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Beyond comparison: The influence of physical size on number estimation is modulated by notation, range and spatial arrangement

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ABSTRACT

Can physical size affect number estimation? Previous studies have shown that physical size influences non-symbolic numerosity in *comparison tasks* (e.g. which of two dots is larger). The current study investigated the conditions under which physical size can affect numerosity *estimation*. We employed a line mapping task in order to avoid the context of comparison and the need to provide a verbal label to estimate a quantity. Adult participants were briefly presented with the digits 2–8 or groups of 2–8 dots in 3 different physical sizes and were asked to estimate the position of a presented numerosity on a vertical line from 0 to 10. Physical size affected number estimation only above the subitizing range (i.e., > 4) and only for non-symbolic numbers (e.g. dot arrays). Presenting non-symbolic numbers as canonical arrangements (like on a game die) reduced the effect of the physical size in the counting range (5–9). Accordingly, we suggest that the effect of task-irrelevant physical size on performance is modulated by the ability of participants to provide an accurate estimate of number: when the estimated number is easier to perceive (i.e., subitizing range or canonical arrangements), the influence of the physical size is smaller compared to when it is more difficult to give an accurate estimate of number (i.e., counting range, random arrangement). By doing so, we describe the factors that modulate the effect of physical size on number processing and provide another example of the important role continuous properties, such as physical size, play in non-symbolic number processing.

1. Introduction

The last few decades have seen a tremendous amount of growth in our understanding of how humans process the total number of items in a set (i.e. non-symbolic numerosities). Focusing on the processing of numerosities, these studies have shown that humans are born with a “number sense” enabling the perception, comparison and estimation of non-symbolic numerosities (e.g., Dehaene, 1997; Piazza, 2010). Moreover, it has been suggested that numerosities are compared and estimated regardless of other visual properties of the group, such as the density of the items or their total surface area (from here on referred to as continuous properties; e.g., Dehaene & Changeux, 1993; Ross & Burr, 2010); so, for example, according to this theory, the numerosity of 6 apples and 6 watermelons will be estimated similarly, and the difference in the items' physical sizes will not affect number estimation. Recently, however, accumulating evidence suggests that non-symbolic numerosity processing is strongly influenced by non-numerical variables (i.e., continuous properties), such as the physical size and the density of object arrays (Leibovich & Ansari, 2016).

Since numerosity is correlated with continuous properties (e.g., usually more items will take more space, will be denser, etc. than fewer items), it is impossible to study numerosity processing in isolation from correlated continuous properties. Indeed, in recent years, it has been repeatedly demonstrated that even when continuous properties are manipulated to ensure that they cannot serve as a reliable cue of numerosity, they nevertheless still affect numerosity processing on a trial by trial basis (Gebuis & Reynvoet, 2012a, 2012b; Leibovich & Henik, 2014; for a review see Leibovich & Henik, 2013). In other words, simply ensuring that different continuous properties are varied sufficiently does not negate their impact on numerosity processing. Indeed, a number of studies have demonstrated that numerosity processing involves not only number but all continuous properties that are available to inform the estimation or comparison of numerosities (e.g., Gebuis & Reynvoet, 2012a; Leibovich & Henik, 2013; Mix, Huttenlocher, & Levine, 2002).

To date, the effect of continuous properties on non-symbolic numerosity processing has been primarily studied in the context of comparison tasks. Namely, it has been repeatedly shown that it is faster and easier to compare two groups of dots when the numerosity is positively correlated with the continuous properties (i.e., more numer-

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ous dots are also larger, denser, occupy more space, etc.), than when numerosity is negatively correlated with continuous properties (Gebuis & Reynvoet, 2012a; Hurewitz, Gelman, & Schnitzer, 2006; Leibovich, Henik, & Salti, 2015; Leibovich, Vogel, Henik, & Ansari, 2016). It is possible that such findings are specific to the context of comparison tasks. In particular, it is possible that comparison tasks force participants to attend to continuous properties. In other words, it may be the case that the use of continuous properties is specific to the comparison task, and does not occur whenever we encounter a numerosity where we are not asked to make a comparison. In order to better understand the role of continuous properties in symbolic and non-symbolic numerosity processing, it is therefore critical to examine their relationships across different task contexts. For example, Defever and colleagues (Defever, Reynvoet, & Gebuis, 2013) employed a non-symbolic comparison task and a same-different task, and found that although continuous properties affected performance in both tasks, the influence of continuous properties differed between the tasks.

