8-1-2022

Number symbols are processed more automatically than nonsymbolic numerical magnitudes: Findings from a Symbolic-Nonsymbolic Stroop task

H. Moriah Sokolowski
Rotman Research Institute

Zachary Hawes
University of Toronto

Tali Leibovich-Raveh
University of Haifa

Daniel Ansari
Western University, daniel.ansari@uwo.ca

Acta Psychologica 228 (2022) 103644

Contents lists available at ScienceDirect

Acta Psychologica

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

Number symbols are processed more automatically than nonsymbolic numerical magnitudes: Findings from a Symbolic-Nonsymbolic Stroop task

H. Moriah Sokolowski [a,d,*], Zachary Hawes [b,d], Tali Leibovich-Raveh [c,d], Daniel Ansari [d]

[a] Rotman Research Institute, Baycrest Hospital, Toronto, Canada
[b] Ontario Institute for Studies in Education, University of Toronto, Ontario, Canada
[c] Department of Mathematics Education, University of Haifa, Haifa, Israel
[d] Department of Psychology, Brain and Mind Institute, University of Western Ontario. London, Ontario, Canada

ARTICLE INFO

Keywords:
Symbolic
Nonsymbolic
Stroop
Numerical
Automaticity
Number processing

ABSTRACT

Are number symbols (e.g., 3) and numerically equivalent quantities (e.g., •••) processed similarly or distinctly? If symbols and quantities are processed similarly then processing one format should activate the processing of the other. To experimentally probe this prediction, we assessed the processing of symbols and quantities using a Stroop-like paradigm. Participants ($N_{Study1} = 80$, $N_{Study2} = 63$) compared adjacent arrays of symbols (e.g., 4444 vs 333) and were instructed to indicate the side containing *either* the greater quantity of symbols (nonsymbolic task) or the numerically larger symbol (symbolic task). The tasks included congruent trials, where the greater symbol and quantity appeared on the same side (e.g. 333 vs. 4444), incongruent trials, where the greater symbol and quantity appeared on opposite sides (e.g. 3333 vs. 444), and neutral trials, where the irrelevant dimension was the same across both sides (e.g. 3333 vs. 333 for nonsymbolic; 333 vs. 444 for symbolic). The numerical distance between stimuli was systematically varied, and quantities in the subitizing and counting range were analyzed together and independently. Participants were more efficient comparing symbols and ignoring quantities, than comparing quantities and ignoring symbols. Similarly, while both symbols and quantities influenced each other as the irrelevant dimension, symbols influenced the processing of quantities more than quantities influenced the processing of symbols, especially for quantities in the counting rage. Additionally, symbols were less influenced by numerical distance than quantities, when acting as the relevant and irrelevant dimension. These findings suggest that symbols are processed differently and more automatically than quantities.

1. General introduction

Basic number processing is a cognitive foundation that supports mathematical thinking. Basic number processing is defined as the ability to understand, estimate, and/or discriminate between numerical magnitudes. From very early in development humans have the ability to process nonsymbolic numerical magnitudes (often referred to as quantities) (e.g., '•••' vs. '••') (Brannon, 2006). This capacity to process quantities is shared with non-human primates as well as other species (For reviews see: Cantlon, 2012; Dehaene, 2007). This suggests that the ability to process quantities has a long evolutionary history. Critically, unlike non-human species and infants, human adults, in cultures that teach math symbolically, have the unique, culturally acquired ability to process numbers symbolically (e.g.,'3').

The dominant assumption in the field of numerical cognition has been that this culturally acquired ability to represent numbers symbolically is linked to an evolutionarily ancient system used to process quantities (Brannon, 2006; Dehaene, 2007; Dehaene et al., 2003; Halberda et al., 2008; Nieder & Dehaene, 2009). However, a growing body of research has revealed that symbols and quantities are processed more distinctly than has been assumed (Cohen Kadosh et al., 2007; Cohen Kadosh et al., 2011; Cohen Kadosh & Walsh, 2009; De Smedt et al., 2013; Holloway et al., 2010; Lyons et al., 2012, 2014; Sokolowski et al., 2017). The majority of previous research has examined how participants process symbols and quantities using active tasks that require participants to attend to the presented stimuli and typically, make a decision based on these stimuli (e.g., Ansari, 2008; Dehaene et al., 1998; Fias et al., 2003; Fulbright et al., 2003; Holloway & Ansari, 2008, 2009; Moyer & Landauer, 1967). Importantly, in these studies, the numerical magnitude acts as the relevant dimension of the task. For example, in a

* Corresponding author at: Rotman Research Institute, Baycrest Hospital, Toronto, ON M6A 2E1, Canada.
E-mail address: h.moriah.sokolowski@gmail.com (H.M. Sokolowski).

https://doi.org/10.1016/j.actpsy.2022.103644
Received 11 September 2020; Received in revised form 12 April 2022; Accepted 9 June 2022
Available online 21 June 2022

number comparison task, participants are presented with two numerical magnitudes (i.e. two symbols or two quantities) and asked to indicate which of the two numerical magnitudes has more items (e.g., Buckley & Gillman, 1974; Holloway & Ansari, 2009; Moyer & Landauer, 1967). While active tasks, such as number comparison tasks, provide insight into the effortful processing of numerical magnitude, relatively less is known about the automaticity of processing numbers.

A small set of studies have attempted to unravel how human adults process symbols and quantities using tasks where the symbols and quantities presented in the task are irrelevant (e.g., Furman & Rubinsten, 2012; Naparstek & Henik, 2010, 2012; Naparstek et al., 2015; Pansky & Algom, 2002; Pavese & Umiltà, 1998, 1999; Windes, 1968). An example of a task where the numerical magnitudes are included as irrelevant stimuli is a Numerical Stroop Task. In a Numerical Stroop Task a participant is presented with two symbols that differ both in numerical magnitude and in physical size (e.g., 3 and 4) and are asked to indicate which symbol is numerically or physically larger (Henik & Tzelgov, 1982; Leibovich et al., 2013). When participants complete this task a so-called size congruity effect (SCE) is obtained. The SCE reflects the finding that the dimension to which the participant does not need to attend (i.e. the irrelevant dimension) influences speed and accuracy on the comparison task. For example, when making a physical size judgment, on a Numerical Stroop task that includes two different Arabic numerals in different size fonts, the numerical magnitude of the symbols being compared influences judgments of the physical size. This finding, that the semantic meaning of a symbols affects physical size judgments, despite the fact that the participants do not need to process the semantic meaning of the number to succeed at the task, has been taken to suggest that the system used to process the physical size of an Arabic numeral is at least partially overlapping with the system used to process the semantic meaning of the Arabic numeral. Critically, although this task is useful in revealing how symbolic numerical magnitudes influence the processing of the non-numerical magnitude, physical size, this paradigm cannot be used to address questions pertaining to the differences and similarities in processing symbolic *and* nonsymbolic numerical magnitudes (i.e. symbols and quantities). A Stroop-like task is an excellent way to explore whether symbols and quantities are processed similarly or distinctly when acting as the relevant and the irrelevant dimension. Indeed, a Symbolic-Nonsymbolic Stroop Task is the ideal task to identify whether symbols and quantities influence the processing of the other and if this influence is symmetrical.

1.1. The role of numerical distance

Among the most frequently cited evidence to support the notion that symbols are fundamentally linked to quantities is the finding that human adults produce a 'distance effect' when making comparative judgments of both symbolic and nonsymbolic numerical magnitudes (e.g., Dehaene et al., 1998; Holloway & Ansari, 2008, 2009; Krajcsi et al., 2016; Moyer & Landauer, 1967; Pavese & Umiltà, 1998; van Opstal & Verguts, 2011). The distance effect is the highly replicable finding that humans are faster and more accurate at judging which of two numerical magnitudes is numerically greater when those magnitudes are numerically far apart, rather than close together (Moyer & Landauer, 1967). There have been many reports of similar distance effects during the processing of symbols and quantities that have been replicated across many studies (Buckley & Gillman, 1974; Holloway et al., 2010; Holloway & Ansari, 2008; Krajcsi et al., 2016; Moyer & Landauer, 1967) and have been taken as evidence that symbols and quantities are represented using a shared analogue magnitude system (Dehaene, 2007; Dehaene et al., 1998). Numerical distance has been shown to influence the processing of numerical magnitudes when the symbol or quantity is the relevant dimension (Buckley & Gillman, 1974; Holloway & Ansari, 2009; Moyer & Landauer, 1967) and the irrelevant dimension (Henik & Tzelgov, 1982; Pavese & Umiltà, 1998, 1999). It is worth noting that the comparison distance effect (i.e., an effect when participants effortfully compare two digits) dissociates from the priming distance effect (i.e., the finding that when a target number is preceded by a priming number, participants automatically respond more quickly when the prime-target numerical distance is smaller), which is thought to be a more direct measure of representational overlap (Van Opstal et al., 2008). Across tasks, the effect of numerical distance has been used to assess the degree to which the underlying representations that support the processing of numerical magnitudes are overlapping and thus have been interpreted to be a measure of representational precision (Nieder & Dehaene, 2009; Verguts & Fias, 2004); however, with effortful tasks this effect may also be related to a more general comparison process. Regardless, assessing whether the influence of symbols and quantities on each other is modulated by numerical distance will add to the current understanding of the connection between symbols and quantities by identifying not only whether symbols and quantities are processed in parallel, but also whether the representational precision of this influence is symmetrical.

1.2. The role of countability

Subitizing is a cognitive ability that allows for the fast, automatic, and accurate identification of the quantity of a small set of items (i.e., sets containing 1–4 items) (Mandler & Shebo, 1982; Trick & Pylyshyn, 1994). Large sets (i.e., sets containing 5 or more items) are considered to be in the 'counting range,' as these sets are evaluated through either the effortful process of counting or approximate estimation. The quantity of a set of items in the subitizing range is named more quickly and accurately than the quantity of a set of items in the counting range (Kaufman et al., 1949;Trick & Pylyshyn, 1994). Subitizing occurs even when objects are presented among distractor objects, provided the subitized and distractor objects differs by perceptual features (Trick & Pylyshyn, 1993), the items being subitized are whole objects (Trick & Enns, 1997), and the distractors are held constant through the block (Liu et al., 2020). Prior research has refuted the idea that there is a single estimation system used to process quantities in both the subitizing and counting range and instead supports the notion that humans possess a dedicated mechanism for processing small subitizable quantities (Revkin et al., 2008). Indeed, the processing of small quantities (i.e., 1–4) is supported by a parallel individuation system (PI system), used to track objects in order to identify the exact number of items in small sets. In contrast, research suggests that an analogue magnitude system (often referred to as an approximate number system (ANS)) supports the processing of quantities with five or more objects. The analogue magnitude system relies on approximate estimation to process larger quantities (For review see: Hyde, 2011). If small quantities are processed by a more exact system, it follows that the processing of symbols should be more similar to the processing of small quantities than large quantities. In line with this, if there is an asymmetry in the way symbols and quantities are processed, it should be greater when comparing symbols to quantities in the counting range than in the subitizing range. Therefore, in addition to comparing symbols to quantities across the full range, the processing of symbols will be compared to the processing of quantities in the subitizing range and the counting range, independently.

1.3. The current study

In the current study, we assess whether symbols and quantities are processed similarly as relevant and irrelevant dimensions. Specifically, this allows us to examine whether the processing of one format activates the processing of the other format. Additionally, we examine how numerical distance influences the processing of symbols compared to quantities. Finally, we assess whether differences in the processing of symbols and quantities are driven by quantities in the counting range, rather than the subitizing range. This study identifies whether there is an asymmetry in the processing magnitudes of different number formats.

2. Experiment 1

2.1. Experiment 1: introduction

In our first experiment, we adapt the famous colour Stroop paradigm (Stroop, 1935) to measure how individuals process symbols and quantities acting as the relevant and irrelevant dimensions, within the same task. Stroop paradigms have been widely used in psychology to examine the degree to which an irrelevant stimulus influences the processing of a relevant stimulus. The original Stroop effect revealed that participants are slower and less accurate at naming a font colour of a printed word if the meaning of the word and font colour conflict (Stroop, 1935). More specifically, participants were slower and less accurate at identifying that the font colour of a word if the font colour is different from the semantic meaning of the printed word (e.g., the word 'red' printed in a green font).

