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Numerical distance and size effects dissociate in Indo-Arabic number comparison

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Numerical distance and size effects (easier number comparison with large distance or small size) are mostly supposed to reflect a single effect, the ratio effect, which is the consequence of the analogue number system (ANS) activation, working according to Weber's law. In an alternative model, symbolic numbers can be processed by a discrete semantic system (DSS), in which the distance and the size effects could originate in two independent factors: the distance effect depends on the semantic distance of the units, and the size effect depends on the frequency of the symbols. While in the classic view both symbolic and nonsymbolic numbers are processed by the ANS, in the alternative view only nonsymbolic numbers are processed by the ANS, but symbolic numbers are handled by the DSS. The current work contrasts the two views, investigating whether the size of the distance and the size effects correlate in nonsymbolic dot comparison and in symbolic Indo-Arabic comparison tasks. If a comparison is backed by the ANS, the distance and the size effects should correlate, because the two effects are merely two ways to measure the same ratio effect, however, if a comparison is supported by other system, for example the DSS, the two effects might dissociate. In the current measurements the distance and the size effects correlated very strongly in the dot comparison task, but they did not correlate in the Indo-Arabic comparison task. Additionally, the effects did not correlate between the Indo-Arabic and the dot comparison tasks. These results suggest that symbolic number comparison is not handled by the ANS, but by an alternative representation, such as the DSS.

Keywords: numerical distance effect; numerical size effect; analogue number system; discrete semantic system;

1 Introduction

In their seminal work Moyer and Landauer (1967) described that in an Indo-Arabic single digit number comparison task the performance is worse (i.e., reaction time is slower and error rate is higher) when the difference between the two numbers is relatively small (numerical distance effect) or when the numbers are relatively large (numerical size effect). They proposed that these two effects are the reflection of a single effect based on the ratio of the numbers: number pairs with smaller ratio are harder to process (Figure 1). This ratio-based performance was thought to be the result of a simple representation working according to Weber's law, similar to the representations working behind simple physical feature comparison tasks. This Analogue Number System (ANS) is supposed to operate behind any number comparison, independent of the notation of the numbers (Dehaene, 1992; Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003). The numerical cognition literature dominantly accepts the ANS interpretation of the number comparison (Dehaene, 1992; Nieder, 2005; Piazza, 2010).

However, an alternative account can also explain the numerical distance and size effects in symbolic number processing. It might be rather intuitive to imagine that symbolic numbers are stored in a Discrete Semantic System (DSS), similar to the mental lexicon or a semantic network. In this system, numbers are represented by nodes, and the connections of the nodes reflect the semantic relations of the nodes. These relations might mainly be directed by the values of the numbers, but other properties might also have an effect, such as parity or primeness. The distance effect might be originated in the semantic relation of the nodes (Figure 1). As a similar distance based non-numerical example, in a picture naming task it was found that naming time was influenced by the previous picture, and the influence was proportional to the semantic distance of the priming and the target pictures (Vigliocco, Vinson, Damian, & Levelt, 2002). This semantic distance effect is similar to the numerical distance effect: in both tasks the performance was influenced by the semantic distance of the items. Although the cited distance effect in the picture naming task is a priming distance effect which is proposed to be different than a comparison distance effect in the number comparison task (Reynvoet, De Smedt, & Van den Bussche, 2009), the current example points out that a discrete representation can also produce a distance based gradual effect. The numerical size effect can also be explained by the DSS view. It is well known that the frequency of numbers is not uniform, but smaller numbers are more frequent than larger numbers (Dehaene & Mehler, 1992). It is also known that stimulus processing is influenced by the stimulus frequency. Based on these starting points one can imagine that larger numbers are harder to process, because they are less frequent (Figure 1). It was also shown that in an artificial number symbol comparison, in which the frequency of the digits can arbitrarily be manipulated, the size effect followed the frequency of the numbers (Krajcsi, Lengyel, & Kojouharova, submittedc), reflecting that the numerical size effect is indeed a frequency effect. Combination of the semantic based distance effect and the frequency based size effect can predict the performance seen in comparison tasks, and this prediction correlates strongly with the ANS model prediction, revealing similar descriptions of the comparison performance by the two models (Krajcsi et al., submittedc). To summarize, the DSS model can give simple explanations for the symbolic numerical distance and size effects (see additional examples how further symbolic numerical effects can be explained in Krajcsi, Lengyel, & Kojouharova, submittedb). It is important to note that the DSS only accounts for the symbolic number processing, while nonsymbolic number processing could still be supported by the ANS.

