Mixing Words and Pictures:
Mixed Evidence for Common Conceptual Representations

Hyekyung Park (hyekpark@iu.edu)
Department of Psychological and Brain Sciences, 1101 E 10th Street
Bloomington, IN 47405 USA

John E. Opfer (opfer.7@osu.edu)
Department of Psychology, 1835 Neil Avenue
Columbus, OH 43210 USA

Abstract

The relationship between symbolic and nonsymbolic representation has been a subject of long-standing debate, with the common system model and the separate systems model providing contrasting predictions. To test these models, we asked participants to compare the size of animals or numerical value of numbers, presented in symbolic-symbolic, symbolic-nonsymbolic, and nonsymbolic-nonsymbolic formats. Consistent with the common system model, performance improved as the ratio between stimuli increased in both animal and number domains, regardless of the format. However, supporting the separate systems model, we observed a switch cost in the symbolic-nonsymbolic number comparison task. Future research should explore the factors contributing to these mixed findings across domains.

Keywords: symbolic representation; analog magnitude system; ratio effect; switch cost; magnitude comparison

Introduction

How symbolic and non-symbolic information is represented in memory is a matter of classic and contemporaneous debate. The classic debate pits two models that purported to explain how we process concrete information. One is the common coding model proposed by Potter and Faulconer (1975). It suggests words and images share a single, amodal system. In support of this model, Potter and Faulconer (1975) replaced sentence words with pictures, and they found no difference in the comprehension compared to words alone. These findings suggest pictures and words tap a common amodal concept.

Alternatively, a dual-coding model proposed functionally independent systems for verbal and nonverbal information. In this view, images and words are processed by separate systems (Clark, 1987; Clark & Paivio, 1991; Paivio, 1991). Evidence for this approach comes from Paivio (1975) who showed that participants had difficulty comparing size when physical size of the pictures was incongruent with the actual size of the stimuli (i.e., a picture of a lamp was larger than a picture of a zebra). In contrast, participants were not affected by the incongruency when words were presented in incongruent sizes (i.e., the word “LAMP” was larger than the word “ZEBRA”).

A similar but more recent debate has arisen regarding the relation between symbolic and nonsymbolic representations of numbers. Like Potter’s common coding model, Dehaene (2011)’s triple-code model has a common code - analog magnitude system - that processes both symbolic numerals and non-symbolic quantities, like the number of objects. The triple-code model proposes that we learn symbolic numeral meanings by connecting them to analog magnitudes (Gilmore, McCarthy, & Spelke, 2010; Halberda, Mazzocco, & Feigenson, 2008; Mundy & Gilmore, 2009). The analog magnitude system encodes numerical information on a logarithmic scale with internal noise. Because of this approximate representation of numbers, the overlap in noise between successive numbers also increases. As a result, one key characteristic of analog magnitudes is their sensitivity to numerical ratios. That is, discrimination between quantities depends on their ratio. For instance, comparing 4 and 8 (a ratio of 2) is easier than comparing 4 and 6 (a ratio of 1.5). Consequently, studies investigating the link between symbolic numerals and non-symbolic quantities often examine this ratio effect. Zhang, Ma, and Zhou (2022), for example, demonstrated that comparing number of dots or symbolic numerals improves as the ratio between them increases. The ratio effect has been replicated in numerous studies (Moyer & Landauer, 1967; Fazio, Bailey, Thompson, & Siegler, 2014; Sasanguie, De Smedt, Defever, & Reynvoet, 2012), supporting the common system view of the number representation.