Previous research studies have used Stroop-like tasks to assess the automatic processing of symbolic numbers (Henik & Tzelgov, 1982; Naparstek et al., 2015; Pansky & Algom, 2002). As discussed above, the Numerical Stroop Task, a task that requires participants to judge which of two digits (e.g., 3 vs 5) was larger either in physical size or in numerical magnitude, is the most widely used assessment of the automatic influence of symbols on judgments of the non-numerical magnitude, physical size. Results revealed that judgments of physical size were faster than judgments of symbols, suggesting that participants are more efficient at processing the relevant dimension when it is size compared to symbolic numerical magnitudes. However, physical size judgments were affected by the numerical magnitude of the symbol. Moreover, the degree to which the numerical magnitude of the symbol influenced the processing of the physical size was associated with numerical distance. Specifically, physical size judgments were more influenced by symbolic numerical pairs with relatively larger numerical distances. Therefore, in the same way that larger numerical magnitudes are more obvious when comparing two magnitudes with a large numerical distance, larger numerical distances between two irrelevant numerical magnitudes make the automatic influence of the irrelevant dimension more salient. This indicates that numerical distance is automatically processed, even when it is irrelevant, to form the judgment of which of two symbols is physically larger. This finding has been taken to suggest that physical size and the semantic meaning of the symbolic numerical magnitudes are processed in parallel. Other research that has examined the automatic processing of symbols and quantities presented participants with a single array containing a quantity of symbols (e.g., a single array containing six of the symbolic Arabic digit '7'). Participants were instructed to compare either the symbol in the array or the quantity of symbols in the array to the number five (comparison task) or to indicate if the numerical magnitude was an even or odd number (parity task) (Naparstek & Henik, 2010). Results revealed that symbols influenced the processing of quantities for both the comparison and parity tasks, whereas quantities only influenced the processing of symbols on the comparison task. This suggests that symbols may be processed more automatically than quantities. Critically, as Naparstek and colleagues included a single array of symbols (e.g., six of the symbol '7'), and asked participants to compare either the symbol or the quantity to the number five, both the symbol and quantity comparison task required participants to hold the symbolic referent ('five') in their minds. Consequently, it is possible that the asymmetry between comparing symbols and quantities to the symbolic referent is due to the fact that, for quantity task, the participants were comparing between formats (i.e., nonsymbolic to symbolic), whereas in the symbolic task, participants were comparing a symbol to a symbolic referent. Consequently, in the current study, we create a Symbolic-Nonsymbolic Stroop paradigm which allows us to examine how symbols and quantities influence each other, without requiring a transformation between formats. We also use this task to assess whether the influence of symbols and quantities on each other is symmetrically modulated by numerical distance. Unlike previous studies, the current study compares the processing of symbols to the processing of quantities in the subitizing range and the counting range separately, as well as together. Findings from the current study will illuminate whether the influence of symbols and quantities on each other is symmetrical and will, therefore, allow us to identify whether symbols and quantities are processed separately or in parallel, and with similar or distinct representational precision. These findings are important to identify whether symbols are processed using the ancient system that evolved to process nonsymbolic magnitudes, or if symbols are supported by a similar but ultimately distinct representational system.

2.1.1. The Symbolic-Nonsymbolic Stroop Paradigm

In the current study, we examined whether processing of symbolic numerical magnitudes (e.g., 3) is distinct from processing quantities (e.g., ●●●) using a novel Symbolic-Nonsymbolic Stroop paradigm. The stimuli in this paradigm consisted of two quantities of symbols (e.g., 3333 vs. 444). The inclusion of two sets of symbols and quantities in all stimuli meant that we were able to not only assess effortful and automatic processing of symbols and quantities independently but also the influence that symbols and quantities have on each other. During this paradigm, participants were asked to compare adjacent arrays of number symbols (e.g., 4444 vs 333) and indicate the side containing *either* the greater quantity of symbols (nonsymbolic task) or the side containing the numerically larger symbol (symbolic task). This means that symbolic and nonsymbolic numerical magnitude acted as *both* the relevant dimension (i.e., the dimension that the participant was instructed to attend to) and the irrelevant dimension (i.e., the dimension that the participant needed to ignore). There were congruent trials, where the larger symbolic and nonsymbolic numerical magnitude appeared on the same side of the screen (e.g., 333 vs. 4444), incongruent trials, where the larger symbolic and nonsymbolic numerical magnitude appeared on opposite sides of the screen (e.g., 3333 vs. 444), and neutral trials, where the irrelevant dimension was the same across both sides of the screen (e.g., 3333 vs. 333 for nonsymbolic; 333 vs. 444 for symbolic). In this task, the numerical distance between the numerical magnitudes being compared was systematically varied across trials. Additionally, follow-up analyses are included to compare the processing of symbols to quantities in the subitizing range and counting range, separately. This examination of the processing of symbols and quantities as the relevant and irrelevant dimensions using a Symbolic-Nonsymbolic Stroop paradigm holds promise to identify whether symbols are processed in the same way as quantities under different attentional conditions and to evaluate the influence of symbols and quantities on each other.

In accordance with the large body of previous literature comparing effortful processing of symbols and quantities, we expect that participants will either perform the same on the symbolic and nonsymbolic tasks or will perform better on the symbolic task. Additionally, we expect that the effortful processing of both symbols and quantities will be influenced by numerical distance, with participants performing better for trials with larger numerical distances.

With respect to automatic processing, we hypothesize that participants behaviour will fit one of the following three patterns

1. Symbols and quantities will automatically influence each other to the same degree.
2. Symbols will influence the processing of quantities more than quantities will influence the processing of symbols across numerical distances.
3. Symbols will influence the processing of quantities across distance conditions, but quantities influence the processing of symbols in a distance dependent way.

Finally, we predict that any differences observed between the processing of symbols and quantities will be more pronounced for magnitudes in the counting range compared to those in the subitizing range.

2.2. Experiment 1: method

2.2.1. Participants

Eighty healthy adult participants (M_{age} = 21.4, SD_{age} = 3.01; 31 males, 49 females) were recruited at the University of Western Ontario in London, Ontario. Participants provided written consent before participating in the study. The session took approximately two hours and participants were compensated $5 CAD per half-hour (average $20 CAD total). All procedures were approved by the University of Western Ontario Non-medical Research Ethics Board.

2.2.2. Materials

2.2.2.1. Symbolic-Nonsymbolic Stroop Task. This task is comprised of two subtasks: the symbolic task and the nonsymbolic task. Stimuli for both subtasks were composed of two arrays of Arabic numerals (numbers 1 to 9) in a four by four array (see Fig. 1). An array contained a certain quantity of Arabic numerals (e.g., six '6's). The remaining spaces in the array were filled with the star symbol (*) as has been done in previous research (Naparstek et al., 2015; Pansky & Algom, 2002), to control for continuous properties such as area (Leibovich & Henik, 2013). Specifically, including '*' in all spaces that did not contain a symbol allowed us to keep the total area of the numerical displays constant throughout all trials. Although this does not remove all associations between continuous properties and quantities (i.e., the proportion of spots filled by digits still changes based on quantity) it does control for salient continuous magnitudes that have been reported to significantly influence the processing of nonsymbolic numerical magnitudes, such as area, density, and convex hull (For review see: Henik et al., 2017; Henik et al., 2011; Leibovich & Henik, 2013; Leibovich et al., 2016). Twenty different versions of each array were generated using MATLAB to ensure that participants did not learn the position of the Arabic digits within the arrays. The stimuli were presented using OpenSesame (Mathôt et al., 2012), with a resolution of 800 × 600. The stimuli, code to create the stimuli, and the OpenSesame experiments (which include trial-lists), are publicly available at on the Open Science Framework (OSF) at https://osf.io/qyczk/.

The participant performed both a symbolic comparison task and a nonsymbolic comparison task on all pairs of arrays. The task took participants approximately 20 min to complete (10 min for each task). The distinction between the symbolic task compared to the nonsymbolic task was that participants performed distinct kinds of magnitude comparisons on the same set of stimuli. In the symbolic task, the participant had to indicate which array contained the numerical symbol with the larger magnitude. In the nonsymbolic task, the participant had to indicate which array contained the greater quantity of numerical symbols (five '3's vs. two '2's). In the congruent condition, the larger symbol and the greater quantity appeared on the same side of the screen. In the incongruent condition, the side with larger symbol appeared opposite to the side with the greater quantity. Importantly, the participant was presented with the same set of stimuli for the symbolic task and the nonsymbolic task for both the congruent and incongruent conditions. In the neutral condition, the irrelevant dimension was the same across both sides of the screen and depended on the condition. In the symbolic neutral condition, the two arrays contained different symbolic numbers, but the quantity of symbolic numbers was held constant between the stimuli and matched one of the two symbolic numbers. In the nonsymbolic neutral condition, the quantity of the symbolic numbers in the two arrays was different, but both arrays contained the same symbolic numbers that were the same as one of the two quantities. In the congruent and incongruent conditions, the distance between the relevant dimension (i.e., what the participant is told to compare) and the irrelevant dimension (i.e., what the participant must ignore) was the same and ranged from 1 to 6, with 12 trials per distance. The distance between the relevant dimension in neutral condition was matched to the congruent and incongruent conditions, and the irrelevant dimension in the neutral condition was always 0. See Fig. 1 for examples of stimuli for congruent, incongruent, and neutral conditions for both the symbolic and nonsymbolic comparison task.

Participants were randomly presented with two blocks of 216 trials (432 total trials) on the symbolic task and on the nonsymbolic task. Of the 216 trials, 72 stimulus pairs were congruent, 72 were incongruent, and the remaining 72 trials were neutral. Each of the 72 trials consisted of 12 trials at each of distance 1–6. Notably, only 108 of the 216 trials had unique number pairs. The other 108 trials had the same numbers as the original 108 trials, but the numbers appeared on opposite sides of the screen. The stimuli in the congruent and incongruent conditions were identical for the symbolic and the nonsymbolic comparison tasks. The stimuli for the neutral conditions differed between tasks because, in the neutral condition, the irrelevant dimension was controlled to have a distance of zero. Within a single trial, participants were presented with a fixation for 500 milliseconds (ms), then a blank screen for 300 ms. Following this, participants were presented with two arrays for 2000 ms

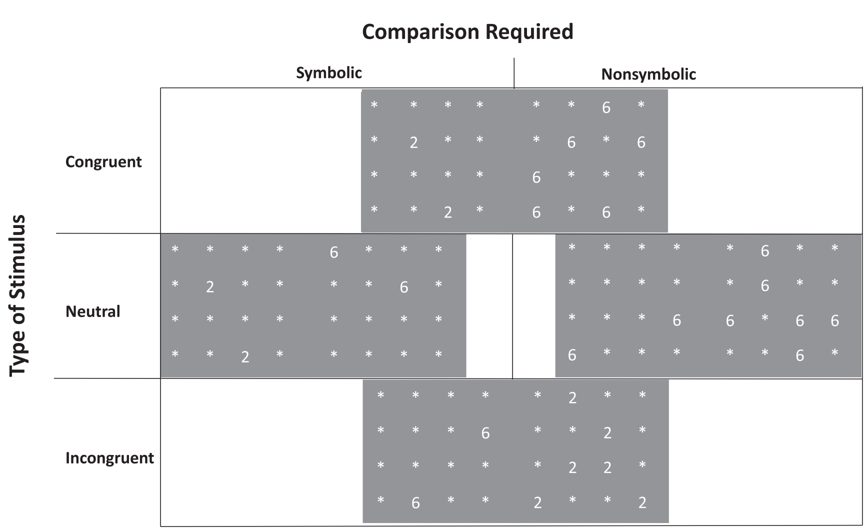

Fig. 1. Examples of types of stimuli presented. For congruent and incongruent, the same stimuli were used for both the symbolic and the nonsymbolic comparisons. The stimuli for the neutral condition differed for the symbolic and the nonsymbolic comparison conditions.

or until a key response was made. Once the participant either made a key response or the 2000 ms was up a blank screen was presented for 500 ms. See the OSF page at https://osf.io/qyczk/.F for a list of the trials.

