La Mont, K., Lipton, J. S., Dehaene, S., Kanwisher, N., & Spelke, E. S. (2006). Non-symbolic arithmetic in adults and young children. *Cognition*, *98*, 199–222.
- Barth, H., La Mont, K., Lipton, J. S., & Spelke, E. S. (2005). Abstract number and arithmetic in preschool children. *Proceedings of the National Academy of Science, USA*, *102*, 14116–14121.
- Bentin, S., & Deouell, L. Y. (2000). Structural encoding and identification in face processing: ERP evidence for separate mechanisms. *Cognitive Neuropsychology*, *17*, 35–54.
- Braeutigam, S., & Swithenby, S. J. (2003). Endogeneous context for visual processing of human faces and other objects. *Neuroreport*, *14*, 1385–1389.
- Brannon, E. M. (2002). The development of ordinal knowledge in infancy. *Cognition*, *86*, 223–240.
- Brannon, E. M., & Terrace, H. S. (1998). Ordering of the numerosities 1 to 9 by monkeys. *Science*, *282*, 746–749.
- Brannon, E. M., & Van de Walle, G. A. (2001). The Development of Ordinal numerical competence in young children. *Cognitive Psychology*, *43*, 53–81.
- Butterworth, B. (2005). The development of arithmetical abilities. *Journal of Child Psychology and Psychiatry*, *46*, 3–18.
- Cantlon, J. F., & Brannon, E. M. (2006). Shared system for ordering small and large numbers in monkeys and humans. *Psychological Science*, *17*, 401–406.
- Cantlon, J. F., Platt, M. L., & Brannon, E. M. (2009). Beyond the number domain. *Trends in Cognitive Sciences*, *13*, 83–91.
- Carey, S. (Ed.) (2009). *The origin of concepts*. Oxford University Press.
- Cohen Kadosh, R., Cohen Kadosh, C., Kaas, A., Henik, A., & Goebel, R. (2007). Notation-dependent and -independent representations of numbers in the parietal lobes. *Neuron*, *53*, 307–314.
- Davis, C. J. (2010). The spatial coding model of visual word identification. *Psychological Review*, *117*, 713–758.
- Dehaene, S. (1992). Varieties of numerical abilities. *Cognition*, *44*(1–42).
- Dehaene, S. (1996). The organization of brain activations in number comparison: Event-related potentials and the additive-factors method. *Journal of Cognitive Neuroscience*, *8*, 47–68.
- Dehaene, S. (1997). *The number sense: How the mind creates mathematics*. Oxford, UK: Oxford University Press.
- Dehaene, S. (2009). Origins of mathematical intuitions: The case of arithmetic. *Annals of the New York Academy*, *1156*, 232–259.
- Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General*, *122*, 371–396.
- Delazer, M., & Butterworth, B. (1997). A dissociation of number meanings. *Cognitive Neuropsychology*, *14*, 613–636.
- Feigenson, L., Dehaene, S., & Spelke, E. S. (2004). Core systems of number. *Trend in Cognitive Science*, *8*, 307–314.
- Ferree, T. C., Luu, P., Russell, G. S., & Tucker, D. M. (2001). Scalp electrode impedance, infection risk, and EEG data quality. *Clinical Neurophysiology*, *112*(3), 536–544.
- Fias, W., Lammertyn, J., Caessens, B., & Orban, G. A. (2007). Processing of abstract ordinal knowledge in the horizontal segment of the intraparietal sulcus. *Journal of Neuroscience*, *27*, 8952–8956.
- Fischer, M. H., Mills, R. A., & Shaki, S. (2010). How to cook a SNARC: Number placement in text rapidly changes spatial-numerical associations. *Brain and Cognition*, *72*, 333–336.
- Fuchs, M., Kastner, J., Wagner, M., Hawes, S., & Ebersole, J. S. (2002). A standardized boundary element method volume conductor model. *Clinical Neurophysiology*, *113*(5), 702–712.