Similar to Paivio’s dual-coding model, researchers have also proposed that numerical symbols are estranged from the quantities they represent and are processed by a system distinct from the analog magnitude system (Lyons, Ansari, & Beilock, 2012; Lyons & Ansari, 2015; Marinova, Sasanguie, & Reynvoet, 2018). The separate systems model argues that symbolic numerals are processed exactly, rather than approximately, and processing symbolic numerals does not involve representing the corresponding quantities. This view has been examined by focusing on the switch cost between different formats of numbers. Lyons et al. (2012) asked participants to compare the number of dots in two dot arrays (nonsymbolic condition), the numerical values of two Arabic numerals (symbolic condition), or compare one Arabic numeral with one dot array (mixed condition). Participants responded faster in the symbolic condition than in the nonsymbolic condition. More importantly, reaction times were longer in the mixed condition than in the nonsymbolic condition. The researchers argued that if symbolic and nonsymbolic numbers are processed by a common system, participants should have responded faster in the mixed condition than in the non-

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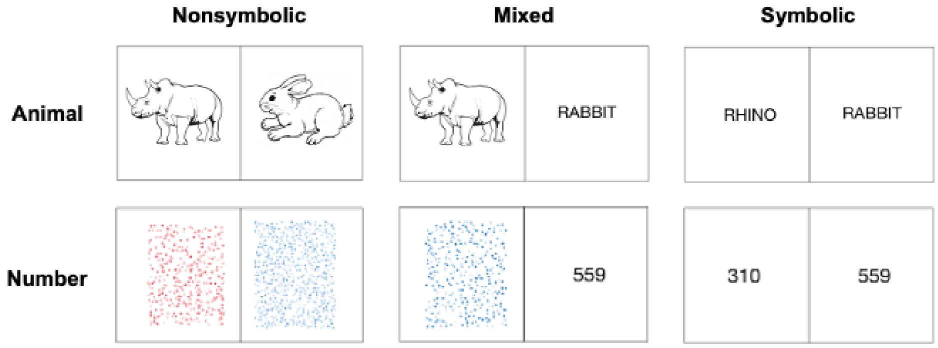

Figure 1: Sample stimuli of the animal size comparison tasks and the number comparison tasks.

symbolic condition. The observed worse performance in the mixed format comparison task has been thought to be caused by the switch cost between separate systems for symbolic and nonsymbolic numbers.

Present study

The present study extended the debates between the common system and separate systems approaches across animal and number domains. By asking participants to compare either the size of animals or the numerical value of numbers, we examined whether the relationship between symbolic (verbal) and nonsymbolic (nonverbal) representations differs between continuous magnitude (size) and discrete magnitude (numerical value). We focused on the animal domain for continuous magnitude, as previous studies on different types of magnitude representations have widely investigated either the number or animal domain (Moyer, 1973; Paivio, 1975; Rubinsten & Henik, 2002; Gliksman, Itamar, Leibovich, Melman, & Henik, 2016).

Previous studies have shown similarities between animal size comparison and number comparison. Comparing animal size was affected by the ratio of the animals' actual sizes, regardless of whether the animals were presented in words or pictures. For example, comparing "RAT" and "CAT" took longer than comparing "RAT" and "ELK" (Moyer, 1973; Paivio, 1975; Rubinsten & Henik, 2002; Paivio, 1975). Furthermore, our preliminary analyses examining the relationship between the animals' actual sizes (Wilson, 2017) and the size ratings of animals from Paivio (1975) showed that animal size is represented logarithmically. Participants tended to overestimate the difference between smaller animals and underestimate the difference between larger animals. Studies on numerosity representation using number line estimation tasks have shown a similar logarithmic pattern (Kim & Opfer, 2018). Nevertheless, the similarities between animal size and number representations do not necessarily imply that the relation between symbolic and nonsymbolic representations can be generalized across domains. Number is a discrete magnitude whereas size is a continuous magnitude. Due to this difference in discreteness, symbols may play a different role depending on the type of magnitudes.