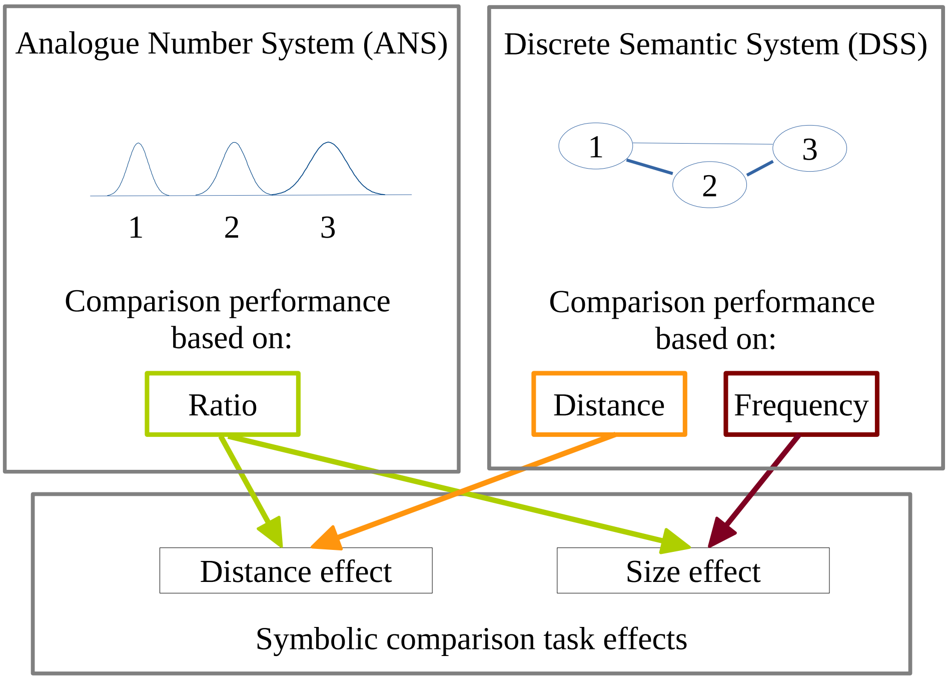


Figure 1. The sources of the symbolic distance and size effects according to the two models.

In the current study the two models are contrasted by correlating the size of the numerical distance and size effects. According to the ANS model, the distance and size effects are merely two ways to measure the same ratio effect, therefore the two effects should be closely related. To discuss this prediction in more detail, in the ANS model, the size of the distance and size effects are influenced by scaling parameters as in Moyer & Landauer (1967) and by the Weber ratio (Dehaene, 2007). Importantly, these parameters modify both the distance and size effects at the same time, because the equations describing the performance handle only the ratio, and the distance and size effects are the consequences of the ratio effect. Because of the way the size of the distance and size effects is calculated it is not trivial to specify whether the relation between the effects is linear, however, the relation should be at least monotonic. It can also be important to note that distance and size effects cannot correlate as an artifact of the way the two effects are calculated, because the distance effect relies on the difference of two numbers to be compared, while the size effect relies on the sum of the two numbers (see also the Results part), therefore the two effects form orthogonal dimensions in the stimulus space, resulting in 0 correlation between the distance and the size of number pairs. According to the DSS model, in symbolic comparison, the distance and the size effects derive from different mechanisms and potentially different parameters, consequently, the two effects could be partly unrelated. At the same time, according to the DSS model it is possible that some parameters are shared between the distance-based and the frequency-based mechanisms (either as DSS specific parameters, or as some general states as recently discussed in Cantlon, 2015), thus, some correlation could be observed. Therefore, according to the DSS model, correlation value might be found in a wide range, but because of the differing mechanisms behind distance and size effects, if the different mechanisms include different parameters that influence performance, then the correlation should be lower than the ANS predicted high correlation.

