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Children automatically process order: Evidence from an 'ordinal Stroop' task

Dana Sury*, Orly Rubinsten

Edmond J. Safra Brain Research Center for the Study of Learning Disabilities, Department of Learning Disabilities, University of Haifa, Israel

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ABSTRACT

The current study focuses on the developmental aspect of order and investigates whether young children can automatically perceive the ordinal elements of a non-symbolic numerical sequence. Children aged 6–7, 8–9, and 10–11 completed ordinal Stroop task with quantities (i.e., dot patterns) as the relevant dimension. Convex hull of the stimuli was manipulated into two conditions: congruent or incongruent with the ordinal direction of quantities. Ratio between quantities was manipulated as well. In all three age groups, results showed a congruity effect indicating that convex hull is automatically processed and affects judgments of the ordinal aspect of quantities. Additionally, even though both Order and Ratio produced a significant main effect, they did not interact with each other. These findings support previous results regarding the role of visual properties in numerical discrimination. Further, they suggest that from an early age, humans automatically extract ordinal features from visual properties of the numerical sequence.

1. Introduction

Increased interest in the processing of order, as a numerical aspect distinct from cardinality, has recently emerged in the study of numerical cognition (e.g., de Hevia et al., 2017; Lyons, Vogel, & Ansari, 2016; Vos, Sasanguie, Gevers, & Reynvoet, 2017). Specifically, neuroimaging and neuropsychological studies suggest that the processing of ordinal and cardinal information is dissociated at both the behavioral and biological levels (Rubinsten, Sury, Lavro, & Berger, 2013; Turconi & Seron, 2002; Turconi, Jemel, Rossion, & Seron, 2004). Further, accumulating evidence indicates the existence of a core system for representing ordinal information. This system may allow humans to automatically analyze perceptual input based on the ordinal information it conveys (Rubinsten et al., 2013). Indeed, occasional evidence suggests that order is involved in processing different stimuli, such as three-dimensional shapes (Norman & Todd, 1998), face recognition (Gilad, Meng, & Sinha, 2009), depth (Todd & Norman, 2003), and size (Kaufmann, Vogel, Starke, Kremser, & Schocke, 2009). Thus, supporting the idea that order might act as an essential cognitive system; serving crucial functions in an ecological context (de Hevia et al., 2017).

The hypothesis that non-symbolic ordinal processing might act as a core cognitive system calls for a deeper understanding of its developmental patterns. Hence, the current study strives to provide further information regarding the existence of a cognitive system dedicated to order. This 'ordinal input analyzer' appears in children and dedicated to processing ordinal information in non-symbolic numerical (and possibly non-numerical) stimuli (de Hevia et al., 2017; Rubinsten et al., 2013). Specifically, by using an ordinal Stroop task in which order was manipulated in both non-symbolic quantities and their visual properties, the current study explores the possibility that children automatically process the order of visual properties in the numerical sequence.

* Corresponding author at: 199 Aba Khoushy Ave., Mount Carmel, Haifa, Israel.
E-mail address: surydana@gmail.com (D. Sury).

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1.1. Non-symbolic ordinal processing

The idea of a cognitive system dedicated to perceiving order is based on previous findings indicating that the ability to process order appears early on in human life [i.e., in infancy (Brannon, 2002; de Hevia et al., 2017; de Hevia & Spelke, 2010; vanMarle, 2013)] as well as in non-human primates (Cantlon & Brannon, 2006), and even in animals that are phylogenetically distant from humans, [e.g., rats (Suzuki & Kobayashi, 2000), parrots (Pepperberg, 2006), jackdaws (Pfuhl & Biegler, 2012), bees (Dacke & Srinivasan, 2008), fish (Petrazzini, Lucon-Xiccato, Agrillo, & Bisazza, 2015), and several-day-old chicks (Rugani, Regolin, & Vallortigara, 2007; Vallortigara, Regolin, Chiandetti, & Rugani, 2010)]. Moreover, several studies suggested that the deficit in non-symbolic ordinal processing might be a characteristic of development dyscalculia (DD) in both children (Attout & Majerus, 2014; Kaufmann et al., 2009) and adults (Rubinsten & Sury, 2011). Hence, non-symbolic ordinal knowledge may critically contribute to the early acquisition of numerical skills and, later on, to mathematical learning.

Several studies have suggested that order is crucial for understanding how humans process numbers and even more abstract arithmetical and mathematical relations (Chen, Xu, Shang, Peng, & Luo, 2014; Kaufmann et al., 2009; Lyons & Ansari, 2015; Lyons & Beilock, 2013; Lyons et al., 2016). Nonetheless, the substantial majority of these studies have focused primarily on the order of symbolic numbers (Franklin, Jonides, & Smith, 2009; Lyons & Ansari, 2015; Lyons & Beilock, 2011; Lyons et al., 2016). However, order of numerical symbols might arise from the inference of ordinal relationships between the non-symbolic quantities they represent (Gallistel & Gelman, 1992). Hence, children may acquire their knowledge about symbolic order not only from the learned symbolic count list but also from the ordinal relationships between non-symbolic quantities. Moreover, it has been proposed that the ability to actively compute non-symbolic ordinal information is an essential skill that might have been selected because it can enhance survival in several ecological contexts. For example, order processing is suggested to support an alerting effect to a progressively approaching object (de Hevia et al., 2017). This idea was recently supported in a paper from the field of paleoanthropology (Wynn, Overmann, Coolidge, & Janulis, 2016) that argued that during human evolution, order served essential functions early on in evolution and developed from the embodied experiences and scaffolding of these experiences. Put together, previous arguments support the current hypothesis about the existence of a core system for representing ordinal information, but they remain mainly within a theoretical framework without explicitly examining whether the order of non-symbolic sequences is indeed automatically processed.

1.2. Automatic processing of order

Cognitive systems that are activated automatically or implicitly (i.e., even when they are irrelevant to the task at hand) are considered phylogenetically primitive systems that serve basic functions fundamental to species' survival (Feigenson, Dehaene, & Spelke, 2004; Reber, 1989; Schacter, 1987; Spelke & Kinzler, 2007). Accordingly, the ordinal input analyzer may allow humans to automatically perceive and analyze ordinal information (Rubinsten et al., 2013). Given this hypothesis, it is essential to test whether humans and specifically children, indeed automatically perceive and analyze perceptual input based on its ordinal information. However, and to best of our knowledge, this hypothesis has never been tested in children.