Most previous studies on animal size and number focused only on symbolic comparison or nonsymbolic comparison. We propose that mixed format comparison provides more direct evidence that can distinguish the common system approach versus the separate systems approach. We focused on two measurements: ratio effect and switch cost. We hypothesized that the ratio effect in the mixed format comparison provides the evidence for the common system account. In the present study, the ratio effect was examined by testing if performance improved with the ratio between magnitudes. The ratio effect suggests that different formats of magnitudes are compared along a common continuum, reflecting a mental association between symbolic and nonsymbolic information (Carey, Shusterman, Haward, & Distefano, 2017; Piazza, Pinel, Le Bihan, & Dehaene, 2007). We also examined the switch cost in the mixed format comparison, which suggests that symbolic and nonsymbolic information may be processed by separate systems (Lyons et al., 2012; Marinova et al., 2018). We defined the switch cost as the worse performance observed in the mixed format comparison task relative to the symbolic or nonsymbolic comparison tasks. By focusing on the mixed format comparison, we aim to bridge the gap between the common system and separate systems model.

Methods

Participants

We tested 39 undergraduate students (*M* = 20.02 years, *SD* = 2.05 years, 18.26 years - 27 years). Participants received course credit for their participation.

Materials and Procedure

The experiment was conducted on a 13-inch laptop, using a MATLAB program. Participants completed the animal size comparison task and the number comparison task (Figure 1). Two stimuli were presented on each side of the screen simultaneously for 1500ms after fixation. Participants were asked to press 'Q' if they thought the left stimulus was larger and 'P' if they thought the right stimulus was larger. Participants were instructed to respond as quickly and as accurately as possible, and they could respond while the stimuli were on the screen. Reaction times and accuracy were recorded.

Two comparison tasks included three conditions: nonsymbolic condition, symbolic condition, and mixed condition. In the nonsymbolic condition, two line drawings of animals were presented for the animal size comparison task. The physical size of the animal drawings was equated regardless of the actual size of the animals. For the number comparison task, two sets of dots were presented. Total surface areas of the dot arrays and convex hull were equated between dot arrays. Size of dots varied within each dot array. The position and the size of each dot were chosen randomly. In the symbolic condition, animal labels were presented for the animal size comparison. Arabic numerals were presented for the number comparison. The size of words and Arabic numerals were equated across trials. These manipulations controlled for magnitude judgment being made based on the physical properties of the stimuli. In the mixed condition, one stimulus was presented in a symbolic format while the other was presented in a nonsymbolic format. The side (left or right) containing the nonsymbolic stimulus was counterbalanced. Participants were instructed to judge the magnitude represented by the stimuli, rather than their physical size.

There were 14 stimuli in each domain (animal: dove, squirrel, rabbit, skunk, goose, raccoon, fox, leopard, lion, zebra, moose, bear, rhino, and elephant; number: 251, 261, 306, 310, 353, 367, 398, 559, 616, 622, 706, 737, 776, and 835). Both sets of stimuli were from Paivio (1975) in which participants were asked to rate the size of the animals from 1 to 9. Among the animal items of this study, we selected the stimuli based on the size ratings that correctly preserved ordinal size of the animals. For the number stimuli, we multiplied 100 by the means of the size ratings of the corresponding animals. By doing so, we increased the probability of equally accurate pairwise comparisons for animals and numbers.

All possible pairs within the domain were presented. There were 91 trials in each condition, total of 546 trials. The orders of domain and condition were counterbalanced separately. We counterbalanced the order of domains. Within the domain, the order of conditions was counterbalanced. Across domains, the order of conditions was equated. Instructions were given at the beginning of each condition. Participants completed the tasks without any feedback.

Results

Responses that took longer than 3 *SD*s from the mean reaction times for each domain and RTs shorter than 200ms were excluded. Excluding outliers yielded 97.97% of the animal domain data and 97.83% of the number domain data. For analyses, we fitted a linear multilevel regression model (Gelman & Hill, 2006) with random intercepts by subject using lme4 package in R. Reaction times (RT) of correct responses were analyzed using a mixed linear model. Accuracy was analyzed using a generalized mixed linear model with logit link.

The ratio for each stimulus pair was calculated by dividing the larger value by the smaller value. The values of the animal size were from the size ratings in Paivio (1975). The ratios tested in the animal and number domains were equal. There were 89 ratios ranging from 1.01 to 3.33.