- Fulbright, R. K., Manson, S. C., Skurdasky, P., Ladadie, C. M., & Gore, J. C. (2003). Quantity determination and the distance effect with letters, numbers, and shapes: A functional MR imaging study of number processing. *American Journal of Neuroradiology*, *24*, 193–200.
- Gallistel, C. R., & Gelman, R. (1992). Preverbal and verbal counting and computation. *Cognition*, *44*, 43–74.
- Gobel, E. W., Parrish, T. B., & Reber, P. J. (2011). Neural correlates of skill acquisition: Decreased cortical activity during a serial interception sequence learning task. *Neuroimage*, *58*, 1150–1157.
- Goodale, M. A., & Milner, A. D. (Eds.). (2004). *Sight unseen: An exploration of conscious and unconscious vision*. Oxford: Oxford University Press.
- Gracia-Bafalluy, M., & Noël, M.-P. (2008). Does finger training increase young children's numerical performance? *Cortex*, *44*, 368–375.
- Han, S., & Northoff, G. (2008). Culture-sensitive neural substrates of human cognition: A transcultural neuroimaging approach. *Nature Review Neuroscience*, *9*, 646–654.
- Hansen, B. C., Jacques, T., Johnson, A. P., & Ellemberg, D. (2011). From spatial frequency contrast to edge preponderance: The differential modulation of early VEPs by natural scene stimuli. *Visual Neuroscience*, *28*, 221–237.
- Hermer-Vazquez, L., Moffet, A., & Munkholm, P. (2001). Language, space, and the development of cognitive flexibility in humans: The case of two spatial memory tasks. *Cognition*, *79*, 263–299.
- Holloway, I. D., & Ansari, D. (2009). Mapping numerical magnitudes onto symbols: The numerical distance effect and individual differences in children's math achievement. *Journal of Experimental Child Psychology*, *103*, 17–29.
- Hyde, D. C., & Spelke, E. S. (2012). Spatio-temporal dynamics of numerical processing: An ERP source localization study. *Human Brain Mapping*, *33*, 2189–2203.
- Hyde, D. C., & Spelke, E. S. (2009). All numbers are not equal: An electrophysiological investigation of small and large number representations. *Journal of Cognitive Neuroscience*, *21*, 1039–1053.
- Ischebeck, A., Heim, S., Siedentopf, C., Zamarian, L., Schocke, M., Kremser, C., et al. (2008). Are numbers special? Comparing the generation of verbal materials from ordered categories (months) to numbers and other categories (animals) in an fMRI study. *Human Brain Mapping*, *29*, 894–909.
- Jacob, N. S., & Neider, A. (2008). The ABC of cardinal and ordinal number representations. *Trends in Cognitive Sciences*, *12*, 41–43.
- Junghefer, M., Elbert, T., Tucker, D. M., & Braun, C. (1999). The polar average referenced effect: A bias in estimating the head surface integral in EEG recording. *Electroencephalography and Clinical Neurophysiology*, *98*, 422–434.
- Jurcak, V., Tsuzuki, D., & Dan, I. (2007). 10/20, 10/10, and 10/5 systems revisited: Their validity as relative head-surface-based positioning systems. *NeuroImage*, *34*(4), 1600–1611.
- Kaufmann, L., Vogel, S. E., Starke, M., & Schocke, M. (2009). Numerical and non-numerical ordinality processing in children with and without developmental dyscalculia: Evidence from fMRI. *Cognitive Development*, *24*, 486–494.
- Kaufmann, L., Vogel, S. E., Wood, G., Kremser, C., Schocke, M., Zimmerhackl, L.-B., et al. (2008). A developmental fMRI study of nonsymbolic numerical and spatial processing. *Cortex*, *44*, 376–385.
- Kaufmann, L., Wood, G., Rubinsten, O., & Henik, A. (2011). Meta-analysis of developmental fMRI studies investigating typical and atypical trajectories of number processing and calculation. *Developmental Neuropsychology*, *36*, 763–787.