Findings regarding the ability to process order are usually interpreted in terms of intentional cognitive activity. However, Rubinsten and colleagues' Event-Related Potentials (ERP) study (2013) implies otherwise. Specifically, by using an ordinal judging task (i.e., judging the order of a sequence of three non-symbolic quantities) with adult participants, Rubinsten and colleagues showed that order was processed very early after stimulus presentation (80–130 ms), too early to be the result of explicit processing. Such indications for implicit order processing were not tested in children. Hence, to study the automatic processing of order, the methodology that we are using is based on the ordinal judging task of Rubinsten and Sury (2011); Rubinsten et al., 2013.

In their ERP study, Rubinsten and colleagues also suggested that order and numerosity are two dissociated systems. Rubinsten et al. (2013) showed that ordinal relationships are perceived earlier than numerosity (i.e., the ratio between items in the sequence), independent of the ratio between every two adjacent quantities. Specifically, ordinal estimation was associated with early scalp parietal and lateral occipital positivity (80–130 ms); while the numerical ratio was associated with a later scalp medial posterior positivity (130–200 ms). These results differentiate between order and quantity processing in a non-symbolic ordinal judging task and indicate different brain activity for the processing of quantity and order. In the current study, by manipulating the order of both numerosities and their visual properties, we aimed to; (1) assess the automatic processing of the ordinal aspect of visual properties beyond the numerical stimuli. (2) provide additional evidence about the relationships between ordinal processing and numerosity by manipulating both the order and the ratio of the non-symbolic numerical sequence (Rubinsten & Sury, 2011; Rubinsten et al., 2013).

1.3. Numerosity: the ratio effect

Numerosity (i.e., the ability to represent and discriminate quantities) is considered a core knowledge system upon which humans build new numerical concepts and skills (Carey, 2009; Gallistel & Gelman, 2000; Spelke & Kinzler, 2007). Many studies in the field of numerical cognition provide evidence that the ability to estimate quantity rests on an ancient evolutionary system (Vallortigara et al., 2010). This system appears early on in human life (Coubart, Izard, Spelke, Marie, & Streri, 2014; de Hevia, Izard, Coubart, Spelke, & Streri, 2014), and is independent of culture or formal education (Dehaene, 2008). A primary signature of this system is the ratio effect. In numerical comparisons (most commonly used to measure numerosity), the ratio between two numerals to be compared is typically found to shape performance. Specifically, accuracy falls and reaction time (RT) increases as the ratio of the numbers approaches one (Barth, La Mont, Lipton, & Spelke, 2005; Dehaene, 1997; Van Oeffelen & Vos, 1982). In humans, this so-called

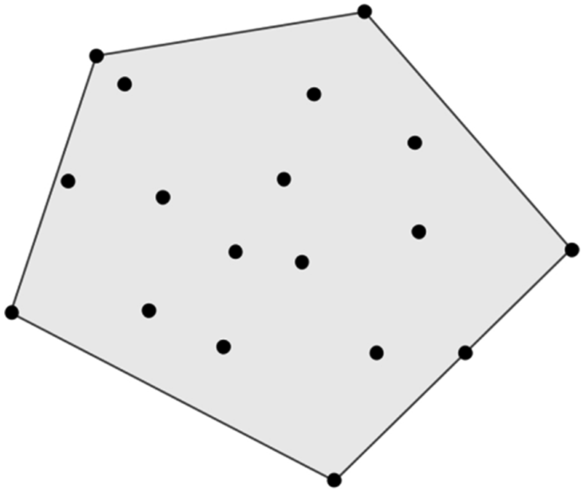

Fig. 1. Illustration of the term 'Convex hull'- the area within the surrounding black lines represent the total 'envelope area' taken up by the dot arrays (adopted from Khor, 2012).

'number sense' is perceived as a stepping stone for later acquisition of formal mathematics (Burr & Ross, 2008; Butterworth, 2005; Dehaene, 1997).

Recent arguments suggests that in numerical comparisons order and numerosity are entwined (Dehaene, Meyniel, Wacongne, Wang, & Pallier, 2015). For example, Turconi, Campbell, and Seron (2006)) showed a reduced distance effect in numerical comparisons when number pairs were presented in an ascending order (i.e., left to right). Therefore, comparison tasks might involve ordinal processing beyond numerosity and hence, do not necessarily represent a pure measure of magnitude representation (Van Opstal, Gevers, De Moor, & Verguts, 2008; Vigliocco, Vinson, Damian, & Levelt, 2002). Thus, here, we use a task that simultaneously manipulates both ratio and order and enables investigation of the interaction between order and numerosity.

1.4. Numerical discrimination and visual properties of quantities

The stimuli commonly used to study non-symbolic numerical processing are sets of items (e.g., dot arrays). Beyond their numerosity, such sets are characterized by different perceptual variables such as total surface area, diameter, density, convex hull (i.e., the total 'envelope area' taken up by the dot arrays, often referred to as 'occupied area,' see Fig. 1 for illustration). Empirical evidence suggests that these characteristics of non-symbolic stimuli affect performance in both numerical estimation and comparison tasks (Leibovich & Ansari, 2016; Leibovich & Henik, 2014). The correspondence between perceptual variables of the numerical stimuli and their quantity (e.g., larger quantity and larger area) facilitates the response to the task (e.g., faster or more accurate response to comparing numerals) and vice versa. This effect is present even when visual features are irrelevant to the task in both children (Defever, Reynvoet, & Gebuis, 2013; Rousselle, Palmers, & Noël, 2004; Tokita & Ishiguchi, 2013) and adults (Gebuis & Reynvoet, 2012a, 2012b; Leibovich & Henik, 2014).

With relevance to the current study (which employs convex hull manipulation) it should be noted that convex hull plays a more prominent role in numerical discrimination compared to other visual properties (e.g., average diameter, aggregate surface, see Gebuis & Reynvoet, 2013b; Tibber, Greenwood, & Dakin, 2012). For example, convex hull could explain numerosity bisection biases in both children and adults [both tend to bisect the line towards the larger convex hull even when numerosity is smaller (Gebuis & Gevers, 2011)]. Hence, in the current study and ordinal Stroop task, a manipulation of the convex hull of the numerical stimuli is used.