We analyzed the effects of domain (animal, number), ratio (1.01 to 3.33), and their interaction on RT and accuracy. Comparing numbers was faster, $\beta = -.32, SE = .01, p < .001$, and less accurate, $\beta = -.46, SE = .06, p < .001$, than comparing animal sizes. The interaction between domain and ratio showed that the ratio effect was smaller in the number domain than in the animal domain for both RT, $\beta = .04, SE = .01, p < .01$, and accuracy, $\beta = -.51, SE = .07, p < .001$. We next examined the ratio effect and the switch cost of the mixed condition separately for each domain to investigate the relation between symbolic and nonsymbolic representations.

Animal Domain

We analyzed the effect of condition (nonsymbolic, symbolic, mixed) and ratio (1.01 to 3.33), and their interaction on RT and accuracy. Since the results did not change after controlling for the length of the words, we report the results of the model that does not include word length as a predictor. After fitting a linear multilevel regression model, the significance of the fixed effects was determined using the *Anova* function from the *car* package, using a Type III ANOVA. Post hoc comparisons were performed using the *emmeans* and *emtrends* functions from the *emmeans* package.

We first analyzed the effect of condition, ratio, and their interaction on RT. The main effects of condition, $\chi^2(2) = 916.02, p < .001$, ratio, $\chi^2(1) = 359.03, p < .001$, and their interaction, $\chi^2(2) = 10.51, p < .01$, were significant. RT was shortest in the nonsymbolic condition (846ms), followed by the mixed condition (996ms, z-score = 21.92, $p < .001$) and the symbolic condition (1045ms, z-score = 6.94, $p < .001$) (Figure 2A). The switch cost was not observed when comparing different formats of animal size. The ratio effect was significant in the nonsymbolic condition, z-score = -18.95, $p < .001$, mixed condition, z-score = -14.01, $p < .001$, and symbolic condition, z-score = -15.58, $p < .001$ (Figure 3A). The ratio effect in the mixed condition indicates that different formats of animal size were represented by a common system.

The results were replicated when we analyzed accuracy. The main effects of condition, $\chi^2(2) = 66.25, p < .001$, ratio, $\chi^2(1) = 252.12, p < .001$, and their interaction, $\chi^2(2) = 49.44, p < .001$, were significant. Accuracy was highest in the nonsymbolic condition (0.97), followed by the mixed condition (0.93, z-score = -6.30, $p < .001$), and the symbolic condition (0.90, z-score = -2.45, $p < .05$) (Figure 2B). The ratio effect was significant in the nonsymbolic condition, z-score = 14.31, $p < .001$, mixed condition, z-score = 15.88, $p < .001$, and symbolic condition, z-score = 14.21, $p < .001$ (Figure 3A). Overall, the results from the animal domain supported the common system approach.

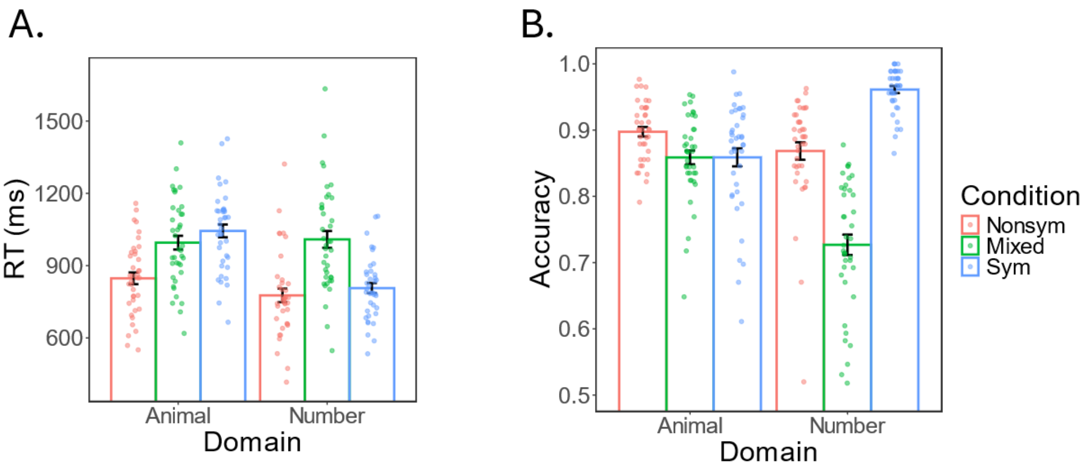

Figure 2: A. RT and B. Accuracy by domain and condition. Bar graph represents mean performance.