2.2.3. Procedure

All included measures were obtained during a single session that took approximately two hours. During the session, participants completed a series of cognitive tasks including the Symbolic-Nonsymbolic Stroop Task (comprised of both the symbolic task and the nonsymbolic task). Only the results from the Symbolic-Nonsymbolic Stroop task are reported here. Participants viewed the stimuli on one of two identical Dell desktop machines that run Windows 8.1. Participants were seated roughly 60–70 cm from the screen, which was an 18.6 by 12.1 in. flat-screen LCD monitor with 1680 × 1050 resolution. The Symbolic-Nonsymbolic Stroop Task was always given at the beginning of the session, but the order that participants completed the subtasks (i.e. the symbolic task and nonsymbolic task) was counterbalanced between participants. Each sub-task (the symbolic task and nonsymbolic task) began with a practice block that randomly presented 5 of the 216 stimuli. Feedback was given at the end of the practice block. Participants continued to the actual experiment if they correctly answered 4 out of 5 practice trials (i.e., 80% correct) for each subtask. If the participant did not get at least 80% of the practice block correct the participant redid the practice block. The actual experiment for each sub-task was composed of two blocks (i.e. two blocks for the symbolic task and two blocks for the nonsymbolic task). The participants got one break between the two blocks. In each block, all 216 stimuli were randomly presented once.

2.2.4. Analysis

Trials with an RT that were + or – 3SD from the mean of the trial type within an individual were considered outliers and removed. This resulted in <1% of the RT data being removed. Following this, the RTs for each trial were adjusted to reflect both the speed and accuracy of performance. Mean RTs and error rates were combined to produce an adjusted rt. using the following formula.

$$Adjusted\ Response\ Time = \frac{Mean\ Response\ Time}{1 - Error\ Rate}$$

An adjusted response time (RT) allows for the RTs to remain unchanged on correct trials and increase proportionally with the number of errors. Adjusted RTs are often used in the literature (e.g., Sasanguie et al., 2012; Simon et al., 2008) as they account for both speed and accuracy. Recently, it has been noted that although adjusted rts do provide a better summary of the findings, these scores increase the variance of the measure, and therefore, it is necessary to further check the data to ensure that the pattern of results for the RT and accuracy is the same (Bruyer & Brysbaert, 2011). In the current study, each of the RT and accuracy produce the same pattern of results as the adjusted rt. Consequently, all results will be reported as adjusted rts. The raw data files are publicly available on the Open Science Framework (OSF) at https://osf.io/qyczk/.

A three-way repeated-measures analyses of variance (ANOVA) was conducted to examine the influence of three independent variables (task, congruency, distance) on adjusted rts from the Symbolic-Nonsymbolic Stroop task. Task included two levels (symbolic, nonsymbolic), congruity included three levels (congruent, neutral, incongruent), and distance included six levels (1, 2, 3, 4, 5, 6). All statistical tests were carried out using a two-tailed test with an alpha of 0.05. Effect sizes were estimated using partial η^2. Mauchly's Test of Sphericity was significant for all main effects and interactions. Therefore, the Greenhouse-Geisser correction was used for all analyses. Descriptive statistics are reported in Table 1.

Table 1
Means and standard deviations (SD) for adjusted RTs for each condition in Experiment 1.

		Nonsymbolic task		Symbolic task	
Congruity	Distance	Mean	SD	Mean	SD
Congruent	1	928.0	195.8	715.8	153.3
	2	761.6	164.9	651.6	132.7
	3	676.7	136.5	618.0	141.9
	4	620.8	128.4	590.8	136.5
	5	597.4	122.1	569.8	124.0
	6	575.9	104.1	561.6	123.5
Neutral	1	1004.2	196.9	739.3	152.0
	2	815.8	161.5	680.1	140.6
	3	707.0	145.2	655.3	143.3
	4	650.6	125.0	627.4	134.8
	5	618.7	106.7	614.1	138.5
	6	594.9	109.3	603.9	126.0
Incongruent	1	1174.3	264.3	762.5	155.1
	2	881.5	156.2	731.8	160.6
	3	777.5	140.0	718.6	151.7
	4	694.8	129.2	712.6	171.2
	5	662.1	127.8	699.4	164.8
	6	628.5	115.9	705.4	177.8

2.3. Experiment 1: results

The key result from this analysis is a significant three-way interaction between task, congruity, and distance, $F(4.5, 357.1) = 34.51$, $p < .001$, $\eta^2 = 0.30$ (Fig. 2 and Table 2). This significant three-way interaction reveals a distance-dependent asymmetry in the influence of symbols and quantities on each other when acting as the irrelevant dimension, thus aligning with the third pattern of behaviour proposed in our hypothesis section. Specifically, symbols influence the processing of quantities across distances, whereas quantities influence the processing of symbols for trials with distances >1.

For completeness, we report findings of main effects and two-way interactions. However, results of the main effects and two-way interaction should be interpreted cautiously in view of the significant three-way interaction. The three main effects were statistically significant.

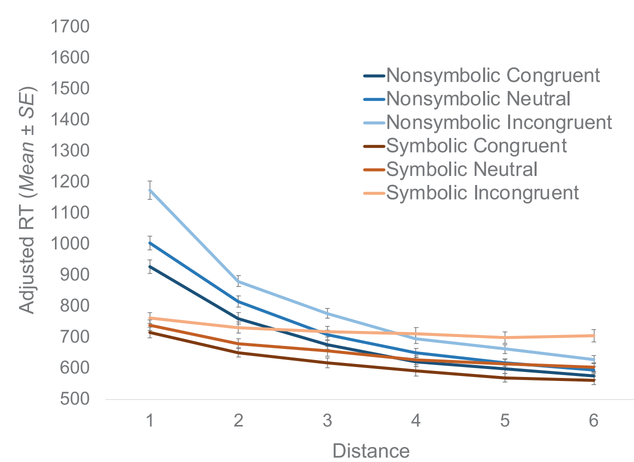

Fig. 2. This figure depicts adjusted rts for symbolic (orange) and nonsymbolic (blue) tasks at each congruity condition (congruent (darkest), neutral (medium) and incongruent (lightest) across all six distances. Error bars represent standard error of the mean. This figure highlights that at large distances, adjusted rts for congruent, neutral and incongruent conditions differ significantly for both the symbolic and nonsymbolic tasks. However, at small distances, participants have higher adjusted rts (i.e., poorer performance) on the nonsymbolic task than the symbolic task and the difference between congruent, neutral, and incongruent is larger on the nonsymbolic than the symbolic task (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Results of post-hoc pairwise comparisons with a Bonferroni for multiple comparisons with a critical *p*-value of $p < .05$ for the 3-way interaction (Task * Congruity * Distance) for Experiment 1. The mean difference is flagged with one star (*) if the corresponding p-value is < 0.05.

Task	Distance	Congruity			Mean Dif	SE	*p*-Value
Nonsymbolic	1	Neutral	vs	Congruent	76.21*	15.28	<0.001
		Incongruent	vs	Congruent	246.39*	27.24	<0.001
		Incongruent	vs	Neutral	170.18*	26.47	<0.001
	2	Neutral	vs	Congruent	54.18*	9.70	<0.001
		Incongruent	vs	Congruent	119.90*	13.55	<0.001
		Incongruent	vs	Neutral	65.71*	12.64	<0.001
	3	Neutral	vs	Congruent	30.27*	5.98	<0.001
		Incongruent	vs	Congruent	100.83*	9.91	<0.001
		Incongruent	vs	Neutral	70.56*	10.57	<0.001
	4	Neutral	vs	Congruent	29.83*	5.87	<0.001
		Incongruent	vs	Congruent	73.98*	8.46	<0.001
		Incongruent	vs	Neutral	44.15*	6.74	<0.001
	5	Neutral	vs	Congruent	21.37*	5.44	<0.001
		Incongruent	vs	Congruent	64.70*	7.57	<0.001
		Incongruent	vs	Neutral	43.33*	7.26	<0.001
	6	Neutral	vs	Congruent	18.99*	3.59	<0.001
		Incongruent	vs	Congruent	52.66*	5.08	<0.001
		Incongruent	vs	Neutral	33.67*	4.33	<0.001
Symbolic	1	Neutral	vs	Congruent	23.50	10.61	0.089
		Incongruent	vs	Congruent	46.70*	9.60	<0.001
		Incongruent	vs	Neutral	23.20	10.16	0.075
	2	Neutral	vs	Congruent	28.49*	6.27	<0.001
		Incongruent	vs	Congruent	80.21*	7.89	<0.001
		Incongruent	vs	Neutral	51.72*	9.81	<0.001
	3	Neutral	vs	Congruent	37.33*	4.86	<0.001
		Incongruent	vs	Congruent	100.61*	8.50	<0.001
		Incongruent	vs	Neutral	63.28*	7.90	<0.001
	4	Neutral	vs	Congruent	36.62*	6.30	<0.001
		Incongruent	vs	Congruent	121.81*	10.95	<0.001
		Incongruent	vs	Neutral	85.19*	9.03	<0.001
	5	Neutral	vs	Congruent	44.33*	5.31	<0.001
		Incongruent	vs	Congruent	129.60*	13.18	<0.001
		Incongruent	vs	Neutral	85.27*	12.25	<0.001
	6	Neutral	vs	Congruent	42.29*	5.61	<0.001
		Incongruent	vs	Congruent	143.79*	14.30	<0.001
		Incongruent	vs	Neutral	101.50*	12.43	<0.001

These main effects of congruity and distance align with known effects, namely that participants exhibited the strongest performance on congruent trials and weakest on incongruent trials, $F(1.34, 106.2) = 297.64$, $p < .001$, $\eta^2 = 0.79$, and that participant performance increased as distance increased $F(2.4, 189.6) = 1006.90$, $p < .001$, $\eta^2 = 0.93$. The main of effect of task indicates that participants performed better on the symbolic compared to the nonsymbolic task, $F(1, 79) = 49.97$, $p < .001$, $\eta^2 = 0.39$. A significant two-way interaction between task and distance illuminates that the enhanced performance on the symbolic compared to the nonsymbolic task was driven by trials with small distances (i.e., distances <4) $F(2.2, 171.4) = 373.66$, $p < .001$, $\eta^2 = 0.83$, negating the likelihood participants perform better on the symbolic task simply because it does not require the estimation or counting of symbols. Notably, the two-way interaction between congruity and distance was also significant, $F(4.2, 333.1) = 4.12$, $p < .01$, $\eta^2 = 0.05$, but uninformative with respect to our hypotheses, as it collapses across symbolic and nonsymbolic number processing, thereby combining effects of the relevant and irrelevant dimensions for this interaction. The two-way interaction between task and congruity was not significant, $F(1.4, 106.7) = 0.19$, *ns*, $\eta^2 = 0.002$.

The findings from this 3-way ANOVA included all single-digit numerical quantities (i.e. quantities one to nine). While this is helpful to understand these effects across the full range of single-digit numbers, small and large nonsymbolic numerical magnitudes are thought to be processed using distinct systems (Hyde, 2011), with small nonsymbolic numerical quantities being processed more similarly to symbols. Therefore, we include follow-up analyses in which we examine only trials where both the symbol and quantity in the subitizing range or in the counting range.

2.4. Follow-up analyses: subitizing vs. count range

Two additional three-way repeated-measures ANOVAs were run to examine the effect of task, congruity and distance on adjusted RT scores of 1) trials in the subitizing range (i.e., 36 trials out of the 216 trials per block) and 2) trials in the counting range (i.e., 48 trials out of the 216 trials per block). Descriptive statistics for these analysis are reported in Table 3.

2.4.1. Subitizing range

The three-way interaction between task, congruity, and distance was significant for trials only in the subitizing range, $F(3.0, 236.0) = 15.28$, $p < .001$, $\eta^2 = 0.16$, revealing that symbols interfered with processing nonsymbolic quantities across all distances, but nonsymbolic quantities interfered with processing symbols more in large distance conditions (Fig. 3, Table 4). Results of the main effects and two-way interactions should be interpreted cautiously in view of this significant three-way interaction.

Significant main effects revealed that participants exhibited the strongest performance on congruent trials and weakest on incongruent trials, $F(1.4, 110.3) = 105.96$, $p < .001$, $\eta^2 = 0.58$, participant performance increased as distance increased, $F(1.8, 139.0) = 344.08$, $p < .001$, $\eta^2 = 0.82$ and participants performed better on the symbolic compared to the nonsymbolic task, $F(1, 78) = 6.95$, $p < .05$, $\eta^2 = 0.082$. The significant two-way interaction between task and distance revealed that distance had a stronger effect on performance on the nonsymbolic task compared to the symbolic task $F(1.8, 138.6) = 85.55$, $p < .001$, $\eta^2 = 0.52$. The two-way interactions between congruity and distance $F(3.0, 232.1) = 1.64$, *ns*, $\eta^2 = 0.021$, and task and congruity, $F(1.5, 117.3) = 0.688$, *ns*, $\eta^2 = 0.008$, were not significant.