Several studies have also indicated that the inhibition of visual properties in numerical processing may be context depended (Park, DeWind, Woldorff, & Brannon, 2016). For example; Content and Nys (2016) had shown that 3–6 years old numerical estimation was not based on continues dimension of stimuli when children were asked to match non-symbolic numerosities. Thus, there are some contradicting findings regarding the role of visual properties in numerical discrimination.

To the best of our knowledge, the effect of perceptual variables on the numerical ordinal judgment in children has not been tested so far. Nonetheless, based on the findings described above, it is possible to assume that similar to numerical discrimination, numerical ordinal judgment may also be affected by order of visual properties (of the sequence). This may suggest that children automatically process the order of the non-numerical characteristics of a sequence. Hence, the primary aim of the current study is to investigate whether automatic processing of visual properties also appears when judging the order of a non-symbolic numerical sequence. Specifically, we ask whether automatic processing of visual properties affects the ordinal judgment of a non-symbolic numerical sequence, or whether the effect of visual properties is restricted to numerical discrimination alone.

1.5. Automatic processing in Stroop tasks

Stroop (1935) demonstrated that task-irrelevant information could interfere with performance. This was classically demonstrated using a task where naming the ink color of a word is slower and less accurate when the word is a conflicting color word (e.g., the word RED printed in green ink). Although the word itself is irrelevant to the task, fluent readers automatically read the word, even at a cost to performance. Stroop paradigms have been used as a tool to understand how humans automatically process meaning from words. This has been extended to understand automatic processing in various cognitive functions using stimuli such as pictures (Macleod, 1991), size (Konkle & Oliva, 2012; Rubinsten & Henik, 2002), and numbers (Besner & Coltheart, 1979; Henik & Tzelgov, 1982). In a typical experiment, both the irrelevant (e.g., color word) and relevant dimension (e.g., ink color) vary. Similar to the current study, the task includes congruent (e.g., the word RED printed in red ink) and incongruent (e.g., the word RED printed in green ink) trials, while participants are instructed to refer solely to one dimension. The Stroop effect manifests as an increase in reaction time and/or error rate in incongruent trials compared to congruent trials (e.g., Henik & Tzelgov, 1982; Konkle & Oliva, 2012; Macleod, 1991; Rubinsten & Henik, 2002).

Drawing on the literature regarding the color-word and number-size Stroop effects (for a review see Macleod, 1991), congruency effects can be explained by interactions that appear during perceptual processing. According to the perceptual interaction view, the representations of task-relevant and task-irrelevant stimulus dimensions are constructed in parallel, and they interact at the level of stimulus perception (Hock & Egeth, 1970). Hence, in the current study, order is manipulated in both the relevant (i.e., numerical quantities) and irrelevant dimension (convex hulls) to test for possible automatic processing of order in visual properties.

1.6. The current study

de Hevia et al. (2017) suggested that the ability to compute ordinal information is an essential skill that might have been selected for its ability to enhance survival in several ecological contexts. The present study aims to explore this possibility by investigating the automatic processing of order in childhood. Specifically, we ask (1) whether the system for evaluating ordinal relationships involves automatic processing in children from the beginning of elementary school. (2) further, we aimed to dissociate between cognitive processes that are involved with order vs. numerosity from a developmental perspective.

To answer the primary research goal, we designed a novel ordinal Stroop task. In this task, we systematically manipulated the (ordinal) congruency between quantities and convex hulls of the numerical sequence. For example, in an incongruent condition, quantities (i.e., dot patterns) of a sequence were presented in an increasing, ordered fashion (e.g., 4,612) but the relationships between the convex hulls of these three quantities were non-ordered (e.g., the convex hull of 4 dots was the smallest, the convex hull of 6 dots was the largest, and the convex hull of 12 dots lay in between, see Fig. 2 for illustration). Children aged 6–10 years old were asked to judge the order of three simultaneously presented quantities by addressing the quantities alone (while ignoring other visual features of the sequence).

Overall, we manipulated 3 different variables: (1) The order of the quantity and convex hulls of these quantities (ordered vs. non-ordered sequences), to study estimation of non-symbolic numerical order [in the current study, ordered sequences meant both increasing or decreasing (left to right) orders]; (2) The congruity between convex hulls' ordinal relationships and order of quantities within the sequence. This was done in order to study the automatically perceived ordinal relationships between perceptual properties of the numerical stimuli and their effect on numerical ordinal estimation. Additionally, we manipulated (3) The numerical ratio of the sequence (two different ratios between adjacent groups of dots), to study core numerical knowledge and its relationship to ordinal processing. We also tested three age groups (first graders aged 6–7 years, third graders aged 8–9 years, and fifth graders aged 9–10 years), to study the developmental pattern of the ability to automatically perceive ordinal relationships. Examining differences between these three age groups allowed an investigation of the developmental patterns of non-symbolic ordinal processing and discovery of changes that may accrue through formal education, acquisition of the writing system and symbolic arithmetic. As development of symbolic number processing has been shown to affect the acuity of non-symbolic numerical processing (e.g., De Smedt, Noël, Gilmore & Ansari, 2014; Sasanguie, Defever, Maertens & Reynvoet, 2014; Schneider et al., 2017), examining three age groups, allowed a comparison between children at different stages of math proficiency. For example, comparing processing patterns of (1) typically developed 6–7 year old children (first-grade) who have just encountered formal education, (2) 8–9 year old children (third grade) who have already acquired broad knowledge regarding the symbolic numerical systems and basic arithmetic (e.g., multiplication) and, (3) 10–11 year old children (fifth-grade) who have already began to learn more abstract mathematical contents such as fractions.