The main question of the current study is whether the distance and size effects strongly correlate in symbolic notation as predicted by the ANS model, or whether the correlation is smaller, as allowed by the DSS model. Correlation is also measured in nonsymbolic notation, because both the ANS and the DSS view suggest that nonsymbolic comparison is backed by the ANS, this nonsymbolic comparison correlation serves as a baseline. Statistically, the main question is whether the correlation of the distance and the size effects is smaller in symbolic Indo-Arabic comparison than in nonsymbolic dot comparison.

2 Methods

The current study reanalyzes the data of two former studies. One of them is a control group data of a neuropsychology study in preparation, and the other study investigates psychophysics properties of nonsymbolic and symbolic comparisons (Krajcsi, Lengyel, & Kojouharova, submitteda). Both the aim of those studies and the analysis are different from the current one. Two sets of data are used to ensure the reliability of the results with their replicability. The two studies mostly used the same methods, and only a few differences can be found.

Participants compared Indo-Arabic numbers in one condition, and they compared dot arrays in another condition.

In a trial two numbers were visible on the left and on the right sides of the screen, and participants had to choose the larger one by pressing one of the two response keys. The stimuli were visible until key press. The response was followed by an empty screen for 500 ms, then the next trial started.

In the Indo-Arabic condition the numbers were between 1 and 9, i.e., all single digit numbers. Processing multi-power numbers include additional mechanisms handling the powers (Hinrichs, Berie, & Mosell, 1982; Poltrock & Schwartz, 1984), therefore, it is more appropriate to use only single digit numbers. All possible pairings of those values were presented, except ties, resulting in 72 possible pairs. All pairs were presented 3 times (study 1) or 10 times (study 2), resulting in 216 or 720 trials, respectively. The order of the trials was randomized.

In the dots condition it is not appropriate to use the same 1-9 range as in the Indo-Arabic condition, because sets with less than 5 objects can be enumerated fast, which fast enumeration is termed subitizing (Kaufman, Lord, Reese, & Volkmann, 1949). Subitizing is not an ANS directed process (Revkin, Piazza, Izard, Cohen, & Dehaene, 2008), but it is most probably based on pattern detection (Krajcsi, Szabó, & Mórocz, 2013; Mandler & Shebo, 1982). Therefore, to measure the ANS based dot estimation, the 1-4 range should be avoided. In order to avoid the 1-4 range, and to keep the critical ratio-based feature at the same time, all numbers between 1 and 9 were multiplied by 5, resulting in a number range between 5 and 45. According to the ANS model, because ratio is the only main source of the performance (Dehaene, 2007), transformations keeping the ratios should not change neither the performance in general, nor the correlations specifically. In an array of dots, black and white dots in random positions were shown against a gray background (Dakin, Tibber, Greenwood, Kingdom, & Morgan, 2011), thus, the luminance of the stimuli was not informative about the numerosity. Dots of an array were drawn randomly in a 2×2 degrees area, with a dot diameter of 0.2 degrees, therefore, density and convex hull correlated with the numerosity. Although our stimuli do not control all perceptual features that might influence the perceived numerosity, perfect visual control might be impossible in some simple methods usually utilized in the literature (Gebuis & Reynvoet, 2012). More importantly, in the current test, nonnumerical influence of the decision process is less relevant, because the ANS model suggests that number comparison is handled by an analogue system that could be used in any continuous physical feature comparison (Dehaene, 2007; Moyer & Landauer, 1967), hence, in a general sense, any continuous physical feature comparison working according to the Weber's law could be an appropriate task in our test. Additionally, a mixture of visual ratio-based performance and numerosity ratio-based performance should also produce an approximately ratio-based performance, as reflected in the similar psychometric functions of visual comparison and numerical comparison tasks. Therefore, the simple and limited visual control of the stimuli should be appropriate for the aim of the current test. As in the Indo-Arabic condition, all possible pairs were presented 3 times (study 1) or 10 times (study 2), resulting in 216 or 720 trials, respectively. The order of the trials was randomized.