Table 3
Means and standard deviations (SD) for adjusted RTs for each condition with trials in the subitizing range and the counting range in Experiment 1.

Congruity	Distance	Nonsymbolic task				Symbolic task			
		Subitizing range trials		Counting range trials		Subitizing range trials		Counting range trials	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Congruent	1	806.5	161.6	1094.7	303.2	724.7	148.8	712.4	197.1
	2	656.5	127.8	838.2	216.1	650.6	150.1	661.3	136.1
	3	608.3	129.5	719.6	165.8	609.1	142.0	629.2	167.9
Neutral	1	856.1	167.7	1241.8	375.3	758.0	164.7	725.3	160.0
	2	691.2	128.5	914.4	229.4	681.4	157.5	689.2	145.1
	3	640.2	143.3	766.8	194.7	646.7	160.7	666.6	146.5
Incongruent	1	991.9	230.9	1482.4	479.4	797.5	188.9	739.9	173.5
	2	726.6	142.8	998.4	212.9	756.8	193.8	732.7	173.9
	3	663.8	121.4	901.1	238.9	777.8	242.7	714.3	156.4

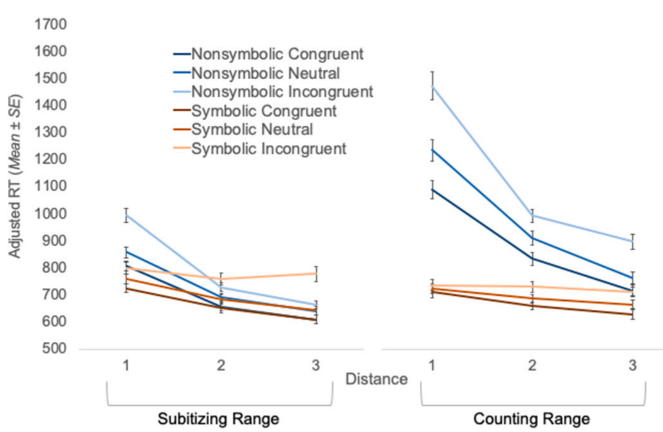

Fig. 3. This figure depicts adjusted rt. for symbolic (orange) and nonsymbolic (blue) enumeration tasks for trials in the subitizing range and the count range when the symbolic and nonsymbolic stimuli are congruent (darkest), neutral (medium) and incongruent (lightest) across all three distances. The error bars represent standard errors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.4.2. *Counting range*

The three-way interaction between task, congruity, and distance was also significant for trials only in the counting range, $F(2.8, 219.1) = 10.48$, $p < .001$, $\eta^2 = 0.12$, revealing that that at symbols interfered with nonsymbolic quantities across all distances, but nonsymbolic quantities interfered with symbols more in large distance conditions (Fig. 3, Table 4). Results of the main effects and two-way interaction should be interpreted cautiously in view of this significant three-way interaction.

Unlike trials in the subitizing, range, the two-way interaction between task and congruity was also statistically significant, $F(1.7, 133.2) = 33.98$, $p < .001$, $\eta^2 = 0.30$ suggesting that, symbols may influence processing of quantities more than quantities influence processing of symbols, even when collapsing across distances for trials in the counting range.

As with trials in the subitizing range, significant main effects revealed that participants exhibited the strongest performance on congruent trials and weakest on incongruent trials, $F(1.7, 126.7) = 108.99$, $p < .001$, $\eta^2 = 0.58$, participant performance increased as distance increased $F(1.5, 121.6) = 315.22$, $p < .001$, $\eta^2 = 0.80$ and participants performed better on the symbolic compared to the nonsymbolic task, $F(1, 79) = 263.49$, $p < .001$, $\eta^2 = 0.77$. The significant two-way interaction between task and distance showed that distance had a stronger effect on performance on the nonsymbolic task compared to the symbolic task, $F(1.4, 110.0) = 219.54$, $p < .001$, $\eta^2 = 0.74$. The two-way interaction between congruity and distance, which is uninformative with respect to our hypotheses as it collapses across task was also significant, $F(2.6, 206.6) = 4.06$, $p < .05$, $\eta^2 = 0.05$.

Together, these follow-up analyses align with our prediction that differences observed between the processing of symbols and quantities are more pronounced for magnitudes in the counting ranges, compared to those in the subitizing range.

Table 4
Results of post-hoc pairwise comparisons with a Bonferroni for multiple comparisons with a critical p-value of $p < .05$ for the 3-way interaction (Task*Congruity*-Distance) for Experiment 1 for trials in the subitizing range and the counting range. The mean difference is flagged with one star (*) if the corresponding p-value is < 0.05.

Task	Distance	Congruity			Subitizing range trials Mean Dif	SE	p-Value	Counting range trials Mean dif	SE	p-value
Nonsymbolic	1	Neutral	vs	Congruent	49.14*	18.77	<0.05	147.06*	34.20	<0.001
		Incongruent	vs	Congruent	185.79*	25.71	<0.001	387.67*	53.48	<0.001
		Incongruent	vs	Neutral	136.66*	25.49	<0.001	240.61*	56.42	<0.001
	2	Neutral	vs	Congruent	34.92*	9.17	<0.001	76.25*	20.80	<0.001
		Incongruent	vs	Congruent	70.73*	13.63	<0.001	160.23*	23.37	<0.001
		Incongruent	vs	Neutral	35.81*	13.25	<0.05	83.98*	23.16	<0.001
	3	Neutral	vs	Congruent	31.30*	10.48	<0.05	47.17*	15.58	<0.01
		Incongruent	vs	Congruent	55.25*	14.38	<0.001	181.50*	20.30	<0.001
		Incongruent	vs	Neutral	23.95	14.52	0.31	134.33*	22.38	<0.001
Symbolic	1	Neutral	vs	Congruent	33.64*	12.88	<0.05	12.93	16.36	1.00
		Incongruent	vs	Congruent	72.83*	14.51	<0.001	27.49	17.72	0.37
		Incongruent	vs	Neutral	39.19*	15.84	<0.05	14.55	16.34	1.00
	2	Neutral	vs	Congruent	30.49	12.60	0.054	27.92*	8.18	<0.001
		Incongruent	vs	Congruent	106.33*	17.09	<0.001	71.36*	11.43	<0.001
		Incongruent	vs	Neutral	75.84*	14.06	<0.001	43.45*	13.69	<0.01
	3	Neutral	vs	Congruent	36.61*	11.00	<0.001	37.45*	10.05	<0.001
		Incongruent	vs	Congruent	168.25*	25.19	<0.001	85.16*	12.16	<0.001
		Incongruent	vs	Neutral	131.67*	26.97	<0.001	47.71*	10.92	<0.001

In summary, the results from experiment 1 produce several key findings. First, as predicted, participants perform better when comparing symbols than comparing quantities when both are acting as the relevant dimension. In contrast to our prediction, the effortful processing of symbols is less affected by numerical distance compared to quantities. With respect to automatic processing, the results from experiment 1 align with the third potential pattern of behavioural results, namely that symbols automatically influence the processing of quantities more than quantities influence the processing of symbols in a distance dependent manner. Specifically, symbols influence the processing of quantities across all numerical distances, whereas quantities influence the processing of symbols, particularly for large distance trials. Finally, the follow-up analyses reveal that the difference between the processing of symbols and quantities is greater when comparing symbols to quantities in the counting range, compared to the subitizing range. Together, these findings provide evidence to suggest that the systems used to process symbols and quantities are partially overlapping, as the irrelevant dimension influences the relevant dimension in both tasks. However, results indicate that the influence of the irrelevant dimension is asymmetrical between numerical formats with symbols influencing quantities more than the reverse.

2.5. Experiment 2

2.5.1. Experiment 2: introduction

The follow-up analyses in experiment 1 examining the processing of symbols and quantities in the subitizing and the counting range revealed that symbols and quantities influence each other regardless of whether the stimuli are in the counting range or subitizing range, but the asymmetry between symbols and quantities is more pronounced for stimuli in the counting range. These findings support our hypothesis that quantities in the subitizing range would act more like symbols due to the fact that they can be processed exactly using a parallel individuation system. Critically, the stimuli in experiment 1 included all single-digit numerical magnitudes (i.e., quantities one to nine), with follow-up analyses examining specific trials that included only symbols and quantities in the subitizing range or the counting range. It is possible that including subitizable quantities within this task biased participants to process quantities in a more exact way, thereby leading to greater influence between symbols and quantities even within the counting range. In other words, results from experiment 1, suggesting that symbolic and nonsymbolic numerical magnitudes influence each other during the Stroop task, could be driven by quantities in the subitizing range. In order to confirm that the Stroop effect (i.e., the finding that symbolic and nonsymbolic numerical magnitudes influence each other) is not simply due to the fact that quantities in the subitizing range are activating exact symbolic representations throughout the task it is critical to replicate this paradigm using only numbers in the counting range. Therefore, in experiment 2, an independent sample of participants completed a modified version of the Symbolic-Nonsymbolic Stroop task that included only numbers in the counting range (i.e., 5–9). We hypothesize that the differences between the automatic processing of symbols and quantities observed in experiment 1 will be stronger in experiment 2.

2.5.2. Experiment 2: method

2.5.2.1. Participants. Sixty-three healthy adult participants were recruited at the University of Western Ontario in London, Ontario. Four participants were excluded from analyses due to poor accuracy (< 70 % on at least one trial type). Therefore, all analyses for experiment 2 include 59 participants ($M_{age} = 23.86$, $SD_{age} = 3.79$; 20 males, 39 females). Participants provided written consent before participating in the study. The session took approximately one hour and participants were compensated $5 CAD per half-hour (average $10 CAD total). All procedures were approved by the University of Western Ontario Non-medical Research Ethics Board.

2.5.3. Materials

2.5.3.1. Symbolic-Nonsymbolic Stroop Task. Each participant completed both the symbolic and nonsymbolic version of the Symbolic-Nonsymbolic Stroop task with all the same parameters described in experiment 1. The trial-list for experiment 2 differed from experiment 1. Namely, the task only included both symbols and quantities in the counting range (5–9). As with experiment 1, the stimuli, code to create the stimuli, and the OpenSesame experiments, which include the trial-lists, are available at on the Open Science Framework (OSF) at https://osf.io/qyczk/. This version of the task took participants approximately 8 min to complete (4 min for each task).

Participants were randomly presented with two blocks of 36 trials repeated twice each (144 total trials) on the symbolic task and on the nonsymbolic task. Of the 36 trials, 12 stimulus pairs were congruent, 12 were incongruent, and the remaining 12 trials were neutral. Each of the 12 trials consisted of 4 trials at each of distance 1–3. Notably, half of the 36 trials, had the same numbers as the other half, but the numbers appeared on opposite sides of the screen. The stimuli in the congruent and incongruent conditions were identical for the symbolic and the nonsymbolic tasks. The stimuli for the neutral conditions differed between tasks because, in the neural condition, the irrelevant dimension was controlled to have a distance of zero. For example, for the comparison of two vs. six, in the symbolic neutral condition (illustrated in Fig. 1), a participant could be presented with two of the digit 2 vs. two of the digit 6 (as in Fig. 1) or with six of the digit 2 vs. six of the digit 6. In the nonsymbolic neutral condition, a participant could be presented with two of the digit 6 vs. six of the digit 6 (as in Fig. 1) or with two of the digit 2 vs. six of the digit 2. The version of neutral trial presented was counterbalanced across participants. Both version A and version B of the paradigm are available on the Open Science Framework (OSF) at https://osf.io/qyczk/.

2.5.4. Procedure

All included measures were obtained during a single session that took approximately one hour, where participants completed a series of basic number processing tasks including the Symbolic-Nonsymbolic Stroop tasks with numbers only on the counting range. Only the results from the counting Symbolic-Nonsymbolic Stroop task are reported here. The procedure is the same as for experiment 1 with the exception that participants were randomly presented with two blocks containing the same 36 trials for each task. The participants got one break between the two blocks.

2.6. Experiment 2: results

As reported in experiment 1, the RT and accuracy produce the same pattern of results as the adjusted rt for experiment 2. Consequently, all results will be reported as adjusted rts. As with experiment 1, the raw data files for experiment 2 are publicly available on the Open Science Framework (OSF) at https://osf.io/qyczk/.