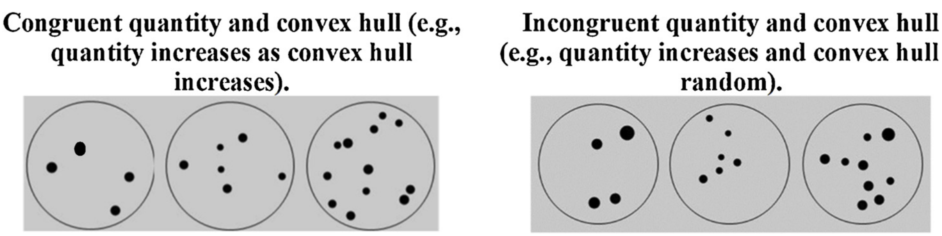

Fig. 2. Illustration of order and congruity manipulation.

Our hypotheses are based on evidence suggesting that order processing appears early on in human development (Cassia, Picozzi, Girelli, & de Hevia, 2012; de Hevia et al., 2017; Ischebeck et al., 2008; Kaufmann et al., 2009; Suanda, Tompson, & Brannon, 2008) and serves as a basic numerical concept (Jacob & Nieder, 2008; Lyons et al., 2016; Nieder, 2005; Wynn et al., 2016). If order is indeed automatically processed, then we expect the relationships (i.e., order) between the convex hulls of the three quantities to affect numerical ordinal judging even if they are irrelevant to the task. Specifically, we expect: (1) A significant effect of order (i.e., the difference between responses to ordered vs. non-ordered sequences) in the congruent condition for all three age groups. This is following previous suggestion that the ability to estimate order appears early on in human life and hence might exhibit continuity throughout human life. In addition, (2) based on evidence that in children, numerosity judgment is affected by the visual properties of the stimuli (Defever et al., 2013; Rousselle et al., 2004; Tokita & Ishiguchi, 2013), we expected to find a significant congruity effect (i.e., a significant difference between the congruent and incongruent conditions) throughout development. However, a congruity effect alone will not indicate it was explicitly the ordinal features of the convex hull that were automatically processed. Hence, (3) we predicted that the congruity effect will significantly interact with order; while order will be significant in the congruent condition (both quantities and convex hulls are ordered), it will be non-significant in the incongruent condition due to the automatic processing of order in other non-numerical features (i.e., convex hull). Hence, we hypothesized that automatic processing of order in visual properties would also appear from an early age, supporting the existence of an ordinal input analyzer (de Hevia et al., 2017; Rubinsten et al., 2013). (4) We also expected to find a significant effect of ratio, based on evidence showing that the numerosity condition (i.e., the ratio effect) is automatically activated even when irrelevant to the task (Dehaene, 1997; Rubinsten & Henik, 2005; Tzelgov, Meyer, & Henik, 1992). (5) As for the relationship between order and numerosity, based on previous evidence (Cheng, Tang, Walsh, Butterworth, & Cappelletti, 2013; Rubinsten & Sury, 2011; Rubinsten et al., 2013), we expected that order and numerosity (i.e., ratio) would not interact. This supports the claim that while order and numerosity are both activated during ordinal judgment, they are processed in parallel and do not modulate the effect of each system (Cheng et al., 2013; Rubinsten & Sury, 2011; Rubinsten et al., 2013; Turconi & Seron, 2002; Turconi et al., 2004).

2. Method

2.1. Participants

An a-priori analysis to compute sample size was conducted in Gpower (http://www.gpower.hhu.de/en.html). Focusing on the interaction between Congruity and Order and, for a repeated measures ANOVA with 3 between group factors (i.e., First, Third and Fifth graders) and 2 within-in group factors [Congruity (congruent or incongruent) and Ordinality (ordered or non-ordered)], a power analysis revealing a minimum sample size of $n = 101$ for a large to medium effect size of 0.3 (absolute value of rho, the correlation coefficient) (with $\alpha = 0.05$ and a power $(1\text{-}\beta) = 0.8$).

One hundred and twenty-three children aged 6–11 were recruited from elementary schools in Israel. The participants were divided into three age groups [59 first graders (mean age = 6.43 ± 3 months), 34 third graders (mean age = 8.2 ± 5 months), and 30 fifth graders (mean age = 10.3 ± 3 months)]. However, 15 participants were excluded from all analyses due to low accuracy rates (see results). Hence, data obtained from 108 participants was analyzed and presented in the current paper (49 first graders, 29 third graders, and 30 fifth graders). The research protocol was authorized by the Israeli Ministry of Education (Department for Science Policy), and the parents of all participants gave written consent for their child's participation in the experiment.

2.2. Procedure

The computerized ordinal Stroop task was presented on a Dell laptop with a 15-in. screen using E-prime 2 software (Psychological Software Tools, Pittsburgh, PA, USA).

2.3. Experimental task

Participants were presented with three non-symbolic quantities (i.e., three groups of dots) on one slide (i.e., one stimulus) and were asked to decide whether they are ordered (either ascending or descending) or not (i.e., no ordinal relationship between all three items). The quantities of the three groups of dots were ordered in two presentations of ordered sequences: ascending direction (i.e., small, medium, large) or descending direction (i.e., large, medium, small). The non-ordered sequences included two possible presentations: (1) medium, small, large quantities or (2) small, large, medium quantities. In each stimulus (i.e., three groups of dots) the

Table 1
Detailed description of the numerical value of quantities presented in the experiment.

Ratio	0.7			0.5		
	First item	Second item	Third item	First item	Second item	Third item
	3	4	6	2	4	8
	4	6	9	3	6	12
	5	7	10	4	8	16

ratio between every two adjacent groups of dots was also manipulated (a ratio of 0.5 or 0.7 between each pair within the three items; see Table 1 for a detailed description of the numerical value) as was the convex hull of the stimuli.

2.4. Materials

Stimuli consisted of 3 groups of multiple black dot patterns presented on a gray background within a black defining circle of 5° visual angle, ranging from 1 to 16 dots per group (see Table 1). The three groups of dots in each stimulus were presented along a (non-visible) horizontal axis, with the central pattern located in the center of the screen. The stimuli were generated using custom-written software (for a detailed description see Appendix 2).

2.4.1. Convex hull

Convex hull was systematically manipulated: Convex hull for each stimulus was controlled and manipulated by creating three types of stimuli for each numerosity (e.g., six dots were created with three convex hulls; small, medium, and large convex hull). Each numerosity contained the same diameter (5° visual angle) and the same range of density (.17–.35 ° visual angle between dots) but three possible areas (i.e., pixels, e.g., numerosity of six with 350 pixels, 700 pixels, and 1050 pixels). This resulted in a different contour for each stimulus (e.g., six dots could appear with three different convex hulls, see Appendix 2 for a detailed description of stimuli generation).