Another way to study the influence of continuous properties on numerosity processing without evoking a comparison process is by using estimation tasks. In such tasks, participants estimate the number of items presented to them (e.g. how many dots do you see?). To date, the evidence as to the influence of continuous properties in estimation tasks is sparse and inconsistent. Specifically, in one study, Gebuis and Reynvoet (2012b) asked adult participants to estimate the quantity of dots (ranging from 12 to 44) and found that estimation was affected by the size of the dots: the number of dots in groups containing smaller dots was over-estimated, whereas the number of dots in groups containing larger dots were under-estimated. In contrast to these findings, a more recent study revealed that continuous properties were found to affect performance only in non-symbolic comparison but not estimation tasks (Smets, Sasanguie, Szücs, & Reynvoet, 2015). The difference between the findings in these two studies can be attributed to the different experimental designs employed in these studies. For example, in different types of stimuli the differences in continuous magnitudes of dot arrays could have been more salient or less salient than the difference in numerosity, resulting in different degrees of influence from the continuous magnitudes. The difference between the tasks, however, may also occur because comparison and estimation tasks have different requirements; in a verbal estimation tasks one has to produce an exact number, to give an exact verbal and symbolic label to an estimated quantity, while in comparison tasks the answer is dichotomous, asking only where there is more, and does not involve exact symbolic labels. This requires much less precision than estimation and may therefore allow continuous properties to exert a greater influence.

In estimation studies such as those discussed above, the to-be-estimated numerosities are typically > 4, i.e., outside of the so-called 'subitizing range'. Subitizing refers to the ability to quickly, without counting or serial shifts of attention, enumerate up to 4 items in a display (Trick & Pylyshyn, 1994). Another factor that influences performance in number estimation tasks is the spatial arrangement of the presented items. Specifically, if non-symbolic numbers appear in a familiar pattern, like the one appearing on a game dice, the quantity is estimated faster and more accurately than the same quantity presented in a random pattern (Mandler & Shebo, 1982).

It is currently unclear whether continuous properties affect numerosity processing within and outside the subitizing range differentially. The only hypothesis regarding the influence of continuous properties in the subitizing range is based on non-symbolic numerosity *comparison* studies with primates (Hauser, Carey, & Hauser, 2000) and infants (Feigenson, Carey, & Hauser, 2002). In such studies continuous properties were found to affect performance only in the subitizing range. Therefore, it has been suggested that "Whereas the first core system [i.e., the approximate number system] outputs *specifically* numerical representations, the second system [responsible for the subitizing range] allows for the representation of *continuous variables and of discrete number*" (Feigenson, Dehaene, & Spelke, 2004, p. 309). In addition, it is also unclear if and how different spatial arrangements can modulate the influence of continuous properties in number estimation tasks.

Another important question concerns the nature of the influence of continuous properties in judging numerosities. If this influence is bottom-up and affected mostly by the stimulus properties, then continuous properties should always influence performance in number judgment tasks similarly. In other words, we would expect the same influence of continuous magnitudes in numerical comparison and numerical estimation tasks. Another possibility, however, is that the influence of continuous properties is not purely perceptual and bottom-up, but adaptive and modulated by task demands. Namely, it is used as an additional source of information about the stimuli when needed to guide decision-making. For example, when choosing the bag with more apples, it is more adaptive, given the strong correlation between the number of apples and their weight, to choose the bag by weight. However, if a recipe requires exactly 5 apples and you have enough time to choose them, continuous properties will be inhibited.

Against this background, the current study employed a line mapping task (mapping quantities/numbers onto a number line) to examine the influence of continuous properties (specifically physical size) on symbolic and non-symbolic number estimation. We also asked whether this influence could be further modulated by spatial arrangement (canonical vs. random). To do so, in Experiment 1, we manipulated the physical size of symbolic (2–8 in Arabic numerals) or non-symbolic (groups of dots) numbers. In Experiment 2, we presented non-symbolic numbers in either a random or a canonical arrangement.

The line mapping task was selected for several reasons. First, it allowed us to test estimation without the need to convert the quantity to an exact number. In other words, instead of using a specific verbal label, participants converted an estimated quantity to an estimated location on a line. Second, the line mapping task allowed us to evaluate how physical size affected non-symbolic numbers outside the context of comparison and conflict, since there was no other stimulus for comparison. Put differently, using the line mapping task, we were able to examine how and under which conditions continuous magnitudes affected processing of a single stimuli. To minimize the possibility of participants using comparisons and in order not to mix different notations, the line appeared without any flankers at the ends. Instead, participants were told that the line started at zero and ended at 10.

We hypothesized that irrelevant continuous properties would be used as an additional source of information *if necessary*. Specifically, we hypothesized that continuous properties would be used when the ability to provide an accurate answer is reduced. Accordingly, we predicted that (1) symbolic number mapping would not be affected by physical size; (2) Non-symbolic number mapping in the subitizing range would be less affected then non-symbolic numbers above the subitizing range; and (3) above the subitizing range, canonical arrangements would be less affected by physical size compared to random arrangements. Experiment 1 compared the influence of physical size on symbolic and non-symbolic numbers, while Experiment 2 compared the influence of physical size on canonical and random arrangements. The experiment files are available here: https://osf.io/2n3mg/

2. Experiment 1: The effect of physical size on symbolic and non-symbolic numbers

2.1. Method

2.1.1. Participants

Fifty students (19 males), participated in the experiment and were compensated for their time. The mean age of the participants was 21.52 years (SD = 5.7). All participants had normal or corrected-to-normal vision, and no learning disabilities or attention deficits. The study was approved by Western University's Non-Medical Research Ethics Board (NMREB).