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BRIEF REPORT

# The Interplay Between Nonsymbolic Number and Its Continuous Visual Properties

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To date, researchers investigating nonsymbolic number processes devoted little attention to the visual properties of their stimuli. This is unexpected, as nonsymbolic number is defined by its visual characteristics. When number changes, its visual properties change accordingly. In this study, we investigated the influence of different visual properties on nonsymbolic number processes and show that the current assumptions about the relation between number and its visual characteristics are incorrect. Similar to previous studies, we controlled the visual cues: Each visual cue was not predictive of number. Nevertheless, participants showed congruency effects induced by the visual properties of the stimuli. These congruency effects scaled with the number of visual cues manipulated, implicating that people do not extract number from a visual scene independent of its visual cues. Instead, number judgments are based on the integration of information from multiple visual cues. Consequently, current ways to control the visual cues of the number stimuli are insufficient, as they control only a single variable at the time. And, more important, the existence of an approximate number system that can extract number independent of the visual cues appears unlikely. We therefore propose that number judgment is the result of the weighing of several distinct visual cues.

*Keywords:* nonsymbolic number, number comparison, visual cues

The number of studies investigating the neural mechanisms underlying nonsymbolic number processes increased drastically in the past years (Cohen Kadosh, Lammertyn, & Izard, 2008). These studies initially focused on the processes or areas involved in the representation of number. However, recently, more attention is devoted to the translation of the visual percept of a number of items into a number (e.g., Dehaene & Changeux, 1993; Emmerton & Renner, 2009; Verguts & Fias, 2004). Still, to date, no model exists showing a direct link between the visual properties of a nonsymbolic number (e.g., diameter or density) and the number it represents. This is surprising, as nonsymbolic number is defined by its visual characteristics. When these are the same between two sets of items, number is also the same. Similarly, when number changes, the visual characteristics change accordingly.

Instead of taking into account a possible role for the visual cues, researchers consider the strong relation between number and its visual properties a problem. They want to investigate nonsymbolic number processes independent of their visual confounds and therefore create complex paradigms (e.g., Izard & Dehaene, 2008; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004; Santens, Roggeman, Fias, & Verguts, 2010). Results from these studies show that participants can process number while visual cues are controlled for, implicating that number is extracted independent of the visual cues. Nevertheless, occasional reports in both the animal and the human literature suggest that this might be otherwise. They show that number judgments are influenced by visual cues such as contour length (Clearfield & Mix, 2001), cumulated surface area (Feigenson, Carey, & Spelke, 2002), convex hull (Gebuis & Gevers, 2011), clustering (Frith & Frith, 1972), or stimulus diameter (Ginsburg & Nicholls, 1988; Sophian, 2007). In line with these reports, Gebuis and Gevers (2011) proposed that number might not be extracted independent of the visual cues but instead weigh the different visual parameters to decide which array contains more items.

Weighing the different visual cues in the stimulus would be a very efficient strategy. In daily life, number and visual cues are highly correlated. For example, a lecture room becomes more densely packed and a larger area of the room will be covered when more students enter. This large correlation between number and the different visual cues (aggregate surface and density) makes it possible to decide which of two lecture rooms contains more students purely on the basis of different visual properties. Depending on the situation, different visual cues are informative about

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number (e.g., convex hull is more informative about number when you have to decide which bag of apples contains more apples, whereas density and aggregate surface are more informative when you have to decide which lecture room contains more students). It would therefore be optimal to give weights to the different visual variables present in the scene according to their size (e.g., a small difference in convex hull and a large difference in density would result in a stronger weight for density compared with convex hull). In this manner, our estimates are, to some extent, even robust to scenes where a single variable or a few variables are uninformative about number as opposed to multiple other variables. Still, in daily life, the strong relation between number and the majority of visual cues is unlikely to be violated; the chances are slim that, for instance, the lecture room containing more students also contains students that are smaller in size than the students in the lecture room containing fewer students, in contrast to the stimuli that are generally used to study number processes. Given this strong relation, it would be very inefficient if the brain did not rely on the visual system when judging number.

In the current study, we aim to investigate whether people indeed weigh different visual parameters to judge number. The outcomes could have major consequences for current research designs as well as theories about number processing. First, contemporary research designs only control a single visual parameter at a time. For instance, in half of the trials, diameter is kept constant, whereas, in the other half of the trials, aggregate surface is equated. Although this method would indeed make a single visual parameter uninformative about number, it would be an insufficient method if people integrated information from multiple visual cues (e.g., if they relied on both diameter and aggregate surface). Second, it is suggested that an approximate number system exists that can extract number from the visual scene independent of the visual cues. However, if multiple visual cues are weighed when people judge number, the presence of an approximate number system would be unlikely.