2.4.2. Congruency

For the Congruent condition, each stimulus in the sequences decreased or increased for both numerosity and area. That is, the larger numerosity in the sequence contained the larger convex hull, and the smallest numerosity contained the smallest convex hull (e.g., four dots with 350 pixels, six dots with 700 pixels, or twelve dots with 1050 pixels). In the Incongruent condition, the area of each numerosity did not correlate with its quantity. Specifically, the smallest numerosity could contain the smallest, medium, or a larger area (e.g., two dots with 350 pixels, four dots with 1050 pixels, or six dots with 700 pixels). However, this was not a random choice; when quantities were presented in an ordered fashion, convex hull was random (e.g., smallest, largest, and medium convex hull) and when quantities were random the convex hull of the dots was ordered (i.e., an increase in the total number of pixels and diameter either ascending or descending, see Fig. 2 for illustration).

Each trial began with a fixation point that flashed for 300 milliseconds (ms). Five hundred ms after elimination of the fixation point, the sequence appeared and remained in view until the participant pressed a key but no longer than 3000 ms. The next trial began 1000 ms after response onset. Participants were asked to decide whether the three groups of dots are ordered or not. Responses were indicated by pressing one of two keys for ordinal/ non-ordinal sequences, counterbalanced between participants. Participants were asked to make their decisions as quickly and as accurately as possible and were informed that an ordinal sequence could appear in both directions (ascending or descending). The precise instructions were “In each trial; you will see three quantities on the screen, you are asked to decide whether the quantities are presented in an ordinal fashion or not. Order sequences may appear in the ascending left to right or descending right to left direction; refer to quantities alone while making your decision. If the quantities are presented in an ordinal fashion press this key (i.e., corresponding key) if the quantities are non-order press this key (i.e., corresponding key)”. An order sequence can appear in either an increased (from the smaller to larger quantity) or decreased order (from larger to smaller quantity)”. A block of 16 practice trials was presented first. After each practice trial, feedback appeared indicating to the participants if their response was correct (green v shape), incorrect (red X) or did not respond within the time limit for each trial (a clock). Accuracy rates for the practice trial appear in Appendix 1.

Four experimental blocks with a total of 192 trials followed the practice trials. Each block contained 48 trials each: 2 directions (ascending, descending), 2 orders (ordered and non-ordered stimuli), 2 ratios (0.5, 0.7), 2 congruencies (convex hull-quantity congruent, convex hull-quantity incongruent), and 3 different numerosities (see Table 1). Presentation of the sequences in each block of trials was random.

2.5. Preliminary analysis

Participants with accuracy rates of less than 50% were excluded from the analysis (accordingly, 10 participants from the 6–7 age group and five from the 8–9 age group were excluded). Thus, data obtained from 108 children were analyzed (49 first graders, 29 third graders, and 30 fifth graders, see Table 1 Appendix 1). Additionally, we calculated correlations between reaction times (RTs) and accuracy rates separately in each group, to search for a ‘trade-off’ pattern, which is commonly seen in young children (e.g.,

Table 2
Correlations between reaction times and accuracy rates in three age groups.

Group	*r*
First-grade	.451**
Third-grade	.590**
Fifth-grade	.354

Ratcliff, Thompson, & McKoon, 2015). The results of this correlation analysis appear in Table 2. While the older age group (i.e., the fifth-grade group) did not show a significant correlation between RTs and accuracy rates (see Table 2), a significant correlation appeared in the other two age groups.

In light of this significant correlation, the dependent measure in the following analysis was a combined measure of RTs and accuracy rates known as the inverse efficiency score (IES, Bruyer & Brysbaert, 2011; Townsend & Ashby, 1983). IES consists of RT divided by the proportion of correct responses (PC = 1-proportion of errors). Thus, for a given participant the mean RT of the correct responses in a particular condition is calculated and divided by PC: $IES = \frac{RT}{PC}$. Since RTs are expressed in ms and divided by proportions, IES is expressed in ms as well. Hence, lower IES represent faster RTs and/or higher accuracy rates, which mean more efficient processing for lower IES. All means and standard deviations of accuracy rates, RTs, and IES for each condition are detailed in Table 1, Appendix 1.

A four-way repeated measures ANOVA analysis was carried out, which included the between-group factor (first, third, and fifth grades) and three within-group variables of Congruity (congruent or incongruent), Order (ordered or non-ordered) and Ratio (0.7, 0.5 ratios). In all analyses, when needed, contrasts were calculated using the Bonferroni method.

2.6. Bayesian statistical analyses

To further test and quantify the strength of the statistical evidence of our hypotheses regarding the absence of an interaction between order and quantity (i.e., ratio), Bayesian statistical analyses were performed, and Bayes factors are reported for the critical tests (Wagenmakers et al., 2017). The Bayesian analyses were performed using JASP (JASP Team, 2017). A Bayes factor (BF) quantifies and indicates the likelihood of one hypothesis over another. Under a standard interpretation, critical significance levels correspond to BFs of under 3. That is, BFs under 0.333 convey support to the H_0 hypothesis while BFs over 0.333 but under 3 convey indecisive discrimination between H_0 and H_1 (Rouder & Morey, 2012). However, BFs of 3–10 convey "positive evidence" for the H_1, BFs of 10–30 convey "strong evidence," 30–100 convey "very strong evidence," and BFs > 100 convey "decisive evidence" for H_1 (Jeffreys, 1961; Wagenmakers et al., 2017). Note that the subscript "01" in BF_{01} indicates that the Bayes factor quantifies the evidence that the data provide for H_0 versus H_1 and vice versa for the subscript "10" in BF_{10}. Hence, here we present evidence of both subscripts alternately according to the research hypotheses and the Frequentist analysis *p*-value. Additionally, for all interaction, the Inclusion Bayes Factor (*BFInlcusion*) will be presented. Inclusion Bayes Factor reflects, the evidence for all models with a particular effect, compared to all models without that particular effect (and not only the null model).