- Libertus, M. E., Woldorff, M. G., & Brannon, E. M. (2007). Electrophysiological evidence for notation interdependence in numerical processing. *Behavioral and Brain Functions*, *3*.
- Luck, S. J., Heinze, H. J., Mangun, G. R., & Hillyard, S. A. (1990). Visual event-related potentials index focused attention within bilateral stimulus arrays. II. Functional dissociation of P1 and N1 components. *Electroencephalography and Clinical Neurophysiology*, *75*, 528–542.
- Mangun, G. R. (1995). Neural mechanisms of visual selective attention. *Psychophysiology*, *32*, 4–18.
- Nieder, A. (2005). Counting on neurons: The neurobiology of numerical competence. *Nature Reviews Neuroscience*, *6*, 177–190.
- Nikolaev, A. R., Gepshtein, S., Kubovy, M., & van Leeuwen, C. (2008). Discussion of early evoked cortical activity in perceptual grouping. *Experimental Brain Research*, *186*, 107–122.
- Omoto, S., Kuroiwa, Y., Otsuka, S., Baba, Y., Wang, C., Li, M., et al. (2010). P1 and P2 components of human visual evoked potentials are modulated by depth perception of 3-dimensional images. *Clinical Neurophysiology*, *386*–391.
- Pascual-Marqui, R. D. (2002). Standardized low-resolution brain electromagnetic tomography (sLORETA): Technical details. *Methods & Findings in Experimental & Clinical Pharmacology*, *24*(Suppl. D), 5–12.
- Paulsen, D. J., Woldorff, M. G., & Brannon, A. B. (2010). Individual differences in nonverbal number discrimination correlate with event-related potentials and measures of probabilistic reasoning. *Neuropsychologia*, *48*, 3687–3695.
- Pavese, A., & Umiltà, C. (1998). Symbolic distance between numerosity and identity modulates Stroop interference. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1535–1545.
- Piazza, M. (2010). Neurocognitive start-up tools for symbolic number representations. *Trends in Cognitive Sciences*, *14*, 542–551.
- Piazza, M., Pinel, P., Le Bihan, D., & Dehaene, S. (2007). A magnitude code common to numerosities and number symbols in human intraparietal cortex. *Neuron*, *53*, 293–305.

- Pinel, P., Dehaene, S., Rivière, D., & LeBihan, D. (2001). Modulation of parietal activation by semantic distance in a number comparison task. *NeuroImage*, *14*, 1013–1026.
- Platt, M. L., & Spelke, E. S. (2009). What can developmental and comparative cognitive neuroscience tell us about the adult human brain? *Current Opinion in Neurobiology*, *19*, 1–5.
- Price, G. R., Holloway, I., Vesterinen, M., Rasanen, P., & Ansari, D. (2007). Impaired parietal magnitude processing in Developmental Dyscalculia. *Current Biology*, *17*, R1024–1023.
- Roggeman, C., Santens, S., Fias, W., & Verguts, T. (2011). Stages of non-symbolic number processing in occipito-parietal cortex disentangled by fMRI-adaptation. *Journal of Neuroscience*, *31*, 7168–7173.
- Rubinsten, O., & Sury, D. (2011). Processing ordinality and quantity: The case of developmental dyscalculia. *PLoS One*, *6*.
- Schleifer, P., & Landerl, K. (2011). Subitizing and counting in typical and atypical development. *Developmental Science*, *14*, 280–291.
- Seeck, M., Michel, C. M., Mainwaring, N., Cosgrove, R., Blume, H., & Ives, J. (1997). Evidence for rapid face recognition from human scalp and intracranial electrodes. *Neuroreport*, *8*, 2749–2754.
- Shaki, S., Fischer, M. H., & Petrusic, W. M. (2009). Reading habits for both words and numbers contribute to the SNARC effect. *Psychonomic Bulletin & Review*, *16*, 328–331.