A three-way repeated-measures analyses of variance (ANOVA) was conducted to examine the influence of three independent variables (task, congruency, distance) on adjusted rts from the Symbolic-Nonsymbolic Stroop task. Task included two levels (symbolic, nonsymbolic), and congruity included two levels (congruent, neutral, incongruent), and distance included three levels (1, 2, 3). Descriptive statistics for each condition are reported in Table 5. All statistical tests were carried out using a two-tailed test with an alpha of 0.05. Effect sizes were estimated using partial η^2. Mauchly's Test of Sphericity was significant for the main effect of distance, and the following interactions: task*distance, congruity*distance, task*congruity*distance. The

Table 5
Means and standard deviations (SD) for adjusted RT for each condition in Experiment 2.

		Nonsymbolic task		Symbolic task	
Congruity	Distance	Mean	SD	Mean	SD
Congruent	1	1324.8	336.5	666.0	144.9
	2	1000.8	243.6	619.1	136.0
	3	880.8	170.9	606.8	113.7
Neutral	1	1421.7	441.5	689.4	149.1
	2	1054.4	212.7	642.2	133.8
	3	932.2	181.3	620.3	126.0
Incongruent	1	1604.1	406.6	699.7	152.0
	2	1159.7	258.7	663.8	186.5
	3	1031.1	176.0	649.8	135.1

Greenhouse-Geisser correction was used for all analyses that violated the assumption of sphericity.

As with experiment 1, the three-way interaction between task, congruity, and distance was used to examine whether there were differences in the congruity effects between tasks and whether these differences were modulated by numerical distance. Unlike the results from experiment 1, the three-way interaction between task, congruity, and distance, was not significant in experiment 2 $F(2.4, 136.2) = 2.36$, *ns*, $\eta^2 = 0.04$. However, in experiment 2, the two-way interaction between task and congruity was significant, $F(2, 116) = 26.09$, $p \leq 0.001$, $\eta^2 = 0.31$, revealing that symbols influence the processing of quantities more than quantities influence processing of symbols, across all distances (Fig. 4, Table 6). These findings align with the second behavioural pattern predicted in our hypothesis section, namely that symbols influence the processing of quantities more than quantities influence the processing of symbols regardless of numerical distance.

As with experiment 1, the three main effects were statistically significant, revealing that participants performance was strongest on congruent trials and weakest on incongruent trials, $F(1.8, 106.9) = 59.18$, $p < .001$, $\eta^2 = 0.5$, performance was better on trials with larger distances, $F(1.6, 94.0) = 297.73$, $p < .001$, $\eta^2 = 84$, and participants performed better on the symbolic compared to the nonsymbolic task, $F(1, 58) = 553.52$, $p < .001$, $\eta^2 = 0.91$. The significant two-way interaction between task and distance, $F(1.5, 84.2) = 213.72$, $p < .001$, $\eta^2 = 0.79$ revealed that distance had a stronger effect on performance on the nonsymbolic task compared to the symbolic task, as discovered in experiment 1. The uninformative two-way interaction between congruity and distance was not significant in experiment 2, $F(2.3, 134.6) = 1.33$, *ns*, $\eta^2 = 0.02$.

Together, these results converge with results from experiment 1 to suggest that symbolic numerical magnitudes are processed more efficiently and are less affected by numerical distance, compared to nonsymbolic numerical magnitudes.

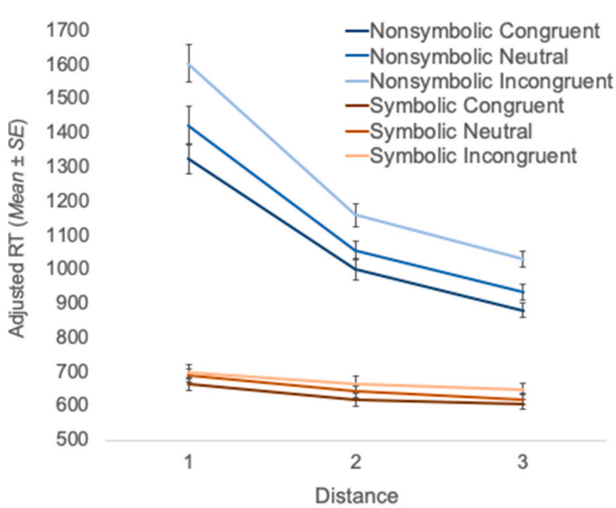

Fig. 4. This figure depicts adjusted rts for symbolic (orange) and nonsymbolic (blue) Stroop tasks when the symbolic and nonsymbolic stimuli are congruent (darkest), neutral (medium) and incongruent (lightest) across all three distances. Error bars represent standard error. This figure highlights that participants have higher adjusted rts (i.e., poorer performance) on the nonsymbolic task than the symbolic task and the difference between congruent, neutral, and incongruent is larger on the nonsymbolic than the symbolic task, across all numerical distances. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.6.1. Bayesian analyses

We ran Bayesian analyses using JASP (JASP Team, 2022) to quantify evidence supporting the null and alternative hypotheses for the three-way interaction between task, congruity and distance in experiment 2 (Benjamin et al., 2018; Rouder et al., 2009; Wagenmakers, 2007). We first ran a Bayesian ANOVA, with default priors (i.e., an effect size of 0 for the null hypothesis and a Cauchy distribution prior centered on the null with a width of 0.707 for the alternative hypothesis; Rouder et al., 2012), to identify whether there is stronger evidence for the alternative or null hypothesis for each model within the ANOVA (Table 7). We interpret the results using Bayes Factors (BF) as they provide an index of the strength of the evidence for the alternative hypothesis (BF_{10}).

The BF_{10} statistics revealed strong evidence against the null hypothesis for all main effects and interaction terms of the ANOVA (Table 7), thereby providing support for the alternative hypothesis, rather than the null hypothesis for all models in the ANOVA.

In view of the frequentist statistic finding that the three-way interaction between task, congruity and distance was not significant, coupled with the finding there is stronger evidence supporting the alternative hypothesis for all models, we conducted a model comparison analysis (comparing the BF_{10} statistics from model 18 and model 19 from Table 7) to examine whether the addition of the three-way interaction improved the model. Quantitative comparison of the BF_{10} statistics for these models revealed that the probability of the model that does not contain the three-way interaction (Model 18) is 7.85 times more likely than the model that does contain the three-way interaction (Model 19), given the data. This suggests that the non-significant three-way interaction between task, congruity, and distance, in experiment 2 (using frequentist statistics) reflects a true null result. Therefore, we conclude that, for magnitudes in the counting range, symbols influence the processing of quantities more than quantities influence the processing of symbols, regardless of the numerical distance of the quantities being compared.

3. Discussion

A fundamental question in the field of numerical cognition concerns whether symbolic numbers are processed in the same way as nonsymbolic numerical magnitudes. To address this question, we developed and used a Symbolic-Nonsymbolic Stroop paradigm to assess the processing of symbolic and nonsymbolic numbers acting as the relevant and irrelevant dimension. By examining whether nonsymbolic and symbolic representations influence one another we can probe how strongly they are linked. If they are strongly linked, then processing one should activate the other. If, however, they are disconnected then they should not influence each other, or the influence should be asymmetrical. In the Symbolic-Nonsymbolic Stroop paradigm we used to probe these possibilities, participants were asked to compare adjacent arrays of symbols (e.g., 4444 vs 333) and instructed to indicate the side containing *either* the greater quantity of symbols (nonsymbolic task) or the side containing the symbol with the greater numerical magnitude (symbolic task). More specifically, this paradigm evaluates both processing of the relevant dimension (i.e., the dimension the participant is instructed to attend to) as well as the degree to which the irrelevant stimulus condition influences judgments being made on the relevant condition. For

Table 6
Results of Post-hoc Pairwise Comparisons with a Bonferroni for Multiple Comparisons with a critical p-value of $p < .05$ for the 2-way Interaction between Task and Congruity for Experiment 2. The mean difference is flagged with one star (*) if the corresponding p-value is < 0.05.

Task	Congruity			Mean Dif	SE	p-Value
Nonsymbolic	Neutral	vs	Congruent	67.267*	19.35	<0.01
	Incongruent	vs	Congruent	196.158*	23.35	<0.001
	Incongruent	vs	Neutral	128.891*	21.40	<0.001
Symbolic	Neutral	vs	Congruent	20.012*	4.06	<0.001
	Incongruent	vs	Congruent	40.455*	5.95	<0.001
	Incongruent	vs	Neutral	20.442*	5.38	<0.01

Table 7
Models of the Bayesian ANOVA conducted for Experiment 2 with Bayes Factors that assess the strength of the evidence for the alternative hypothesis (BF_{10}).

	ANOVA model	BF_{10}
1	Null model (incl. subject)	1
2	Task	1.487e + 170
3	Congruity	258.499
4	Task + Congruity	8.120e + 177
5	Task + Congruity + Task ✻ Congruity	3.793e + 180
6	Distance	6.302e +25
7	Task + Distance	7.207e + 234
8	Congruity + Distance	6.418e +28
9	Task + Congruity + Distance	1.646e + 246
10	Task + Congruity + Task ✻ Congruity + Distance	3.943e + 250
11	Task + Distance + Task ✻ Distance	7.944e + 287
12	Task + Congruity + Distance + Task ✻ Distance	2.163e + 303
13	Task + Congruity + Task ✻ Congruity + Distance + Task ✻ Distance	4.984e + 309
14	Congruity + Distance + Congruity ✻ Distance	2.874e +26
15	Task + Congruity + Distance + Congruity ✻ Distance	1.916e + 244
16	Task + Congruity + Task ✻ Congruity + Distance + Congruity ✻ Distance	4.678e + 248
17	Task + Congruity + Distance + Task ✻ Distance + Congruity ✻ Distance	4.432e + 301
18	Task + Congruity + Task ✻ Congruity + Distance + Task ✻ Distance + Congruity ✻ Distance	9.590e + 307
19	Task + Congruity + Task ✻ Congruity + Distance + Task ✻ Distance + Congruity ✻ Distance + Task ✻ Congruity ✻ Distance	1.221e + 307

example, when comparing which side contains the numerically larger symbol (i.e., the relevant dimension), does the actual number of symbols present (i.e., the irrelevant dimension) influence performance? Using this approach, we found that participants had a faster adjusted RT when comparing symbolic numerical magnitudes than when comparing nonsymbolic numerical magnitudes, which suggests that symbols are processed more automatically as both the relevant and the irrelevant dimensions.

Indeed, across conditions, participants performed better (i.e., responded faster and more accurately) on the symbolic task compared to the nonsymbolic task. This suggests that as the relevant dimension, symbols are processed more efficiently. Additional asymmetries were observed through much stronger distance effects during nonsymbolic judgments compared to symbolic judgments, especially when comparisons were made in the counting range. Critically, unlike other paradigms, this task has the capacity to examine automaticity of processing symbolic and nonsymbolic numerical magnitudes when these number formats act as the irrelevant dimensions. By including a neutral condition in our task, we were able to measure the extent to which the irrelevant dimension either helped (facilitated) or hindered (interfered) task performance on the relevant dimension. Our findings revealed an asymmetry in the interference and facilitation patterns of symbolic compared to nonsymbolic numerical judgments. Symbols, as compared to nonsymbolic numerical magnitudes, led to both greater facilitation and interference effects. Notably, when including trials in both the subitizing and counting range, as was the case in experiment 1, this asymmetry in the congruity effects between the symbolic and nonsymbolic task is stronger for trials with small distances. A comparison of trials in the subitizing vs. counting ranges separately supported our prediction that quantities in the subitizing range are processed more similarly to symbols than quantities in the counting range. Taken together, our findings demonstrate that symbolic numerical magnitudes are processed more efficiently than nonsymbolic numerical magnitudes as both the relevant and irrelevant dimensions. In what follows, we discuss how this finding indicates asymmetric processing of symbolic and nonsymbolic numerical magnitudes and suggest differences in the ways in which each format is processed and potentially represented.