3. Results

Results reveal a main effect of congruity [F (1, 105) = 15.697, p = .0001, $\eta2$ = .130, BF_{10} = 57.910] due to lower (i.e. more efficient) IES in the congruent condition (3010 ± 117 ms) vs. the incongruent condition (3442 ± 131 ms). Additionally, a main effect of ratio [F (1, 105) = 34.922, p = .0001, BF_{10} = 99800.233] was found, due to lower IES in the 0.5 ratio (2951 ± 113 ms) vs. the 0.7 ratio (3500 ± 128 ms).

Group differences were also significant [F (2, 105) = 8.723, p = .0001, $\eta2$ = .142, BF_{10} = 8.4806]. The IES of the fifth-grade group was the lowest (2698 ± 205 ms) and significantly differed from that of the first-grade group (3775 ± 161 ms, p = .0001). The IES of the third-grade group lay in-between (3205 ± 209 ms) and did not differ significantly from any of the groups (p ≥ .09). Note that lower IES reflect a combination of higher accuracy score and lower RTs and hence, more efficient processing.

The Frequentist analysis indicates congruity and ratio significantly interacted. Yet a Bayesian analysis produces indecisive evidence for this interaction [F (1, 105) = 4.300, p = .041, $\eta2$ = .039, $BF_{Inclusion}$ = .369]. The effect of congruity was significant in the 0.7 ratio [F (1, 105) = 16.358, p = .0001, $\eta2$ = .131, BF_{10} = 21.413] but marginal in the 0.5 ratio with Bayes factors supporting the H_0 hypothesis [F (1, 105) = 3.521, p = .063, $\eta2$ = .032, BF_{10} = .308]. Further, the effect of order was non-significant in the

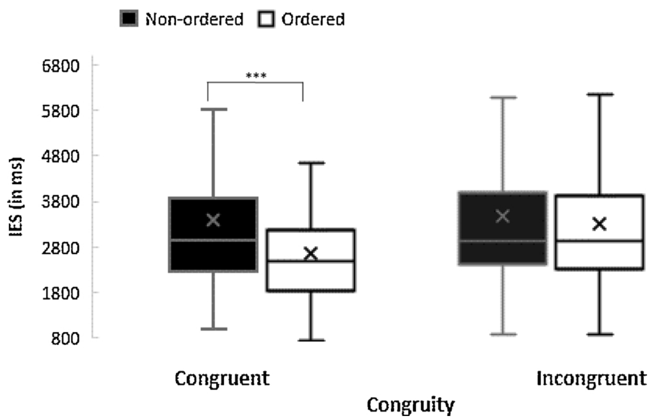

Fig. 3. Mean IES as a function of congruity (congruent vs. incongruent condition) and order (ordered vs. non-ordered sequences).

Frequentist analysis with Bayes Factor (BF_{01}) conveying evidence against the H_0 hypothesis [F (1, 105) = 2.601, p = .110, $\eta2$ =.024, BF_{01} = .077]. Congruity and order significantly interacted [F (1, 105) = 16.654, p = .0001, $\eta2$ =.137, $BF_{Inclusion}$ = 15.548, see Fig. 3]; order was significant only in the congruent condition in which both the relevant (numerosity) and the non-relevant (convex hull) conditions had the same order structure [F (1, 105) = 11.392, p = .001, $\eta2$ = .098, BF_{10} = 7328.764], but not in the incongruent condition [F (1, 105) = .050, p = .823, $\eta2$ = .0001, BF_{01} = 9.627] and these result were further supported by Bayesian analysis. Additionally, it should be noted that in the incongruent condition, order and group did not interact [F (2, 105) = .864, p = .424, $\eta2$ = .016, $BF_{Inclusion}$ = .042], suggesting that difficulties with inhibiting the order of convex hulls appear similar in all three age groups.

To note, order and ratio did not significantly interact as was also supported by the results of the Bayesian analysis [F (1, 105) = 1.126, p = .291, $\eta2$ = .001, $BF_{Inclusion}$ = .184]. Additionally, group differences did not interact with any of the other variables [e.g., congruity and group [F (2, 105) = .564, p = .577, $\eta2$ =.011, $BF_{Inclusion}$ = .063] or order and group [F (2, 105) = .776, p = .463, $\eta2$ = .015, $BF_{Inclusion}$ = .168], (all $F \leq$ 1.128, $p \geq$ .328, $\eta2 \leq$ .021)] indicating similar performance patterns across all three age groups. All other interactions (i.e., the interaction between congruity, order, and ratio) were non-significant as well (all $F \leq$ .001, $p \geq$ .970, $\eta2 \leq$ .0001).

In order to consider the effect of individual differences on current results, an additional analysis using a multilevel approach was performed on RTs. This analysis included all 123 participants that completed the ordinal judging task. Results of this analysis indicated similar results with a significant main effect for ratio, order and congruity and, a significant interaction between order and congruity. A detailed description of the multilevel approach analysis and results appears in Appendix 3.

3.1. Additional analysis of the ordered sequence

In the current experiment, ordered sequences could appear in both the ascending (left to the right) or descending (right to the left) direction. Further, participants in the current study were Hebrew speaking, who read and write from right to left but use Arabic numerals written from left to right. Based on evidence that the effect of the reading and writing direction of mental number line [e.g., "spatial–numerical association of response codes” effect (SNARC effect, Wood, Willmes, Nuerk, & Fischer, 2008)] is not commonly found in Hebrew speakers (e.g., Fischer, Mills, & Shaki, 2010; Fischer, Shaki, & Cruise, 2009; Shaki, Fischer, & Petrusic, 2009), we did not expect to find an effect of direction (i.e., ascending vs. descending ordered sequences) in the current study. However, due to the significant effect of order and, to examine a possible cultural effect on ordinal processing, we proceeded to analyze the effect of direction in the ordered sequences. Hence, a two-way repeated measures ANOVA was carried out, with the between-group factor (first, third, and fifth-grade grades) and direction (ascending and descending) of the ordered sequences as within-group variables.

Supporting our prediction, the difference between ascending (3153 ± 400 ms) and descending (3007 ± 251 ms) ordered sequences was non-significant [F (1, 105) = .097, p = .576, $\eta2$ = .001, BF_{01} = 6.026], as was the interaction between group and direction [F (2, 105) = .004, p = .996, $\eta2$ = .0001, $BF_{Inclusion}$ = .129].