- Spehlmann, R. (1965). The average electrical responses to diffuse and to patterned light in the human. *Electroencephology and Clinical Neurophysiology*, *19*, 560–569.
- Spelke, E. S. (2000). Core knowledge. *American Psychologist*, *55*, 1233–1243.
- Spelke, E. (2003). What makes us smart? Core knowledge and natural language. In D. Gentner & S. Goldin-Meadow (Eds.), *Language in mind: Advances in the investigation of language and thought* (pp. 277–311). Cambridge, MA: MIT Press.
- Suanda, S. H., Tompson, W., & Brannon, E. M. (2008). Changes in the ability to detect ordinal numerical relationships between 9 and 11 months of age. *Infancy*, *13*, 308–337.
- Sury, D., & Rubinsten, O. (2012). Ordinal processing of numerical and non-numerical information. In Z. Breznitz, O. Rubinsten, V. J. Molfese, & D. L. Molfese (Eds.), *Reading, Writing, Mathematics and the Developing Brain: Listening to Many Voices* (Vol. 6, pp. 209–232). Dordrecht, New York: Springer.
- Szűcs, D., & Csépe, V. (2004). Access to number representations is dependent on the modality of stimulus presentation in mental addition: A combined behavioral and ERP study. *Cognitive Brain Research*, *19*, 10–27.
- Szűcs, D., Soltész, F., Jármi, É., & Csépe, V. (2007). The speed of magnitude processing and executive functions in controlled and automatic number comparison in children: An electro-encephalography study. *Behavioral and Brain Functions*, *3*.
- Temple, E., & Posner, M. I. (1998). Brain mechanisms of quantity are similar in 5-year-olds and adults. *Proceedings of the National Academy of Sciences USA*, *95*, 7836–7841.
- Tucker, D. M. (1993). Spatial sampling of head electrical fields: The geodesic sensor net. *Electroencephalography and Clinical Neurophysiology*, *87*(3), 154–163.
- Turconi, E., Campbell, J. I. D., & Seron, X. (2006). Numerical order and quantity processing in number comparison. *Cognition*, *98*, 273–285.
- Turconi, E., Jemel, B., Rossion, B., & Seron, X. (2004). Electrophysiological evidence for differential processing of numerical quantity and order in humans. *Cognitive Brain Research*, *21*, 22–38.
- Turconi, E., & Seron, X. (2002). Dissociation between order and quantity meaning in a patient with Gerstmann syndrome. *Cortex*, *38*, 911–914.
- Ungeleider, L. G., & Mishkin, M. (1982). Two cortical visual systems. In D. J. Ingle, M. A. Goodale, & R. J. W. Mansfield (Eds.), *Analysis of visual behavior*. Cambridge, Mass: MIT Press.
- van Oeffelen, M. P., & Vos, P. G. (1982). A probabilistic model for the discrimination of visual number. *Perception and Psychophysics*, *32*, 163–170.
- Van Opstal, F., Fias, W., Peigneux, P., & Verguts, T. (2009). The neural representation of extensively trained ordered sequences. *Neuroimage*, *47*, 367–375.
- Wilson, A. J., & Dehaene, S. (2007). Number sense and developmental dyscalculia. In D. Coch, G. Dawson, & K. Fischer (Eds.), *Human behavior, learning and the developing brain: Atypical development*. New York: Guilford Press.
- Wood, G., Nuerk, H. C., Willmes, K., & Fischer, M. H. (2008). On the cognitive link between space and number: A meta-analysis of the SNARC effect. *Psychology Science Quarterly*, *50*, 489–525.
- Zorzi, M., Di Bono, M. G., & Fias, W. (2011). Distinct representations of numerical and non-numerical order in the human intraparietal sulcus revealed by multivariate pattern recognition. *Neuroimage*, *15*, 674–680.