In the first study all sessions started with the Indo-Arabic condition, and finished with the dot condition. In the second study, the order of the conditions was counterbalanced across participants.

Presentation of the stimuli and the measurement of the responses were managed by the PsychoPy software (Peirce, 2007).

In the first study 19 university students participated for partial credit course. No participants were excluded from the analysis. In the sample there were 2 males, the age range was 18-24 years, with a mean of 20.1 years. In the second study 24 university students participated for partial credit course. Four participants were excluded, because their error rates were higher than 1.5 standard deviation + mean error rates at least in one of the conditions (6% in the Indo-Arabic condition and 15% in the dots condition). Among the remaining 20 participants there were 4 males, the age range was 19-24 years, with a mean of 21.0 years.

2.1 Analysis

The slopes of the distance and size effects based on reaction times were calculated for all participants and for both notations. For the slopes reported here mean reaction times were calculated for all distance values (absolute value of the difference of the two numbers) or for all size values (sum of the numbers) for all participants and notations, and linear regression slopes were calculated on these mean values. The effects were alternatively calculated (a) with only the correct responses, (b) using the median instead of the mean, or (c) with the slope divided by the mean of the comparison time to handle the slope change caused by general speed differences. These alternative calculation methods revealed the very same results as the first one (i.e., significant correlation in the nonsymbolic comparison, nonsignificant correlation in the symbolic comparison and significant difference between the symbolic and nonsymbolic correlations), thus, their results are not reported here. In the dot comparison task, for the distance effect the slope was calculated as if the number of dots were between 1 and 9, although the dots were between 5 and 45, but this method reflected more appropriately the ANS model driven consideration, that the two notations cover the same ratio range. Importantly, this linear transformation of the slopes do not change the correlational coefficients.

For the correlational analysis, (1) Pearson's product-moment coefficient was calculated, which makes the current result comparable with previous correlational studies. Additionally, (2) Spearman's rank correlation coefficient was also calculated, because in contrast with the Pearson correlation, (a) it is not sensitive to outliers, (b) to violation of normality, (c) to violation of homoscedasticity, (d) and it can measure nonlinear monotonic relation more sensitively. Finally, (3) reliability of the variables in the correlation was handled. In any correlation the variables include both the signals to be measured and the noise. The noise decreases the reliability of the variables, which in turn constrains the maximum correlation one might see. Because the ANS model predicts a high correlation between distance and size effects, it is essential to handle the potential unreliability of the variables to see if the two variables measure the same mechanism. Also, it is possible that there could be smaller distance effect-size effect correlation in the Indo-Arabic comparison, because it has a smaller signal-to-noise ratio (resulting in smaller reliability, and consequently lower correlation), and not because symbolic comparison is processed by the DSS, therefore, the critical difference of the correlations between the notations might be a bias of different signal-to-noise ratio in those notations. Spearman's method was applied to estimate the “real” correlation of the variables, removing the role of the unreliability (Spearman, 1904). Distance and size effects were calculated again, as for the main analysis, but similar to an even-odd split-half method, even and odd trials were handled separately, thus, for all effects even and odd versions were calculated. Corrected correlation was calculated as

$$\frac{r(distance_{even}, \mathrm{size}_{even}) + r(distance_{even}, \mathrm{size}_{odd}) + r(distance_{odd}, \mathrm{size}_{even}) + r(distance_{odd}, \mathrm{size}_{odd})}{4 \times \sqrt{r(distence_{even}, distance_{odd}) \times r(\mathrm{size}_{even}, \mathrm{size}_{odd})}},$$

where r is the Pearson correlation coefficient.