To address both issues, we created four nonsymbolic number comparison tasks, each consisting of two congruency conditions. Participants had to indicate which of two dot arrays contained more dots. The current and previous studies investigating the effect of visual cues on number had two important differences. First, we did not manipulate the visual cues (e.g., increase the size of the dots to investigate the influence of dot size on number processing) but controlled the relation between each visual cue and number according to current standards. Now we could investigate whether participants rely on the visual cues even though they are uninformative about number across trials. Second, we investigated the effect of not only a single visual cue but also multiple visual cues on number processes. To this end, we created two conditions where only a single visual cue (or subset of visual cues) was manipulated and two conditions where these parameters were combined in opposite directions (see the Method section for details). Given the fact that we controlled our visual cues according to current standards, we hypothesized that the presence of congruency effects confirms that current methods to control for the visual cues are insufficient and that people rely on multiple visual cues when judging number. Both conclusions would be further underlined if the congruency effect scales with the number of visual cues manipulated.

# Method

## Participants

Twenty-eight participants between 19 and 30 years of age took part in the experiment. Three participants were excluded from the analysis, as their performance was more than 2 standard deviations from the mean performance of the group. All participants had normal or corrected-to-normal vision.

## Materials

The stimuli were arrays of gray dots presented on a dark background (dot size ranged between 0.11° and 0.79° visual angle). The stimuli were generated using modified versions of the program developed by Gebuis and Reynvoet (in press). The different visual cues manipulated were (a) convex hull (smallest contour around the dot array), (b) density (aggregate surface divided by convex hull), (c) aggregate surface, and (d) average diameter.

The experiment consisted of four tasks (192 trials each) that again consisted of 50% congruent trials (96 trials) and 50% incongruent trials (96 trials). Each trial consisted of two consecutively presented dot arrays. One dot array always represented 24 dots and the other 16, 18, 20, 29, 32, or 36 dots, resulting in three ratio conditions (ratios of 1:2, 1:3, and 1:5 for numbers smaller and larger than 24).

A stimulus was considered congruent when the dot array containing more dots was also defined by larger visual properties. To establish four different congruency conditions (see Figures 1 and 2), we manipulated the visual cues that are considered to influence number judgments: convex hull, average diameter, aggregate surface, and density. In two tasks, only a single visual parameter or a subset of visual parameters was manipulated, whereas, in the other two tasks, both parameters were combined, albeit in opposite directions. To this end, we pitched convex hull against diameter, aggregate surface, and density. We were not able to differentiate between aggregate surface, diameter, and density because they are highly related. If aggregate surface increases, diameter and density also increase, whereas convex hull can remain constant. We created the following tasks: (a) *convex hull task*, in which convex hull was congruent with number in half of the trials and incongruent with number in the other half of the trials, and the remaining visual properties were equated across congruency conditions; (b) *diameter, density, and surface task* ("the diameter task" hereafter), in which only density, average diameter, and aggregate surface were manipulated while convex hull was kept constant across congruency conditions; (c) *fully congruent task*, in which all visual properties were congruent with number in half of the trials and incongruent in the other half; and (d) *partial congruent task*, in which the stimuli were the same as for the fully congruent task except that the convex hull was manipulated in the opposite direction. Note that even though visual properties were manipulated differently in the four tasks (see Figures 1 and 2), they were not an informative cue of number: (a) In each task, number and the visual properties were congruent in half of the trials and incongruent in the other half, and (b) the difference in visual properties and the (relative) number distance did not significantly correlate for each participant and task, $R^2 < .01$, $p > .08$ (Gebuis &