4. Discussion

This study aimed to explore the automatic processing of order in children from the age of six to eleven years. By using an ordinal Stroop task, current findings support the idea that from an early age, children automatically process numerical information also based on its visual ordinal characteristics. This view is supported by the congruity and order interaction found in the current study; order was significant (i.e., a significant difference between ordered and non-ordered sequences) in the congruent condition, but not in the incongruent condition. This significant interaction suggests that even when children were instructed to attend only to the order of quantities, they could not ignore the order of the irrelevant dimension, in this case, the convex hulls of the numerical stimuli (i.e., dot patterns) which modulated their response to the order of numerals.

Overall, current findings contribute to the idea of a non-symbolic ordinal input analyzer. The automatic response to the order of convex hulls further suggests that this system may be able to perceive order regardless of the directions or another general pattern of the sequence.

Current results also replicate a ratio dependent performance, namely a typical ratio effect. The significant ratio effect adds to the typically found ratio effect (Dehaene, 1997; Rubinsten & Henik, 2005; Tzelgov et al., 1992) by suggesting that the performance in an ordinal judging task was supported by or at least involved numerosity. This is not surprising, given strong and well-established prior evidences showing that this numerical system is automatically activated even when it is irrelevant to the task at hand (Cohen Kadosh, Cohen Kadosh, & Henik, 2008; Dehaene, 1997; Feigenson et al., 2004; Rubinsten & Henik, 2005).

In what follows, we will discuss the automatic processing of order and the relationships between order, numerosity, and visual properties.

4.1. Order is automatically processed

Current findings indicate that children automatically dissociate ordered from non-ordered sequences based on visual cues. That is, even though participants were asked to exclusively refer to the order of quantities presented in the sequence, they could not ignore the order of the irrelevant dimension: convex hull. When the relationships between convex hulls were random, children had more difficulty perceiving the order between quantities (i.e., higher IES, decreased efficiency). Hence, current findings suggest that in children, ordinal representation is not restricted to numerosity. Instead, children may automatically attend to the order of visual stimuli in everyday visual scenes.

Furthermore, the effect of order was non-significant in the incongruent condition (rather than merely a reduced effect), suggesting that children not only struggle with dissociating the order of quantity and convex hull but also expect ordered sequences to be holistically ordered. Specifically, the interaction between order and congruity indicate that participants did not blindly respond to the ordinal changes of quantity or convex hull, but rather, they turned to an inference between these two. One possible explanation for this pattern is that when judging the order of a numerical sequence, children perceive order as a whole and expect all characteristics of the sequence to be ordered accordingly. Therefore, current findings suggest that children show a preference for ordinal sequences only when these are entirely ordered in all relevant and irrelevant features of the sequence. According to the argument, order can be defined as *a state of similar pattern between a sequence's elements and this pattern appears similar within different dimensions of the sequence*. Thus, processing order is predicting the evolvement of the sequence based on a shared regularity between dimensions. However, this hypothesis remains to be examined in different sequences and different dimension of a sequence.

The idea that non-ordinal attributes of convex hulls result in a violation of expectations was previously suggested by Gebuis and Reynvoet (2013a). In this ERP study, adult participants passively viewed a sequence of five quantities (presented one after the other). While both quantity and visual properties (i.e., convex hull, aggregate surface, density, diameter, and contour length) increased in the four first items, the visual cues and/or quantity of the fifth stimuli was manipulated and could correspond or not to the pattern presented in the first four elements (e.g., while the first four items increased in numerosity and visual properties, the fifth item increased in numerosity but decreased in visual cues). Results indicated an interaction between numerosity and sensory cues in the absence of any main effect. Hence, participants created expectations about the fifth item based on the ordinal relations in the first four items in both numerals and visual properties, thus, supporting our claim that in a non-symbolic numerical sequence, sensory cues are expected to match the change in numerosity completely. Further, based on current and former findings (e.g., Cassia et al., 2012; Lewkowicz, 2004; Lewkowicz & Berent, 2009), it seems this expectation is not restricted to adults but instead appears through-out lifespan. Current results demonstrate, and for the first time, that children from the age of six years old 'expect' the sequential attributes of both sensory cues and numerosity to correspond with each other similar to adults.

According to the perceptual interaction view (e.g., Hock & Egeth, 1970), in the current task, the representations of numerical order and convex hull's order are constructed in parallel and interact at the level of stimulus perception. To further validate this hypothesis, it is expected to also introduce participants to a 'reverse task' in which, participants are requested to judge the order of convex hull (rather than quantity). Due to the age of participants and the level of difficulty, such a task was not employed in the current study. Thus, while current findings suggest order of visual cues is automatically activated while judging a sequence of non-symbolic quantities, the reverse effect is yet to examine. While performance on the ordinal judging task differed between age groups, the performance of the different age groups did not significantly interact with other variables.

Similarly, Rousselle and Noël (2008) showed that sensitivity to irrelevant continuous magnitudes remains stable across ages 3 to 6. Current findings expand this notion showing the sensitivity to convex hole also appears in children from the age of 6 to 10. Furthermore, current findings indicate the ability to estimate non-symbolic order already exist at the age of six and, show minimal changes through elementary school years. This is compatible with previous findings showing that non-symbolic numerical information does not go through critical changes throughout childhood (Cantlon, Brannon, Carter, & Pelphrey, 2006; Emerson & Cantlon, 2015) and expand this argument also to non-symbolic ordinal processing.

Our findings do not overrule the notion that order perception has a protracted period of development and might show little change from six to ten years, but more developmental changes may appear after the age of ten. For example, in Rubinsten and Sury (2011), while completing an ordinal judging task, adult participant showed a significant preference to a descending direction of the ordered sequence. An effect that was not replicated in the current study and this may indicate an additional development change that occurs after the age of ten.