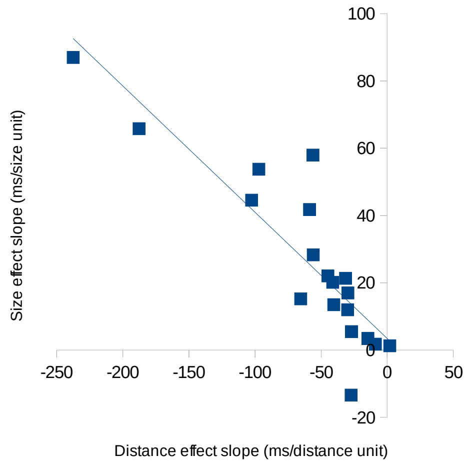
3 Results

In the main analysis the correlation of the slopes of the two effects were investigated in both notations and in both studies. In the dot comparison task the distance and size effects strongly correlated in both studies (Figure 2, left side). Critically, the estimated correlation coefficients removing the unreliabilities of the variables show values very close to the value one[1], reflecting a perfect correlation between distance and size effects in nonsymbolic dot comparison. In the Indo-Arabic comparison task the correlation is weak and not significant in any of the studies (Figure 2, right side). These results are not the artifact of outliers, non-normality of the variables or heteroscedasticity, because the very same results can be observed with both the Pearson's and Spearman's correlation coefficient. The difference between the correlations is significant in both studies.

1It is possible to have a larger than 1 value for the corrected correlation coefficient. Still, the corrected correlation coefficient of the dot comparison effects in the second study (-1.06) is very close to the value 1.

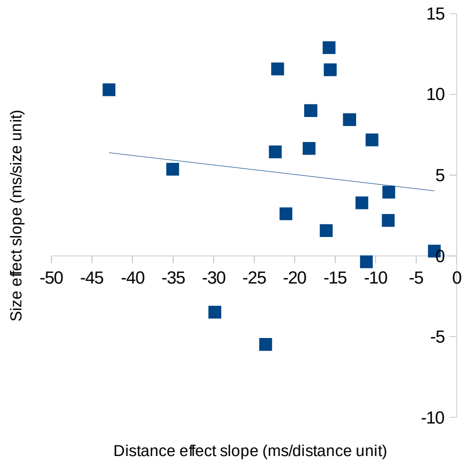
Study 1

Dot notation



(1) Pearson $r(17) = -0.88$, $p < 0.001$,
95% CI of r [-0.95, -0.70]
(2) Spearman $r_s(17) = -0.9$, $p < 0.001$,
95% CI of r_s [-0.96, -0.75]
(3) Corrected with reliability $r = -0.99$

Indo-Arabic notation

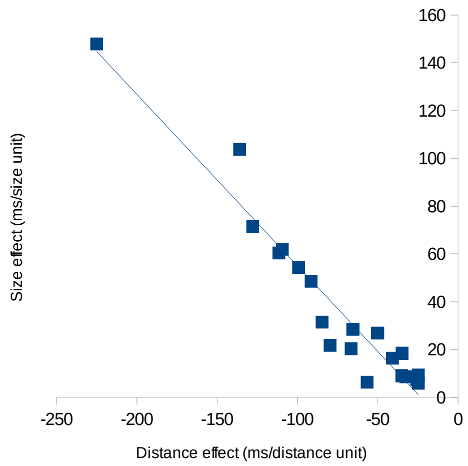


(1) Pearson $r(17) = -0.11$, $p = 0.65$,
95% CI of r [-0.54, 0.36]
(2) Spearman $r_s(17) = -0.11$, $p = 0.66$,
95% CI of r_s [-0.54, 0.36]
(3) Corrected with reliability $r = -0.22$

Difference between the Pearson correlations: $Z = 3.5$, $p < 0.001$

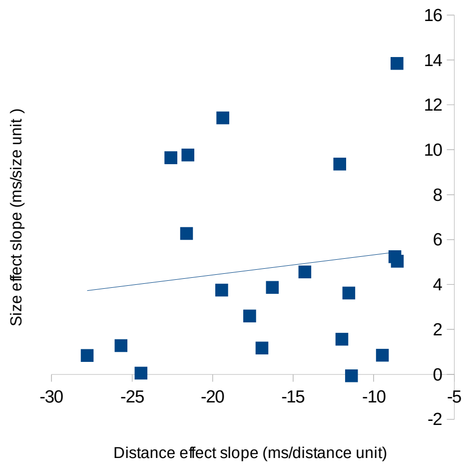
Study 2

Dot notation



(1) Pearson $r(18) = -0.96$, $p < 0.001$,
95% CI of r [-0.99, -0.91]
(2) Spearman $r_s(18) = -0.92$, $p < 0.001$,
95% CI of r_s [-0.97, -0.8]
(3) Corrected with reliability $r = -1.06$