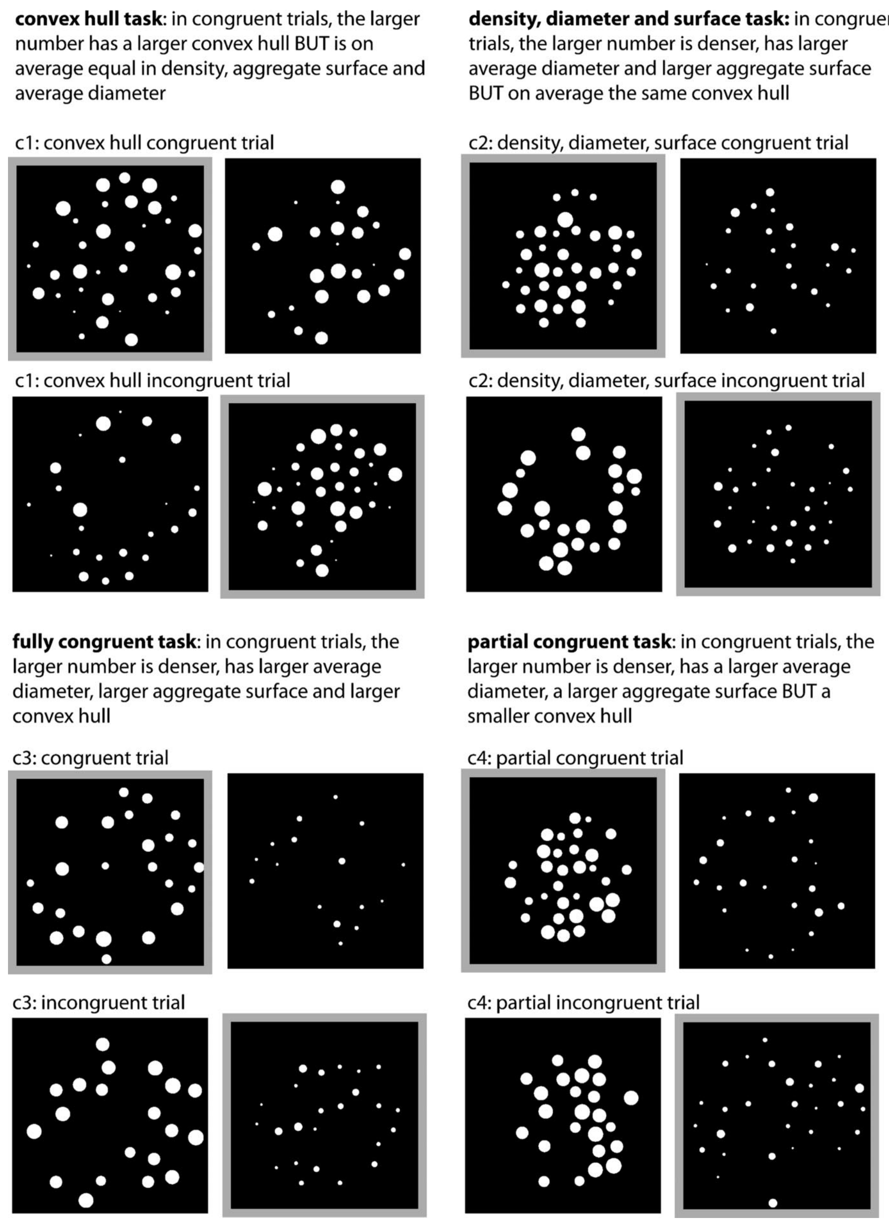


*Figure 1.* Examples of the (partially) congruent and incongruent stimulus pairs of each task. For each of the four tasks, two example stimuli are given, a (partial) congruent and a (partial) incongruent stimulus. The stimulus with the gray border is the stimulus representing more dots.

Reynvoet, in press). Only in the convex hull task was the aggregate surface informative; it was always larger for the larger number (see Figure 2C, Task c1). We could not control for this visual cue without making other cues informative. Nevertheless, the difference in aggregate surface between the two dot arrays in the congruent and incongruent tasks was similar. Hence, aggregate surface cannot explain possible differences in congruency.

## Procedure

Participants perceived a green fixation cross for 500 ms, followed by the first dot array for 300 ms, a blank screen for 500 ms, the second dot array for 300 ms, and a red fixation cross until the participant responded. Participants had to decide which display contained more dots. The four tasks were fully randomized, and the target stimulus appeared an equal number of times at the first and second intervals.