3.1. *Congruity effects*

Regardless of condition (i.e., making symbolic or nonsymbolic comparisons), participants were faster and more accurate at making comparisons when the two stimulus dimensions were congruent compared to when they were incongruent with each other. Furthermore, in the neutral condition, participants' performance was in between that obtained from the other two conditions, suggesting that congruent conditions facilitate performance and incongruent conditions interfere with performance. These findings are noteworthy in that they show the powerful effect of the irrelevant stimulus on one's ability to make basic numerical judgments. One interpretation of these findings is that symbolic and nonsymbolic numerical magnitudes are processed in parallel and potentially under the same regulatory system (e.g., see Henik & Tzelgov, 1982). Applying this line of reasoning to the current study, if symbolic and nonsymbolic numerical magnitudes bore no relation to one another and were processed by independent systems entirely, one would not expect to find evidence of facilitation or interference effects. In other words, if symbolic and nonsymbolic numbers were processed using two entirely distinct systems there would not be a Stroop-effect. Therefore, our findings provide some evidence of parallel or simultaneous processing of symbolic and nonsymbolic magnitudes. However, these findings should be interpreted with caution in light of the many significant interactions discussed below. Nonetheless, these findings align with a large body of theory and empirical findings demonstrating a close relation between number symbols and the nonsymbolic numerical magnitudes they represent (e.g., Cantlon et al., 2009; Dehaene, 2007; Dehaene et al., 1998; Nieder & Dehaene, 2009; Piazza et al., 2007).

However, our findings also challenge this line of research and instead suggest that there are key differences in the ways symbolic and nonsymbolic numerical magnitudes are processed. Indeed, our results revealed that in comparison to nonsymbolic numerical magnitudes, number symbols (i) were processed more efficiently (i.e., faster and more accurately) as the relevant dimension, (ii) had a greater influence on task performance as the irrelevant dimension, and (ii) were less influenced by the numerical distance between magnitudes as the relevant and irrelevant dimension. Notably, distance only moderated the relationship between task and congruity when including all numbers from 1 to 9, but not when only examining numbers in the counting range. We now address each one of these points in turn and discuss the findings in terms of evidence of asymmetrical processing of symbolic and nonsymbolic numerical magnitudes.

3.2. Effects of the relevant dimension

Overall, participants performed better (i.e., were more efficient) comparing symbols than quantities, as predicted. Although other researchers have reported similar findings (e.g., see Buckley & Gillman, 1974), this is the first study to do so within the context of a Symbolic-Nonsymbolic Stroop paradigm, where the task-irrelevant influence of one dimension on the other dimension (e.g., symbolic on nonsymbolic) can be measured. In fact, our results run counter to findings from the standard Numerical Stroop paradigm produces a size-congruity effect. Recall that the standard paradigm has participants compare Hindu-Arabic digits based on either the physical size of the numerals (e.g., 3 vs. 5) or the numerical value. Results from this paradigm show that participants are faster at judging physical size and are less influenced by the symbolic value of the digits than the size. The most straightforward explanation for the discrepancy in findings is that in our task the nonsymbolic condition involves serial processing of discrete units (i.e., the total number of number symbols present). Conversely, the symbolic task can be approached by attending to a single unit (i.e., any given symbol present). Thus, both the physical size and symbolic task within the traditional Numerical Stroop paradigm is more akin to our symbolic task in which comparisons can be made by attending to a single stimulus. This discrepancy between the current study and previous Numerical Stroop paradigms that produce a size congruity effect provides evidence in support of the notion that the quantity discrimination task in the Symbolic-Nonsymbolic Stroop paradigm is capturing more than the processing of continuous magnitudes (e.g., area), an inherent confound of nonsymbolic number comparison tasks (For review see, Leibovich & Henik, 2013). If participants were solving the nonsymbolic task in the current study using purely a physical size strategy, one would predict that the results would closely mirror the Size Congruity Effect, namely that like participants are better at processing size than symbols. As such, participants would be more efficient at processing nonsymbolic numerical magnitudes compared to symbols. However, we presented the quantities within an array in try to ensure that participants could not use a physical size strategy, thereby forcing them to rely on quantity. In doing this, we find the reverse pattern of results from the Size Congruity Effect, namely that as the relevant dimension, symbols are processed more efficiently than nonsymbolic numerical magnitudes. Although the finding that humans are better at effortfully processing symbols compared to quantities is neither new (e.g., Buckley & Gillman, 1974; Lyons & Ansari, 2009), nor surprising, it highlights the general efficiency and cultural utility of symbols and number symbols more specifically (see Núñez, 2017).

3.3. Effects of the irrelevant dimension

As previously discussed, results revealed a congruity effect (i.e., greater efficiency in processing congruent compared to incongruent trials) in both the symbolic and nonsymbolic comparison conditions. Indeed, participant's performance on comparisons in both the symbolic task and the nonsymbolic task was most efficient when the two stimulus dimensions were congruent, followed by when they were neutral, and participants performance was worst on incongruent conditions. Therefore, both symbols and the nonsymbolic numerical magnitudes that they represent are processed as the irrelevant dimension and influence number processing of the relevant dimension. As discussed above, the findings that the irrelevant stimulus influences the relevant stimulus provide support for the idea that there is some parallel processing of symbols and quantities, as there would be no effect of the irrelevant stimulus on the relevant stimulus (i.e., no Symbolic-Nonsymbolic Stroop effect) if symbolic and nonsymbolic numerical magnitudes were processed in serial or using two entirely distinct systems. Therefore, the presence of a Stroop effect in the current study supports the idea that symbolic and nonsymbolic numerical magnitudes are processed simultaneously at some stage of processing.

Critically, however, our results also revealed important differences in how symbols influenced and interfered with judgments of nonsymbolic numerical magnitudes compared to the way that nonsymbolic numerical magnitudes influenced and interfered with symbolic judgments. That is, irrelevant number symbols were found to have a much larger impact on performance compared to when nonsymbolic numerical magnitudes acted as the irrelevant dimension. Although many studies have reported that symbols influence the processing of quantities (Bush et al., 1998; Francolini & Egeth, 1980; Morton, 1969; Pavese & Umiltà, 1998, 1999; Windes, 1968), relatively few have examined whether quantities interfere with symbolic processing (Flowers et al., 1979; Furman & Rubinsten, 2012; Naparstek et al., 2015; Naparstek & Henik, 2010, 2012; Pansky & Algom, 2002). The only other study to quantify both symbolic and nonsymbolic interference required participants to compare a quantity to a symbolic referent (Naparstek & Henik, 2010). This study revealed that symbols interfered with quantity processing regardless of task demands, whereas the interference of quantity depended on the task. Results from the current study extend finding this to reveal that this asymmetry in the processing of symbols and quantities as the irrelevant dimension is present even in a task that does not require the participant to compare the nonsymbolic numerical magnitude to a symbolic referent. Therefore, findings from the current study align with previous research to suggest that while there is some overlap in the way that symbolic and nonsymbolic numerical magnitudes are processed, symbols seem to more consistently influence the processing of nonsymbolic numerical magnitudes.

3.4. Influence of numerical distance

As discussed above, participants perform better on comparative judgments of symbolic compared to nonsymbolic numerical magnitudes across all distances. However, results from the current study also highlight that in addition to symbols being processed more efficiently than nonsymbolic numerical magnitudes, the effortful processing of symbols is less influenced by numerical distance. This finding from the current study, namely, that nonsymbolic processing is more influenced by distance than symbolic number processing has been previously reported in the literature in both adults and children (e.g., Buckley & Gillman, 1974; Butterworth, 2005; Furman & Rubinsten, 2012; Holloway et al., 2010; Holloway & Ansari, 2008, 2009; Holloway & Ansari, 2010; Moyer & Landauer, 1967; Rubinsten et al., 2002).

Several models for this discrepancy of the effect of numerical distance on the processing of symbols and quantities have been proposed. A seminal computational model was put forward that suggests that symbolic and nonsymbolic numerical magnitudes are transformed into cardinal representation (i.e., place-coded) by different pathways (Verguts & Fias, 2004). Specifically, nonsymbolic numbers are transformed into cardinal representations through a noisy process referred to as 'summation coding.' The noise in this process proportionally relates to the number of inputs being "summed." In contrast, the summation step of this model is not required for processing symbolic numbers, leading to sharper representations for symbolic numbers and consequently a reduced reaction time and higher accuracy (Verguts & Fias, 2004). This computational model, which has been supported with empirical neuroimaging data (Holloway et al., 2010; Lyons et al., 2014; Piazza et al., 2007; Roggeman et al., 2007), provides a compelling explanation for the discrepancies found in the current data between the way that distance modulates the processing of symbolic compared to nonsymbolic numerical magnitudes as the relevant dimension. Notably, there are other explanations for the differences between the processing of symbolic and nonsymbolic numerical magnitudes. Converging recent behavioural data has indicated that the similar behavioural effects observed in different formats of numerical magnitudes (i.e., symbolic and nonsymbolic) do not correlate with each other (Holloway & Ansari, 2009; Krajcsi et al., 2016; Lyons et al., 2015), and may, in fact, be supported by two similar, but distinct representational systems. Indeed, while nonsymbolic numerical magnitudes are likely processed using an evolutionarily ancient analogue magnitude system, where the ratio of the stimuli's intensity affects performance (Weber's law) (Moyer & Landauer, 1967) the processing of symbols is likely supported by a different more exact system. A proposed system that may support symbolic numerical magnitudes is the discrete semantic system (DSS) (Krajcsi et al., 2016). In a DSS, symbolic numerical magnitudes are stored within a large semantic network, with each symbolic numerical magnitude acting as a node within that network. A DSS would produce a 'distance effect' because the strength of the associations between symbolic numerical magnitudes (i.e., nodes) would correlate with the strength of the semantic relations between the numbers (Krajcsi, 2017; Krajcsi et al., 2016). Evidence that symbolic numerical magnitudes may be supported by a DSS rather than an approximate magnitude system has accumulated both behaviourally (Krajcsi et al., 2016, 2018) and at the neural level of analysis (Lyons & Beilock, 2018). Data from the current study cannot discern between various theories predicting what representations might underpin symbolic compared to nonsymbolic numerical magnitudes. However, these data do provide support for the growing body of evidence indicating that there are striking differences in the way that symbols and nonsymbolic numerical magnitudes are processed.

The results from the current study provide some evidence to suggest that there may be an asymmetry between symbolic and nonsymbolic numerical magnitudes in the way that distance modulates the influence of the irrelevant dimension. In experiment 1, distance affects the influence of irrelevant quantities during the symbolic comparison more than distance modulates the influence of irrelevant symbols during the nonsymbolic comparison task. More specifically, numerical distance most strongly affects the processing of symbolic numerical magnitudes when the magnitude of the symbol and the quantity are congruent, suggesting that the influence of the congruent quantity may, in fact, be responsible for the distance effect. Interestingly, previous research that has examined whether distance influences the performance on nonsymbolic naming tasks and tasks that require participant to refer to a symbolic referent revealed that when the symbols were numerically close to the quantity that the participants had to verbally name, there was a larger interference effect (Furman & Rubinsten, 2012; Naparstek & Henik, 2010, 2012; Pavese & Umiltà, 1998, 1999). Critically, in experiment 2 of the current study, where only numbers in the counting range were included, distance does not significantly modulate the automatic processing of symbols or nonsymbolic numerical magnitudes. The use of Bayesian statistics allows us to conclude that there is no evidence in support of the three-way interaction. More specifically, the Bayesian analyses that were conducted allowed us to quantify and compare the probabilities of different hypotheses (i.e., null or alternative), given the data. The BF_{10} of the three-way interaction between task, congruity and distance was 7.85, which is considered to be moderate evidence for the alternative hypothesis. However, findings from the Bayesian model testing revealed that for experiment 2, the probability of the null hypothesis (i.e., the model *without* the inclusion of the three-way interaction) is stronger than the probability of the alternative hypothesis (i.e., the model *with* the inclusion of the three-way interaction), given the data. These model comparison findings suggest that statistically insignificant three-way interaction between task, congruity, and distance was not significant due to lack of power, but instead reflects a true null finding. Therefore, we conclude that for numbers that are only in the counting range, symbols influenced the processing of quantities more than quantities influenced the processing of symbols across all distances. In view of this, the current data suggest that numerical distance does not influence the processing of the magnitude of the irrelevant dimension when including only numbers in the counting range. This finding provides further evidence that nonsymbolic numerical magnitudes do not influence the processing of numerical symbols. Indeed, even quantities with the strongest salience (i.e., quantities with large distances), in the counting range, do not influence effortful symbolic number processing. However, this should be interpreted with caution due to the fact that there is an inherent confound of including numbers only in the counting range, namely it narrows the range of possible numerical distances from six to three. Additionally, as this was the first time this task has been implemented, it was not possible to include all combinations of possible distances for both the relevant and irrelevant stimuli (e.g., see data of this nature from the size congruity task: Leibovich et al., 2013) However, even with these caveats, this research provides compelling evidence that symbols and quantities are processed using similar, but ultimately distinct processing systems.