Indo-Arabic notation



(1) Pearson $r(18) = -0.13$, $p = 0.57$,
95% CI of r [-0.33, 0.54]
(2) Spearman $r_s(18) = 0.14$, $p = 0.56$,
95% CI of r_s [-0.32, 0.55]
(3) Corrected with reliability $r = 0.26$

Difference between the Pearson correlations: $Z = 6.53$, $p < 0.001$

Figure 2. Relation of the distance and size effect slopes displayed on scatter plots and measured with correlation coefficients in dot comparison (left) and Indo-Arabic comparison (right)

According to some former reports, nonsymbolic dot comparison performance and the mainly symbolic mathematical performance are related (e.g., Halberda, Ly, Wilmer, Naiman, & Germine, 2012; Halberda, Mazzocco, & Feigenson, 2008; Lourenco, Bonny, Fernandez, & Rao, 2012), therefore, it could be of interest how the symbolic and nonsymbolic comparisons are related in the current data. The correlations of the effects across the notations were calculated, e.g., whether Indo-Arabic distance effect and dot distance-effect correlate. None of the effects correlated across the notations: in the first study, for the distance effects $r(17) = 0.00$, $p = 1.00$, 95% CI of r [-0.45, 0.46], $r_s = 0.08$, for the size effects $r(17) = 0.13$, $p = 0.59$, 95% CI of r [-0.34, 0.55], $r_s = 0.11$, in the second study, for the distance effects $r(18) = 0.15$, $p = 0.52$, 95% CI of r [-0.31, 0.56], $r_s = 0.12$, for the size effects $r(18) = 0.32$, $p < 0.17$, 95% CI of r [-0.15, 0.67], $r_s = 0.24$.

4 Discussion

In the present work it was investigated how strongly the numerical distance and size effect slopes correlate in Indo-Arabic and dot comparison tasks. (1) It was found that distance and size effect slopes strongly correlate in the dot comparison task (Figure 2, left side), and after correcting for the reliabilities of the variables, the correlation is very close to the value of 1, reflecting a perfect connection between the two effects. This result is in line with the classic ANS model that suggests that in a comparison task the distance and the size effects are the direct consequences of the ratio effect (Moyer & Landauer, 1967), and since both distance and size effects are modified by the same parameters, the two effects should strongly correlate. Additionally, the very strong correlation demonstrates that the method used in the present study is appropriate to reveal this strong relation between the distance and the size effects. (2) It was also found that the distance and the size effects are barely related in the Indo-Arabic comparison task (Figure 2, right side), and the correlation is clearly smaller than the correlation found in the dot comparison task. This result is in conflict with the classic ANS model, because according to the ANS model the same strong correlation should have been found as in the dot comparison task, because the distance and size effects are directed by a single ratio-based effect. However, the result is in line with the DSS model, which suggests that the distance and the size effects rely on different mechanisms and probably partly on different parameters: the distance effect could be rooted in a mechanism based on the semantic relation of the units (as in Vigliocco et al., 2002), while the size effect might be related to the frequency of the symbols (Dehaene & Mehler, 1992; Krajcsi et al., submittedc). (3) Finally, it was found that the effects do not correlate between the notations: it seems that the size of the distance effect in the Indo-Arabic comparison is independent of the size of the distance effect in the dot comparison, and the same holds for the size effect. Although it was suggested that nonsymbolic performance correlates with mathematical achievement, suggesting that the ANS is one of the main root of mathematical knowledge (e.g., Halberda et al., 2012, 2008; Lourenco et al., 2012), the current data are not in line with these findings, but reflect the finding of a more systematic review, revealing that only symbolic comparison correlates with children's mathematical achievement, but nonsymbolic comparison and mathematical achievement mostly do not correlate (De Smedt, Noël, Gilmore, & Ansari, 2013). The current results also replicate the findings of studies which demonstrate that symbolic and nonsymbolic comparisons do not correlate in children (Holloway & Ansari, 2009;

Sasanguie, Defever, Maertens, & Reynvoet, 2014), although in those reports in the nonsymbolic comparisons set sizes from the subitizing range (i.e., 1-4) were also applied, thus, the validity of some of those data could be questioned.