## Analyses

Average correct response for each congruency condition of each task was calculated and subjected to a 4 (task) × 2 (congruency) repeated-measures analysis of variance. In case of a main effect or

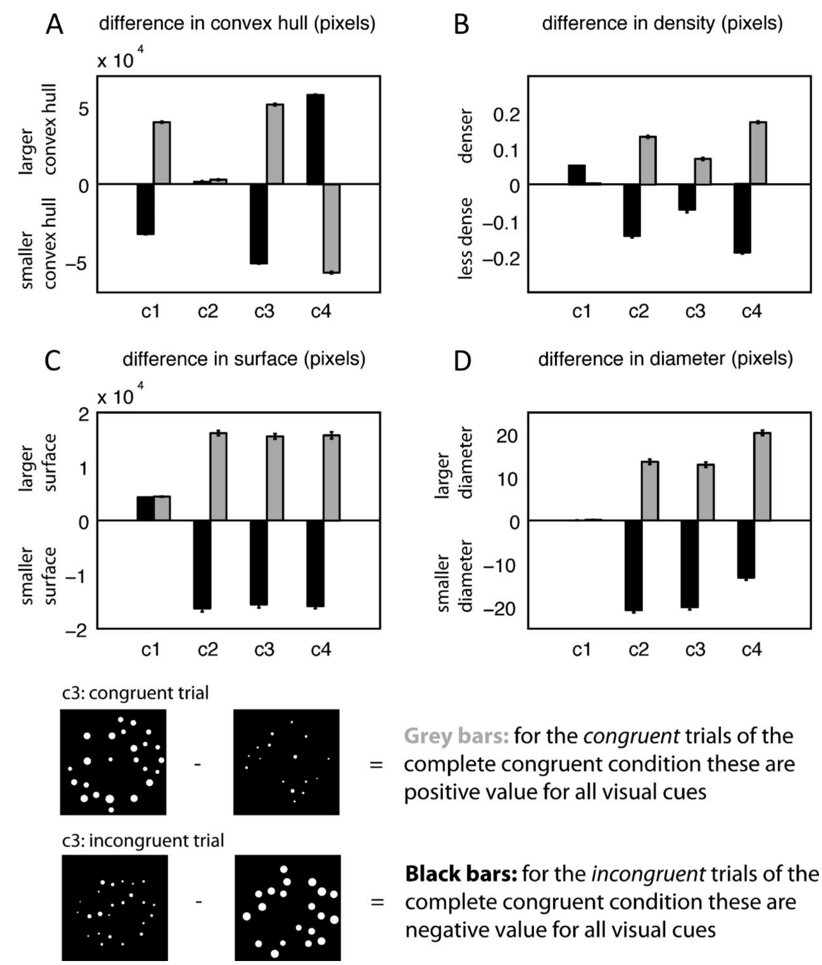


*Figure 2.* The difference in visual properties of all stimulus pairs. Each panel describes the difference in visual properties of the stimulus containing more dots relative to the stimulus containing fewer dots of each of the four task conditions: c1 = convex hull task, c2 = diameter task, c3 = fully congruent task, and c4 = partial congruent task. The gray and black bars represent the difference in visual properties of each number pair (visual cues of the larger number minus the visual cues of the smaller number) for the congruent and incongruent trials, respectively. See, for instance, the example given for the fully congruent condition (c3), here in half of the trials, the larger number has a larger convex hull (gray bar, Panel A), is denser (gray bar, Panel B), has a larger aggregate surface (gray bar, Panel C), and on average larger dots (gray bar, Panel D). The opposite is true for the other half of the trials (dark bars).

interaction, we compared performance across tasks and between congruency conditions using Bonferroni corrected paired-samples *t* tests.

## Results

The analyses revealed a main effect of task, $F(3, 72) = 10.6$, $p < .001$, $\eta_p^2 = .3$, and congruency, $F(1, 24) = 10.5$, $p = .003$, $\eta_p^2 = .3$, as well as an interaction between task and congruency, $F(3, 72) = 27.9$, $p < .001$, $\eta_p^2 = .5$. The interaction was the result of poorer performance in the partial congruent compared with the fully congruent, $t(24) = 3.23$, $p = .024$; the convex hull, $t(24) = -5.6$, $p < .01$; and the diameter tasks, $t(24) = -4.2$, $p < .01$ (see Figure 3A), implicating that performance is dependent on how the nonsymbolic stimulus is created (i.e., through which combination of visual characteristics).