Considering the developmental curse of order perception, accuracy rates of the different age group should be addressed. Mean accuracy rates for the current task were relatively low and indicated that children were faced with a difficult task and could not easily judge the order of the numerical sequence with congruent sequences being processed more efficiently. This difficulty seems to be more prominent in the younger age groups. While no age-related differences in the effect of congruity were detected (i.e., no interaction between group and congruity, see also appendix 3), significant group differences indicate an improvement in the ability to explicitly judge numerical ordinality from the age of six to eleven. Future studies should determine what aspect of numerical order (e.g., size of numerosity, manipulation of visual cues, sequential vs. simultaneous presentation) more critically affect explicit judgment of numerical order in children. Numerical order processing may implicitly effect perception from infancy (e.g., Brannon, 2002; Cassia et al., 2012; Picozzi, de Hevia, Girelli, & Cassia, 2010). Yet explicit judgment of numerical order did not seem to reach high efficiency in the current age groups.

To summarize, current findings suggest that children automatically attend to the order of different visual stimuli in the surrounding world. Hence, the current results imply the existence of an ordinal input analyzer that might tend to perceive visual ordered sequence, on condition that the sequence is 'holistically' ordered (i.e., all of the sequences' different features are congruently ordered), but unrelated to the relationship (e.g., the ratio between sequence items) of the sequence. Moreover, this ability seems to be related to domain-general mechanisms rather than explicitly to numerical processing.

4.2. The direction of the ordered sequence

Current findings suggest that non-symbolic order is not significantly affected by direction. On the one hand, it has been shown that both human infants and monkeys show a preference to the ascending direction of an ordered numerical sequence (Brannon &

Terrace, 2000; de Hevia et al., 2017) that seem to decrease with age (Picozzi et al., 2010; Srinivasan & Carey, 2010). However, it should be noted that studies regarding the asymmetry in ordinal preference used sequential presentation (i.e., stimuli appeared one after the other) contrary to the simultaneous presentation in the current task. Hence, the difference between the spatial and temporal direction of the sequence should be further examined to support the absence of the asymmetry signature in children.

An alternative explanation for the lack of direction effect in the current study is related to the language of participants. Children who participated in the current study were native Hebrew speakers who read and write from right to left but use Arabic numbers from left to right. This dissociation between the reading and writing direction of numbers and letters or words has been shown to affect the mental number line and specifically the directional bias of this representation (Fischer et al., 2009, 2010; Shaki et al., 2009; Wood et al., 2008). It was further suggested that cultural factors, such as the direction of reading and writing, influences numerical representation even before formally acquiring the written systems (i.e., school age) (Göbel, Shaki, & Fischer, 2011; Shaki, Fischer & Göbel, 2012). Hence, this 'absence' effect of direction does not necessarily apply for other languages. That is, children accustomed to the same writing and reading direction for both letters and numbers may show a preference to the ascending direction even when sequences are presented stimulatingly due to the cultural effect on numerical representation.

4.3. *The relationship between ratio, convex hull, and order*

Supporting our hypothesis, ratio produces a significant effect. This automatic activation of numerosity is compatible with numerous studies establishing the view that numerosity is automatically activated (Cohen Kadosh et al., 2008; Dehaene, 1997; Feigenson et al., 2004; Rubinsten & Henik, 2005). Current findings, however, do not provide support to recent claims regarding the role of visual features in numerical discrimination. Bayesian analysis provided indecisive evidence regarding the interaction between congruity and ratio. Thus, when explicitly attending to the order of the sequences, a more prominent effect is found for the interaction between order and congruity rather then ratio and congruity.

Indeed, performance in the current task involved numerosity. However, if ratio was the sole catalyst for children's performance in the current task, then a different pattern should have been predicted. Specifically, it should be emphasized that changing the order of the sequences also resulted in a decreased ratio. For example, randomizing the ordered sequences of 4, 8, and 16 dots (0.5 ratios) results in a sequence of 4, 16, and eight dots, 16, 4, and eight dots, or 8, 16, and four dots, etc. Hence, 4 and 16 dots will appear successively, and the ratio will be smaller (i.e., easier) than the original ratio of the ordinal sequence. Thus, relying mainly on numerosity will result in a significant interaction between ratio and order [or a reversed order effect -lower IES for the non-ordered condition, with smaller ratio sequences due to a decrease in ratio (e.g., Barth et al., 2005; Dehaene, 1997; Halberda, Mazzocco, & Feigenson, 2008)]. However, in the current study, the significant effect of order in the congruent sequences, was a result of more efficient processing for ordered vs. non-ordered sequences (i.e., lower IES for ordered vs. non-ordered sequences) and despite that smaller ratio in the non-ordered sequences. Hence, ratio could not have been the sole catalyst for performance. Further, even the decrease in ratio in the non-ordered sequences did not manage to neutralize the effect of order. This suggests that order and numerosity might act two separate systems that are simultaneously activated during numerical processing (Cheng et al., 2013; Delazer & Batterwoth, 1997; Rubinsten & Sury, 2011; Rubinsten et al., 2013).

5. Limitations

Despite the contribution of current findings to the discussion regarding order processing in non-symbolic quantities, several limitations of the study should be noted. As mentioned earlier, we did not employ a "reverse task" in which participants are asked to judge the order of convex hull rather than quantities. Thus, it remains unknown whether order of quantity similarly affects the ordinal judgment of another dimension of the sequence. Additionally, the relatively smaller sample size may have masked some mild developmental changes that occur between the age of six to ten years old.

6. Conclusions

The idea that an ordinal input analyzer could be involved in various cognitive functions and serve as a basic system crucial for survival has been neglected in contemporary science. This despite evidence suggesting that this system is involved in different cognitive functions (Gilad et al., 2009; Kaufmann et al., 2009; Koenderink, Avan Doorn, Kappers & Todd, 2002; Norman & Todd, 1998; Todd & Norman, 2003). Current findings not only support previous evidence regarding the role of visual properties in numerical processing but also demonstrate that even young children automatically dissociate between ordered and non-ordered sequences based on their visual properties. Furthermore, our findings support previous evidence regarding the existence of two systems involved in numerical processing; order and quantity (Cheng et al., 2013; Rubinsten & Sury, 2011; Rubinsten et al., 2013). Thus, the current study reinforces the idea of a cognitive system dedicated to order -the ordinal input analyzer. The automatic processing of visual properties further indicates that future studies should examine whether automatic ordinal processing is indeed involved in perceiving other non-numerical sequences such as color or shape.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.cogdev.2019.

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