Number Domain

We first analyzed the effects of condition (nonsymbolic, symbolic, mixed) and ratio (1.01 to 3.33), and their interaction on RT. The main effects of condition, $\chi^2(2) = 1311.26, p < .001$, and ratio, $\chi^2(1) = 594.09, p < .001$, and their interaction effect, $\chi^2(2) = 151.91, p < .001$, were significant. RT was shortest in the nonsymbolic condition (779ms), followed by the symbolic condition (801ms, z-score = 3.29, $p < .01$) and the mixed condition (1020ms, z-score = 30.80, $p < .001$) (Figure 2A). Unlike in the animal domain, the switch cost was significant in the number domain. The ratio effect was significant in the nonsymbolic condition, z-score = -24.37, $p < .001$, symbolic condition, z-score = -11.60, $p < .001$, and mixed condition, z-score = -7.05, $p < .001$ (Figure 3B).

The results were replicated when accuracy was analyzed. The main effects of condition, $\chi^2(2) = 511.70, p < .001$, and ratio, $\chi^2(1) = 252.88, p < .001$, and their interaction, $\chi^2(2) = 76.40, p < .001$, were significant. Accuracy was highest in the symbolic condition (0.98), followed by the nonsymbolic condition (0.95, z-score = -4.92, $p < .001$), and the mixed condition (0.76, z-score = -14.85, $p < .001$) (Figure 2B). The ratio effect was significant in the symbolic condition, z-score = 7.18, $p < .001$, nonsymbolic condition, z-score = 15.90, $p < .001$, and mixed condition, z-score = 15.52, $p < .001$ (Figure 3B). Consistent with the common system model, we observed the ratio effect in the mixed condition. Consistent with the separate systems model, we observed the switch cost.

Given the mixed results in the number domain, we examined whether the advantage of symbolic numerals is affected by ratio. According to the separate systems model of number representation, symbolic numerals are processed by the exact system. This model predicts that comparing symbolic numerals would be faster and more accurate than comparing nonsymbolic numerosities, regardless of the ratio. However, our results showed that as the ratio increased, the nonsymbolic comparison (95% CI[599.47, 691.35] at a ratio of 2.5) became faster than the symbolic comparison (95% CI[694.46, 788.44] at a ratio of 2.5).

Discussion

The present study explored the mental structures of symbolic and nonsymbolic representations. We compared the animal and number domains to explore whether different formats of magnitudes are processed by a common system, and whether the findings can be generalized across different magnitudes. A novel feature of our study was to investigate the mixed format comparison which could provide direct evidence for either a common system or separate systems models. To test the common system model, we examined the ratio effect. To test the separate systems model, we examined the switch cost.

The ratio effect supported the common system approach in both animal and number domains. Performance improved as the ratio increased when comparing different formats of animal size or numerical magnitude. However, the switch cost provided mixed evidence. Consistent with the common system approach, we did not find the switch cost in the animal domain. Comparing different formats of animal size was faster and more accurate than comparing symbolic format of animal size. In contrast, consistent with the separate systems approach, we found the switch cost in the number domain. Comparing different formats of numerical magnitude took longer and less accurate than comparing same format of numerical magnitude.