We also compared the different congruency conditions for each task separately using Bonferroni corrected paired-samples *t* tests. Except for the full congruent task, $t(24) = 0.8$, $p = .44$, Cohen's $d = 0.33$, a significant congruency effect was present for the convex hull, $t(24) = -7.7$, $p < .01$, Cohen's $d = -3.14$; the diameter, $t(24) = 4.3$, $p < .01$, Cohen's $d = 1.76$; and the partial congruent tasks, $t(24) = -6.9$, $p < .01$, Cohen's $d = -2.81$ (see Figure 3B). It is interesting that the congruency effects were not all in the same direction (see Figure 3B, c1 vs. c2 and c4). Participants were more accurate when the more numerous array had a larger convex hull (see Figure 3B, c1) but a smaller average diameter aggregate surface and was less dense (see Figure 3B, c2). The partial congruent task (see Figure 3B, c4) consisted exactly of this combination of visual cues. In this case, the congruency effect was

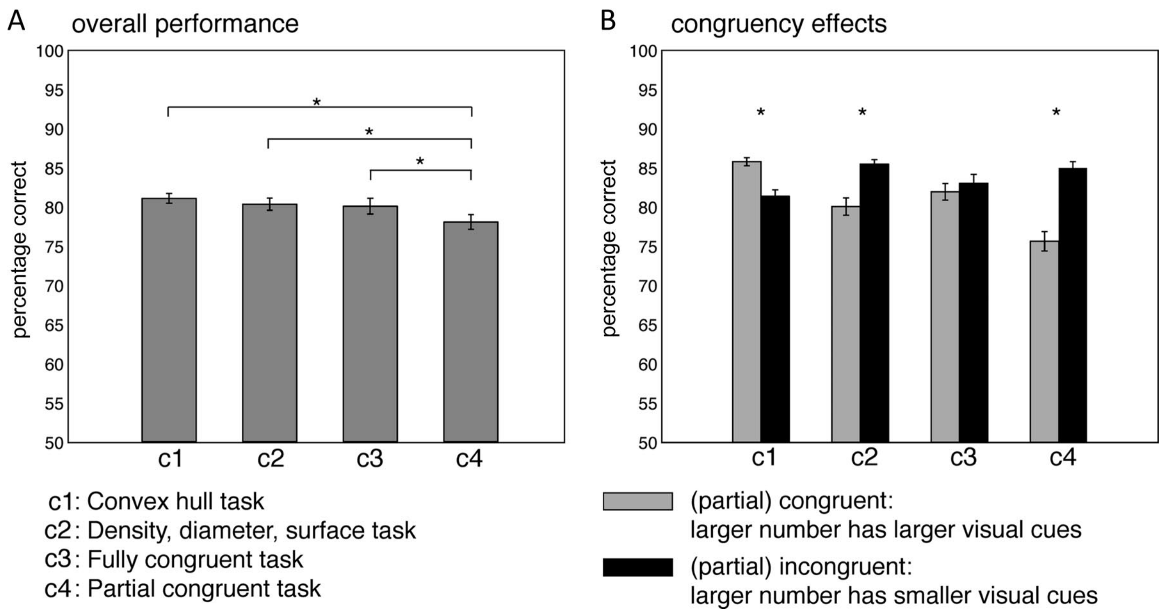


*Figure 3.* Behavioral results. In the left panel, the overall congruency effect is presented. Participants performed worse in the partial congruent task (c4) compared with the other three tasks. In the right panel, performance per congruency condition is shown. No congruency effect is present for the fully congruent task (c3). Furthermore, a significantly larger congruency effect is present in the partial congruent (c4) compared with the convex hull (c1) and the diameter tasks (c2). Note that the black and gray bars in this figure correspond to the black and gray bars of Figure 2. For example, the gray bar of Task c3 represents the trials where the larger number had a larger convex hull, was denser, had a larger aggregate surface, and had a larger average diameter. The asterisks indicate significant results ($p < .05$).

significantly larger compared with the convex hull, $t(24) = 3.7$, $p < .01$, Cohen's $d = 1.51$, and the diameter tasks, $t(24) = 2.8$, $p < .05$, Cohen's $d = 1.14$.