3.5. *Subitizing vs. counting range*

Our final prediction was that differences observed between the processing of symbols and quantities would be more pronounced for magnitudes in the counting range compared to those in the subitizing range, because subitizable quantities can be processed exactly. Results from the current study revealed symbols influenced the processing of quantities more than quantities influenced the processing of symbols trials in the subitizing range and counting range. However, the discrepancy in mean differences between influence of symbols on quantities, compared to quantities on symbols, was nearly five times larger in the counting range compared to the subitizing range in experiment 2. This suggests that although the processing quantities in subitizing range is distinguishable from how we process symbols, we process symbols and quantities in a more similar way for magnitudes subitizing range compared to the counting range. These findings provide compelling evidence in support of the idea that nonsymbolic quantities are automatically processed using the PI system for small subitizable sets an analogue magnitude for larger sets (Hyde, 2011).

3.6. *Interpretations and future directions*

Taken together, our results provide strong evidence for asymmetrical processing of symbolic and nonsymbolic numerical magnitudes. Specifically, when we process nonsymbolic numerical magnitudes, symbolic representations have an influence. However, when we process symbolic magnitudes, nonsymbolic representations of numerical magnitudes have a negligible effect. A predominant view in the field of numerical cognition has been that symbolic number representations are formed by simply attaching symbols to analogue nonsymbolic quantity representations (e.g., Cantlon, 2012; Dehaene, 2007, 2008; Feigenson, 2007; Lyons & Ansari, 2009; Nieder & Dehaene, 2009; Piazza et al., 2007). In recent years, it has been suggested that number symbols constitute a separate system in which processing symbols can be done independently from accessing nonsymbolic representations of the quantities the symbols represent. Instead, symbols may be understood based on their associations with other symbols (For a comprehensive review see, Núñez, 2017). This view has been supported by recent behavioural and neuroimaging research that reports that processing of symbolic numbers is at least somewhat distinct from processing quantities (Bulthé et al., 2014; Cohen Kadosh, 2008; Lyons et al., 2012, 2014; Lyons & Beilock, 2018). The finding from the current study, that symbols are processed more automatically than the quantities that they represent provides evidence that supports the notion that symbols may not simply be labels for pre-existing representations of quantities. Indeed, the findings from the current study suggest that the human mind does not need to access a representation of a nonsymbolic numerical magnitude to automatically process the semantic meaning of a number symbol, even when the symbol is irrelevant to the task. Instead, data from the current study provides evidence in support of the theory that symbols may themselves be supported by culturally acquired automatic semantic representations (Lyons & Beilock, 2018; Núñez, 2017). This convergent body of evidence that suggests that adults process symbols more automatically than nonsymbolic numerical magnitudes, introduces an important developmental question. Namely, it is of great importance to learn how symbols are learned, and when in development symbols become automatic. A longstanding question in the field of numerical cognition has been, 'how do symbols acquire meaning?' However, based on this data, an equally important follow-up question is 'when does the symbolic system become independent?' The use of the Symbolic-Nonsymbolic Stroop task in a developmental sample is ideally suited to answer this question, as it can be used to illuminate how the representational precision (i.e., distance effects) of symbols and quantities at different levels of processing (i.e., effortful and automatic) change, and likely diverge, across developmental time.

4. Conclusions

In order to further our understanding of the association between evolutionary ancient, nonsymbolic representations of numerical magnitudes and culturally constructed symbolic representations, the current study examined whether the processing of symbols and quantities as the relevant and irrelevant dimensions are the same or distinct using a Symbolic-Nonsymbolic Stroop paradigm. Results revealed that regardless of the task, participants were more efficient at making comparisons when the two stimulus dimensions were congruent compared to incongruent. This could be taken to suggest that at some stage of processing symbolic and nonsymbolic numbers are processed in parallel; however, due to the fact that the interaction terms are significant, this finding should be interpreted with caution. Interaction effects from the current study revealed asymmetries the processing of symbolic and nonsymbolic numerical magnitudes when each magnitude type is the relevant and irrelevant dimension. The key finding from the current study is that symbols influenced nonsymbolic numerical magnitude processing more than nonsymbolic numerical magnitudes influenced the processing of numerical symbols. This highlights that there is an asymmetry in the way that the human mind processes symbols and quantities. Further support for this idea that symbols and quantities are processed distinctly is that the effortful processing of symbols was more efficient and less affected by numerical distance than quantities. Additionally, numerical distance modulated nonsymbolic interference more than it modulated symbolic interference when including all numbers (1–9). However, numerical distance did not influence the automatic interference of symbols or quantities when all numbers in the experiment were in the counting range. These data provide support for the idea that there is an asymmetry in the way that humans process symbolic compared to nonsymbolic numerical magnitudes, even when the magnitude is irrelevant to the task. Together, these findings, that symbols are processed more automatically than numerically equivalent nonsymbolic numerical magnitudes, suggest that processing symbols do not require accessing a representation of quantity. These findings contribute to efforts to forge a deeper understanding of how the mind forms a symbolic number processing system.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgements

This work was supported by funding from the Canadian Institutes of Health Research (CIHR), The National Sciences and Engineering Research Council of Canada (NSERC), Canada Research Chairs program (CRC) and an Advanced Research Fellowship from the Klaus J. Jacobs Foundation to Daniel Ansari as well as an NSERC Doctoral Scholarship to H. Moriah Sokolowski and a SSHRC Doctoral Scholarship to Zachary Hawes. The researchers also acknowledge the Canada First Research Excellence Fund to BrainsCAN award.

References

Ansari, D. (2008). Effects of development and enculturation on number representation in the brain. *Nature Reviews. Neuroscience, 9*(4), 278–291. https://doi.org/10.1038/nrn2334

Benjamin, D. J., Berger, J. O., Johannesson, M., Nosek, B. A., Wagenmakers, E. J., Berk, R., Bollen, K. A., Brembs, B., Brown, L., Camerer, C., Cesarini, D., Chambers, C. D., Clyde, M., Cook, T. D., De Boeck, P., Dienes, Z., Dreber, A., Easwaran, K., Efferson, C.Johnson, V. E., … (2018). Redefine statistical significance. *Nature Human Behaviour, 2*(1), 6–10. https://doi.org/10.1038/s41562-017-0189-z

Brannon, E. M. (2006). The representation of numerical magnitude. *Current Opinion in Neurobiology, 16*(2), 222–229. https://doi.org/10.1016/j.conb.2006.03.002

Bruyer, R., & Brysbaert, M. (2011). Combining speed and accuracy in cognitive psychology: Is the inverse efficiency score (IES) a better dependent variable than the mean reaction time (RT) and the percentage of errors (PE)? *Psychologica Belgica, 51*(1), 5. https://doi.org/10.5334/pb-51-1-5

Buckley, P. B., & Gillman, C. B. (1974). Comparisons of digits and dot patterns. *Journal of Experimental Psychology, 103*(6), 1131–1136.

Bulthé, J., De Smedt, B., & Op de Beeck, H. P. (2014). Format-dependent representations of symbolic and non-symbolic numbers in the human cortex as revealed by multi-voxel pattern analyses. *NeuroImage, 87*, 311–322. https://doi.org/10.1016/j.neuroimage.2013.10.049

Bush, G., Whalen, P. J., Rosen, B. R., Jenike, M. A., McInerney, S. C., & Rauch, S. L. (1998). The counting stroop: An interference task specialized for functional neuroimaging–validation study with functional MRI. *Human Brain Mapping, 6*(4), 270–282. https://doi.org/10.1002/(SICI)1097-0193(1998)6:4<270::AID-HBM6>3.0.CO;2-0 [pii] [pii].

Butterworth, B. (2005). The development of arithmetical abilities. *Journal of Child Psychology and Psychiatry, 46*(1), 3–18. https://doi.org/10.1111/j.1469-7610.2005.00374.x

Cantlon, J. F. (2012). Math, monkeys, and the developing brain. *Proceedings of the National Academy of Sciences of the United States of America, 109*(Supplement_1), 10725–10732. https://doi.org/10.1073/pnas.1201893109. Suppl.

Cantlon, J. F., Libertus, M. E., Pinel, P., Dehaene, S., Brannon, E. M., & Pelphrey, K. A. (2009). The neural development of an abstract concept of number. *Journal of Cognitive Neuroscience, 21*(11), 2217–2229. https://doi.org/10.1162/jocn.2008.21159

Cohen Kadosh, R. (2008). Numerical representation: Abstract or nonabstract? *Quarterly Journal of Experimental Psychology, 61*(8), 1160–1168. https://doi.org/10.1080/17470210801994989 (2006).

Cohen Kadosh, R., Bahrami, B., Walsh, V., Butterworth, B., Popescu, T., & Price, C. J. (2011). Specialization in the human brain: The case of numbers. *Frontiers in Human Neuroscience, 5*(July), 62. https://doi.org/10.3389/fnhum.2011.00062

Cohen Kadosh, R., Cohen Kadosh, K., Kaas, A., Henik, A., & Goebel, R. (2007). Notation-dependent and -independent representations of numbers in the parietal lobes. *Neuron, 53*(2), 307–314. https://doi.org/10.1016/j.neuron.2006.12.025

Cohen Kadosh, R., & Walsh, V. (2009). Numerical representation in the parietal lobes : Abstract or not abstract ? *Behavioral and Brain Sciences, 32*, 313–373.

De Smedt, B., Noël, M.-P., Gilmore, C., & Ansari, D. (2013). How do symbolic and non-symbolic numerical magnitude processing skills relate to individual differences in children's mathematical skills? A review of evidence from brain and behavior. *Trends in Neuroscience and Education, 2*, 48–55. https://doi.org/10.1016/j.tine.2013.06.001

Dehaene, S., Dehaene-Lambertz, G., & Cohen, L. (1998). Abstract representations of numbers in the animal and human brain. *Trends in Neurosciences, 21*(8), 355–361. http://www.ncbi.nlm.nih.gov/pubmed/9720604.

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology, 20*(3), 487–506. https://doi.org/10.1080/02643290244000239

Dehaene, S. (2007). *The number sense: How the mind creates mathematics. Book.* Oxford University Press. http://www.amazon.com/The-Number-Sense-Creates-Mathematics/dp/0199753873/ref=pd_sim_sbs_b_1?ie=UTF8&refRID=0D2G1RM5K1933GCCSV5G.

Dehaene, S. (2008). Symbols and quantities in parietal cortex: Elements of a mathematical theory of number representation and manipulation. In P. Haggard, & Y. Rosetti (Eds.), *Vol. XXII. Sensorimotor foundations of higher cognition: Attention and performance* (pp. 527–574). Oxford University Press. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.147.5912&rep=rep1&type=pdf.

Feigenson, L. (2007). The equality of quantity. *Trends in Cognitive Sciences, 11*(5), 185–187. https://doi.org/10.1016/j.tics.2007.01.006

Fias, W., Lammertyn, J., Reynvoet, B., Dupont, P., & Orban, G. A. (2003). Parietal representation of symbolic and nonsymbolic magnitude. *Journal of Cognitive Neuroscience, 15*(1), 47–56. https://doi.org/10.1162/089892903321107819

Flowers, J. H., Warner, J. L., & Polanski, M. L. (1979). Response and encoding factors in "ignoring" irrelevant information. *Memory and Cognition, 7*(2), 86–94.