The results in the animal domain suggest that both verbal and nonverbal information about animal size is processed within a common system. In the number domain, however, it remains unclear whether symbolic (e.g., numerals) and nonsymbolic (e.g., dot arrays) formats are processed by a common system. Nevertheless, the ratio effect observed in our findings provides the evidence that numbers are represented approximately by the analog magnitude system regardless of format. One possible explanation for the differences be-

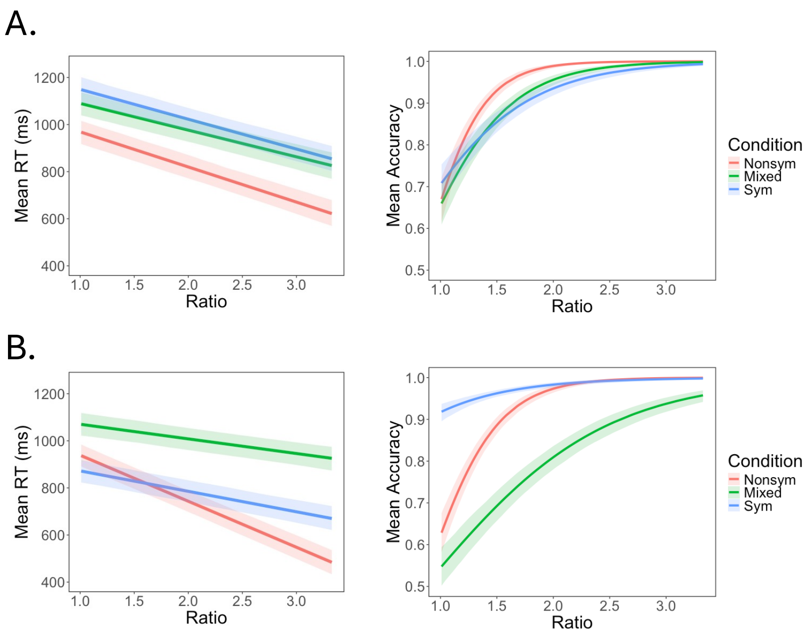

Figure 3: Ratio effects by condition in A. the animal domain and B. the number domain. Solid lines with 95% confidence intervals represent mean performance generated from 1000 simulations of the fitted model.

tween domains is that symbolic and nonsymbolic information is represented by a common system, but the way of accessing the common system may differ depending on the domain. Accessing animal size information through symbolic format may involve additional processes such as converting symbols into nonsymbolic format. In contrast, symbolic numerals may be represented more directly by the common system without additional processes.

If different formats of numbers are represented by the common system, then the switch cost might be due to the difference in representational noise between formats, which drives ratio effect. Our results showed a stronger interaction between ratio and format in the number domain (RT: $\chi^2(2) = 151.91$; Accuracy: $\chi^2(2) = 76.40$) than in the animal domain (RT: $\chi^2(2) = 10.51$; Accuracy: $\chi^2(2) = 49.44$). This suggests that the effect of format on representational noise is greater for numbers than for animal size. Consequently, when comparing different formats of numbers, participants may need to account for differences in representational noise, which could require additional cognitive processing. For example, comparing a symbolic numeral to a dot array might be analogous to comparing a regularly aligned dots to randomly scattered dots. If so, the switch cost observed in the number domain may reflect the cognitive process of calibrating differences in representational noise, rather than switching between separate systems. This possibility is supported by the results demonstrating that the advantage of symbolic numerals was more evident at smaller ratios, but was reduced as the ratio increased. If symbolic numerals were processed by a distinct system from nonsymbolic numerosities, the symbolic comparison should have outperformed the nonsymbolic comparison regardless of the ratio. Future research could test this possibility by directly manipulating the noise in dot arrays or by studying children whose symbolic number representations are as noisy as nonsymbolic representations.

Although similar debates about the mental representation of magnitudes exist across various domains, few studies have directly compared multiple domains using measures that clearly distinguish between competing theoretical accounts. The mixed findings of the present study make it challenging to determine whether a common system or separate systems account better explain the structure of mental representations. Nevertheless, more fine-grained analyses of the ratio effect suggest that a common underlying mechanism may process both symbolic and nonsymbolic information. While the current study focused on different types of magnitude representation, future studies could extend beyond the domain of magnitude, given that symbols can facilitate learning by efficiently conveying nonsymbolic information. Continued research on the relationship between symbolic and nonsymbolic representations will shed light on how we form fundamental concepts.

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