The current results are not in line with the ANS model, which model suggests that the same type of process handles both the symbolic and nonsymbolic numbers (Dehaene, 1992; Eger et al., 2003). Although there could be differences between the symbolic and nonsymbolic number processing (e.g., different Weber fractions across notations, see Dehaene, 2007), the ANS model unequivocally states that the performance is based on the ratio of the values, coming from a representation working according to Weber's law, and this feature is independent of the notation of the values, let it be symbolic or nonsymbolic. Therefore, the current results cannot be explained by the fact that there are differences between symbolic and nonsymbolic comparisons, and the current data simply could be another example of those differences, because according to the ANS model the distance-size effects correlation should be observable in any number comparisons.

While the current results are in line with the DSS model, and give some support to this alternative view, this single study clearly does not test the DSS model extensively. It is also possible that another alternative could be found. Still, the DSS seems a reasonable alternative at the moment, and it can explain not only former data about symbolic number comparison, or number processing in more general, but it can also explain the current new findings. Further research should reveal whether the DSS model is an appropriate explanation for symbolic number processing or other alternative should be found.

Based on the current data, it can be possible that while comparing symbolic numbers, both the ANS and the DSS are activated, and both of them influence the observed performance. It may be possible that the correlation of the effects in symbolic comparison is smaller than in nonsymbolic comparison, because the contribution of the DSS decreases the coefficient, yet, part of the correlation still might be originated in the ANS processing. Although the very low coefficients seen in symbolic comparison hint a pure DSS processing, still, because of the uncertainties of the analysis methods, it is hard to precisely quantify the different predictions of a pure DSS activation and a mixed DSS and ANS activation explanations. Still, it is clear that the symbolic comparison results are not in line with a pure ANS explanation.

These results and interpretations are in accord with some former results of the literature. A few studies have shown that effects that should be related according to the ANS model are actually independent. In an artificial new number symbol system it was found that the size effect follows the frequencies of the symbols, independent of the ratio of the values (Krajcsi et al., submittedc). In a connectionist simulation, various symbolic numerical effects could be modeled coherently, and importantly, the size effect could be modeled with the introduction of the frequencies of the values, independent of the distance effect (Verguts, Fias, & Stevens, 2005). Similarly, in another connectionist model of number comparison, the distance and the size effects emerge from independent components of the network (Zorzi & Butterworth, 1999). Finally, the comparison distance effect and the priming distance effect (in a priming task the size of the priming effect depends on the distance of the prime and the target numbers) were found to be independent

(Reynvoet et al., 2009), although they should be related according to the ANS model. In a different group of works it was found that the symbolic and nonsymbolic number processing have differences where the ANS model would predict similarities. In a detailed analysis it was demonstrated that contrary to former analyses while the ANS model can describe dot comparison performance relatively well, the model has systematic biases in describing Indo-Arabic comparison, therefore, symbolic and nonsymbolic number comparison might rely on two different representations (Krajcsi et al., submittedb). Also, as it was mentioned above, according to several findings symbolic and nonsymbolic comparisons do not correlate in children (Holloway & Ansari, 2009; Sasanguie et al., 2014), and nonsymbolic comparison mostly does not correlate with typically symbolic mathematical achievement (De Smedt et al., 2013).

The current work investigated a fundamental prediction of the ANS model, whether distance and size effects correlate in any number notations, and the results do not support the model in symbolic comparison. While it is clear that the ANS model is supported by many empirical results and by many theoretical considerations, the DSS can explain many phenomena that was formerly attributed to the ANS model, and in some contrasts the DSS can offer better account for former and new phenomena. To explore the status of the ANS and the DSS models, further effort should be taken to clarify the scope of the former data, and new tests and considerations are required to evaluate the competing models.

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