## Discussion

In the current study, we investigated the interplay between perceived number and visual properties by using four nonsymbolic number tasks. Overall, performance showed that participants were less accurate on the partial congruent task compared with the other three tasks. This result cannot be attributed to numerical difficulty: All four tasks consisted of the same number ratio conditions. Consequently, the difference in performance can only be attributed to the different combinations of visual cues. This is a striking result, as each visual cue was not informative about number, nor did the difference in visual cues correlate with number distance in any of the four tasks. To gain further insight into the interaction between the visual cues and performance, we investigated the congruency effects. In the convex hull task, performance was more accurate when the dots were spread over a larger area (remaining cues were equated). Similarly, in the diameter task, participants were more accurate when the larger number had a smaller average diameter, a smaller aggregate surface, and lower density (convex hull was equated). In these conditions, only a single cue or a subset of visual cues was manipulated, but when we combined both parameters (convex hull and diameter), as was the case in the fully congruent condition, the congruency effect diminished. Apparently, the opposite congruency effects in the convex hull and the diameter tasks canceled each other out. In contrast, combining both in opposite directions, as was the case in the partial congruent task, resulted in an increased congruency effect. These results suggest that people do not process number independent of the visual cues, nor do they attend a single cue, but they do integrate multiple visual cues. Consequently, current methods that only control a single visual parameter at the time are insufficient (e.g., if diameter is equated, aggregate surface will be used), and results from studies that used these methods should be interpreted with caution.

Our results not only reveal caveats in current research designs but can also explain discrepancies in the literature. For instance, some studies reported that participants associate larger dots with a larger number (Gebuis, Kenemans, de Haan, & van der Smagt, 2010; Hurewitz, Gillman, & Schnitzer, 2006; Rousselle & Noel, 2008; Soltesz, Szucs, & Szucs, 2010), whereas others reported the opposite pattern (Gebuis & Van der Smagt, in press; Ginsburg & Nicholls, 1988; Miller & Baker, 1968; Sophian, 2007). This discrepancy can easily be explained if number judgments are based on weighing multiple visual cues. Differences in the weights given to each variable could already change the direction of the congruency effect. Consider, for instance, the results of our fully congruent task, where the effects of convex hull and diameter canceled each other out. If convex hull had been more pronounced, its weight would have been stronger (than that of diameter). Now performance would be better for trials with dot arrays that have a larger convex hull (and larger dots). Although the effect is solely attributable to the stronger weight given to the convex hull, we would (incorrectly) interpret that stimuli with larger dots are considered more numerous.[1]

The result that people do not extract number independent of the visual cues but instead weigh the different visual cues is not surprising, given the strong relation between number and visual cues in daily life. If you are presented with two bags of apples and have to judge which bag contains more apples, you will simply choose the one that is larger in size. Or, if you have to decide which train compartment to enter, you will choose the one that looks less dense. In neither of these occasions would you estimate the number of apples or fellow travelers and compare the two estimates. As people can compare number on the basis of visual cues, it would be very inefficient if the brain did not rely on the visual system when judging number. The (approximate) number system is frequently suggested to be an evolutionary ancient system with which people are equipped at birth. If this is indeed the case, it should be a fairly efficient system. But then why would the brain develop a neural mechanism that is capable of extracting number independent of visual cues when these two are rarely confounded in real life? Indeed, why would people create such a mechanism at all, as relying on visual cues not only suffices but is often more accurate? For instance, when visual cues are controlled, participants can dissociate numbers differing with a ratio of 6:7 (Piazza et al., 2004), but when visual cues are not controlled, performance increases to a ratio of 7:8 (van Oeffelen & Vos, 1982).

To oppose our theory, one could argue that visual cues are only useful when people have to make size judgments but are not useful in number estimation tasks. People's very poor ability to estimate number (Izard & Dehaene, 2008) already suggests that if a separate approximate number system is present, it is not a very good one. Furthermore, when considering tribes where exact (symbolic) number processing is not yet introduced, people differentiate 1, 2, and sometimes 3, as well as *few* and *many* (Butterworth, Reeve, Reynolds, & Lloyd, 2008; Gordon, 2004). For these people, who only work with nonsymbolic number, it suffices to dissociate *small* and *large*. How much *large* is exactly is irrelevant to them. Exact large numbers were only introduced when the symbolic number system was developed, a system that is invented by humans. Processes underlying estimates of large nonsymbolic numbers are thus unlikely to be evolutionary ancient.

In sum, our results suggest that the current designs to control visual cues in number approximation studies do not suffice. We showed that people integrate different visual variables when deciding which array contains more dots. This, together with the strong relation between number and visual cues in daily life, suggests that it is unlikely that a special mechanism exists that can process nonsymbolic number independent of its visual cues. However, more evidence is needed to fully support our theory.

[1] Note that if the congruency effect is a combination of weights given to multiple visual cues, the direction of congruency effect does not give us insight in a possible intrinsic association between number and a visual cue. For instance, we cannot infer from our congruency effect in the diameter task that participants are biased toward thinking that dot arrays with smaller dots are more numerous.

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