Francolini, C. M., & Egeth, H. E. (1980). On the nonautomaticity of "automatic" activation: Evidence of selective seeing. *Perception & Psychophysics, 27*(4), 331–342. https://doi.org/10.3758/BF03206122

Fulbright, R. K., Manson, S. C., Skudlarski, P., Lacadie, 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 Radiology, 24*(2), 193–200. http://www.ncbi.nlm.nih.gov/pubmed/12591633.
Furman, T., & Rubinsten, O. (2012). Symbolic and non symbolic numerical representation in adults with and without developmental dyscalculia. *Behavioral and Brain Functions, 8*, 1–15. https://doi.org/10.1186/1744-9081-8-55
Halberda, J., Mazzocco, M. M. M., & Feigenson, L. (2008). Individual differences in non-verbal number acuity correlate with maths achievement. *Nature, 455*(7213), 665–668. https://doi.org/10.1038/nature07246
Henik, A., Gliksman, Y., Kallai, A., & Leibovich, T. (2017). Size perception and the Foundation of Numerical Processing. *Current Directions in Psychological Science, 26*(1), 45–51. https://doi.org/10.1177/0963721416671323
Henik, A., Leibovich, T., Naparstek, S., Diesendruck, L., & Rubinsten, O. (2011). Quantities, amounts, and the numerical core system. *Frontiers in Human Neuroscience, 5*(January), 186. https://doi.org/10.3389/fnhum.2011.00186
Henik, A., & Tzelgov, J. (1982). Is three greater than five: The relation between physical and semantic size in comparison tasks. *Memory & Cognition, 10*(4), 389–395.
Holloway, I. D., & Ansari, D. (2008). Domain-specific and domain-general changes in children's development of number comparison. *Developmental Science, 11*(5), 644–649. https://doi.org/10.1111/j.1467-7687.2008.00712.x
Holloway, I. D., & Ansari, D. (2009). Mapping numerical magnitudes onto symbols: The numerical distance effect and individual differences in children's mathematics achievement. *Journal of Experimental Child Psychology, 103*(1), 17–29. https://doi.org/10.1016/j.jecp.2008.04.001
Holloway, I. D., & Ansari, D. (2010). Developmental specialization in the right intraparietal sulcus for the abstract representation of numerical magnitude.Pdf - Google drive. *Journal of Cognitive Neuroscience, 22*(11), 2627–2637. https://drive.google.com/file/d/0B5JyY7bDUjP_TVRVLURwc2dSVjA/edit.
Holloway, I. D., Price, G. R., & Ansari, D. (2010). Common and segregated neural pathways for the processing of symbolic and nonsymbolic numerical magnitude: An fMRI study. *NeuroImage, 49*(1), 1006–1017. https://doi.org/10.1016/j.neuroimage.2009.07.071
Hyde, D. C. (2011). Two systems of non-symbolic numerical cognition. *Frontiers in Human Neuroscience, 5*, 150. https://doi.org/10.3389/fnhum.2011.00150
JASP Team. (2022). *JASP (Version 0.16.3)* [Computer software].
Kaufman, E. L., Lord, M. W., Reese, T. W., & Volkmann, J. (1949). The discrimination of visual number. *The American Journal of Psychology, 62*(4), 498. https://doi.org/10.2307/1418556
Krajcsi, A. (2017). Numerical distance and size effects dissociate in indo-arabic number comparison. *Psychonomic Bulletin & Review, 24*(3), 927–934. https://doi.org/10.3758/s13423-016-1175-6
Krajcsi, A., Lengyel, G., & Kojouharova, P. (2016). The source of the symbolic numerical distance and size effects. *Frontiers in Psychology, 7*(1–16), 1795. https://doi.org/10.3389/fpsyg.2016.01795. Www.Frontiersin.Org.
Krajcsi, A., Lengyel, G., & Kojouharova, P. (2018). Symbolic number comparison is not processed by the analog number system: Different symbolic and non-symbolic numerical distance and size effects. *Frontiers in Psychology, 9*(124), 1–16. https://doi.org/10.3389/fpsyg.2018.00124
Leibovich, T., Diesendruck, L., Rubinsten, O., & Henik, A. (2013). The importance of being relevant: Modulation of magnitude representations. *Frontiers in Psychology, 4*, 369. https://doi.org/10.3389/fpsyg.2013.00369
Leibovich, T., & Henik, A. (2013). Magnitude processing in non-symbolic stimuli. *Frontiers in Psychology, 4*(June), 375. https://doi.org/10.3389/fpsyg.2013.00375
Leibovich, T., Katzin, N., Harel, M., & Henik, A. (2016). From 'sense of number' to 'sense of magnitude' – the role of continuous magnitudes in numerical cognition. *Behavioral and Brain Sciences, 40*, Article e164. https://doi.org/10.1017/S0140525X16000960
Liu, W., Zheng, P., Huang, S., & Cicchini, G. M. (2020). Subitizing, unlike estimation, does not process sets in parallel. *Scientific Reports, 10*(1), 1–8. https://doi.org/10.1038/s41598-020-72860-4
Lyons, I. M., & Ansari, D. (2009). The cerebral basis of mapping nonsymbolic numerical quantities onto abstract symbols: An fMRI training study. *Journal of Cognitive Neuroscience, 21*(9), 1720–1735. https://doi.org/10.1162/jocn.2009.21124
Lyons, I. M., Ansari, D., & Beilock, S. L. (2012). Symbolic estrangement: Evidence against a strong association between numerical symbols and the quantities they represent. *Journal of Experimental Psychology. General, 141*(4), 635–641. https://doi.org/10.1037/a0027248
Lyons, I. M., Ansari, D., & Beilock, S. L. (2014). Qualitatively different coding of symbolic and nonsymbolic numbers in the human brain. *Human Brain Mapping*. https://doi.org/10.1002/hbm.22641
Lyons, I. M., & Beilock, S. L. (2018). Characterizing the neural coding of symbolic quantities. *NeuroImage, 178*(February), 503–518. https://doi.org/10.1016/j.neuroimage.2018.05.062
Lyons, I. M., Nuerk, H.-C., & Ansari, D. (2015). Rethinking the implications of numerical ratio effects for understanding the development of representational precision and numerical processing across formats. *Journal of Experimental Psychology: General, 144*(5), 1021–1035. https://doi.org/10.1037/xge0000094
Mandler, G., & Shebo, B. J. (1982). Subitizing: An analysis of its component processes. *Journal of Experimental Psychology. General, 111*(1), 1–22. http://www.ncbi.nlm.nih.gov/pubmed/6460833.
Mathôt, S., Schreij, D., & Theeuwes, J. (2012). OpenSesame: An open-source, graphical experiment builder for the social sciences. *Behavior Research Methods, 44*(2), 314–324. https://doi.org/10.3758/s13428-011-0168-7
Morton, J. (1969). Categories of interference: Verbal mediation and conflict in card sorting. *British Journal of Psychology, 60*(3), 329–346.
Moyer, R. S., & Landauer, T. K. (1967). Time required for judgements of numerical inequality. *Nature, 215*(2), 1519–1520. http://www.nature.com/nature/journal/v215/n5109/abs/2151519a0.html.
Naparstek, S., & Henik, A. (2010). Count me In! On the automaticity of numerosity processing. *Journal of Experimental Psychology: Learning Memory and Cognition, 36*(4), 1053–1059. https://doi.org/10.1037/a0019766
Naparstek, S., & Henik, A. (2012). Laterality briefed: Laterality modulates performance in a numerosity-congruity task. *Consciousness and Cognition, 21*(1), 444–450. https://doi.org/10.1016/j.concog.2011.12.006
Naparstek, S., Safadi, Z., Lichtenstein-Vidne, L., & Henik, A. (2015). Flanking magnitudes: Dissociation between numerosity and numerical value in a selective attention task. *Journal of Experimental Psychology: Learning Memory and Cognition, 41*(4), 1262–1268. https://doi.org/10.1037/xlm0000067
Nieder, A., & Dehaene, S. (2009). Representation of number in the brain. *Annual Review of Neuroscience, 32*(1), 185–208. https://doi.org/10.1146/annurev.neuro.051508.135550
Núñez, R. E. (2017). Is there really an evolved capacity for number? *Trends in Cognitive Sciences, 21*(6), 409–424. https://doi.org/10.1016/j.tics.2017.03.005
Pansky, A., & Algom, D. (2002). Comparative judgment of numerosity and numerical magnitude: Attention preempts automaticity. *Journal of Experimental Psychology: Learning Memory and Cognition, 28*(2), 259–274. https://doi.org/10.1037/0278-7393.28.2.259
Pavese, A., & Umiltà, C. (1998). Symbolic distance between numerosity and identity modulates stroop interference. *Journal of Experimental Psychology: Human Perception and Performance, 24*(5), 1535–1545. https://doi.org/10.1037/0096-1523.24.5.1535
Pavese, A., & Umiltà, C. (1999). Further evidence on the effects of symbolic distance on stroop-like interference. *Psychological Research, 62*(1), 62–71. https://doi.org/10.1007/s004260050040
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*(2), 293–305. https://doi.org/10.1016/j.neuron.2006.11.022
Revkin, S. K., Piazza, M., Izard, V., Cohen, L., & Dehaene, S. (2008). Does subitizing reflect numerical estimation?. https://pdfs.semanticscholar.org/93eb/438188a0d9503e7256c587e8ee0437d49b5c.pdf.
Roggeman, C., Verguts, T., Fias, W., Vergutsa, T., & Fias, W. (2007). Priming reveals differential coding of symbolic and non-symbolic quantities. *Cognition, 105*(2), 380–394. https://doi.org/10.1016/j.cognition.2006.10.004
Rouder, J. N., Morey, R. D., Speckman, P. L., & Province, J. M. (2012). Default bayes factors for ANOVA designs. *Journal of Mathematical Psychology, 56*(5), 356–374. https://doi.org/10.1016/J.JMP.2012.08.001
Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G. (2009). Bayesian t tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin & Review, 16*(2), 225–237. http://pcl.missouri.edu/sites/default/files/Rouder.bf_.pdf.
Rubinsten, O., Henik, A., Berger, A., & Shahar-Shalev, S. (2002). The development of internal representations of magnitude and their association with arabic numerals. *Journal of Experimental Child Psychology, 81*(1), 74–92. https://doi.org/10.1006/jecp.2001.2645
Sasanguie, D., Van den Bussche, E., & Reynvoet, B. (2012). Predictors for mathematics achievement? Evidence from a longitudinal study. *Mind, Brain, and Education, 6*(3), 119–128. https://doi.org/10.1111/j.1751-228X.2012.01147.x
Simon, T. J., Takarae, Y., DeBoer, T., McDonald-McGinn, D. M., Zackai, E. H., & Ross, J. L. (2008). Overlapping numerical cognition impairments in children with chromosome 22q11.2 deletion or turner syndromes. *Neuropsychologia, 46*(1), 82–94. https://doi.org/10.1016/j.neuropsychologia.2007.08.016
Sokolowski, H. M., Fias, W., Mousa, A., & Ansari, D. (2017). Common and distinct brain regions in both parietal and frontal cortex support symbolic and nonsymbolic number processing in humans: A functional neuroimaging meta-analysis. *NeuroImage, 146*. https://doi.org/10.1016/j.neuroimage.2016.10.028
Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*(6), 643–662. https://doi.org/10.1037/h0054651
Trick, L. M., & Enns, J. T. (1997). Clusters precede shapes in perceptual organization. *Psychological Science, 8*(2), 124–129. https://doi.org/10.1111/j.1467-9280.1997.tb00694.x
Trick, L. M., & Pylyshyn, Z. W. (1993). What enumeration studies can show us about spatial attention: Evidence for limited capacity preattentive processing. *Journal of Experimental Psychology. Human Perception and Performance, 19*(2), 331–351. http://www.ncbi.nlm.nih.gov/pubmed/8473843.
Trick, L. M., & Pylyshyn, Z. W. (1994). Why are small and large numbers enumerated differently? A limited-capacity preattentive stage in vision. *Psychological Review, 101*(1), 80–102.
Van Opstal, F., Gevers, W., De Moor, W., & Verguts, T. (2008). Dissecting the symbolic distance effect: Comparison and priming effects in numerical and nonnumerical orders. *Psychonomic Bulletin and Review, 15*(2), 419–425. https://doi.org/10.3758/PBR.15.2.419
van Opstal, F., & Verguts, T. (2011). The origins of the numerical distance effect: The same–different task. *Journal of Cognitive Psychology, 23*(1), 112–120. https://doi.org/10.1080/20445911.2011.466796
Verguts, T., & Fias, W. (2004). Representation of number in animals and humans: A neural model. *Journal of Cognitive Neuroscience, 16*(9), 1493–1504. https://doi.org/10.1162/0898929042568497
Wagenmakers, E.-J. (2007). A practical solution to the pervasive problems ofp values. *Psychonomic Bulletin & Review, 14*(5), 779–804. https://doi.org/10.3758/BF03194105
Windes, J. D. (1968). Reaction time for numerical coding and naming of numerals. *Journal of Experimental Psychology, 78*(2 PART 1), 318–322. https://doi.org/10.1037/h0026289