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Dissecting the symbolic distance effect: Comparison and priming effects in numerical and nonnumerical orders

Filip Van Opstal, Wim Gevers, Wendy De Moor, and Tom Verguts
Ghent University, Ghent, Belgium

When participants are asked to compare two stimuli, responses are slower for stimuli close to each other on the relevant dimension than for stimuli further apart. Previously, it has been proposed that this comparison distance effect originates from overlap in the representation of the stimuli. This idea is generally accepted in numerical cognition, where it is assumed that representational overlap of numbers on a mental number line accounts for the effect (e.g., Cohen Kadosh et al., 2005). In contrast, others have emphasized the role of response-related processes to explain the comparison distance effect (e.g., Banks, 1977). In the present study, numbers and letters are used to show that the comparison distance effect can be dissociated from a more direct behavioral signature of representational overlap, the priming distance effect. The implication is that a comparison distance effect does not imply representational overlap. An interpretation is given in terms of a recently proposed model of quantity comparison (Verguts, Fias, & Stevens, 2005).

The distance effect in number comparison (Moyer & Landauer, 1967; we will call this the *comparison distance effect*) is a classical finding in numerical cognition research. It indicates that discriminating two numbers that are numerically far apart is easier than discriminating numbers that are numerically close.

Since Restle (1970) proposed that this distance effect in number comparison is due to the placement of numbers on an analogue continuum, it has been an influential view in numerical cognition (e.g., Gallistel & Gelman, 1992). In this view, numbers are represented as a mental number line with small numbers on the left and large numbers on the right (e.g., Dehaene, Bossini, & Giraux, 1993). The subjective location of a number is then represented as a distribution around the true location of that number on the line. These distributions overlap more for numbers that are numerically close. The difficulty of discriminating two numbers is thus a function of the distributional overlap of their representations (e.g., Cohen Kadosh et al., 2005; Kaufmann et al., 2005; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004; Turconi, Campbell, & Seron, 2006). This view on the comparison distance effect will be called the *representational overlap view*.

Other domains exhibiting a comparison distance effect include comparing the size of animals (Paivio, 1975), geographical locations (Maki, 1981), letters of the alphabet (Jou & Aldridge, 1999), and the hierarchical order of social status (Chiao, Bordeaux, & Ambady, 2004). It has been suggested that the representational overlap view can be applied to nonnumerical stimuli also, in the sense that they are represented on a spatial continuum (Jou & Aldridge, 1999) similar to the mental number line (Chiao et al., 2004).

In contrast to the representational overlap view, others have stressed the role of response-related processes for the comparison distance effect (e.g., Banks, 1977; Holyoak & Patterson, 1981; Shaki, Leth-Steensen, & Petrusic, 2006). Recent implementations of this idea appear in neural network models of number processing (Verguts, Fias, & Stevens, 2005) and of order processing more generally (Leth-Steensen & Marley, 2000). To explain this, consider the number comparison model of Verguts et al. If the task is to choose the larger of two numbers, it has two output nodes, *left larger* and *right larger*, and the model is required to activate the correct output node. The model is trained to adapt its weights to solve the task. After training, large numbers on the left input layer have strong connections with the left larger output. The right input layer obtains the reversed pattern: Large numbers on the right input layer have weak connections to the left larger output. Connection patterns from the left and right input layers to the left larger output node thus show a monotonic increase or decrease. When the task is to compare a target number with a fixed standard number, the standard can be assumed to function as one of the numbers (e.g., the left number), the target as the other one (e.g., the right number), and the output nodes can be labeled accordingly *target smaller than standard* and *target larger than standard*. Except for this change in labels, the architecture and the weights of the model remain unchanged (Figure 1A): Large numbers on the target input layer have strong connections

F. Van Opstal, filip.vanopstal@ugent.be

with the *target larger than standard* output (right inset, Figure 1A), whereas the standard input layer obtains the reversed pattern (left inset, Figure 1A). On each trial, the standard number is presented on the standard input layer and the target number on the target input layer. Hence, if the model is given a large target number (e.g., 9) and a small standard (e.g., 2), the combined activation going to the *target larger than standard* output node is very large. On the other hand, a large target number combined with a standard number of average magnitude (e.g., 5) propagates a smaller amount of activation to the *target larger than standard* output node, because the connection strength from the standard input to the output node is smaller. The monotonic connection weights thus lead to the comparison distance effect: As the stimuli are further apart, the activation of the correct output node increases, decreasing response time (RT). Importantly, monotonic weight patterns naturally develop in networks trained to compare two stimuli, independently of stimulus type (e.g., Leth-Steensen & Marley, 2000). We will call the view that the comparison distance effect originates from monotonicity in weight patterns the *monotonic connection view*.

The two opposing views on the origin of the comparison distance effect can be tested with a different effect, the priming distance effect. In a number-priming experiment, participants have to judge whether a target number that is preceded by a prime number is smaller or larger than a standard (e.g., 5). The priming distance effect is the finding that when a target number is preceded by a prime number, participants respond more quickly when the prime–target numerical distance is smaller (e.g., Dehaene et al., 1998). This effect is explained by representational overlap between the prime and the target: Presenting a number activates the memory representation of the number itself, but also that of numbers numerically close to it, according to a Gaussian function (see the target input layer in Figure 1A): If 8 is presented as a prime, the node for the number 9 is primed more than it would be if the prime were 4 (similar to a popular conceptualization of semantic priming in psycholinguistics; see, e.g., Masson, 1995). Unlike the comparison distance effect, the priming distance effect cannot be explained by monotonic weight patterns: Representational overlap is necessary to allow the prime to evoke activation of the target representation to shorten RTs. The monotonic connection view itself makes no predictions concerning the priming distance effect.

The priming distance effect is important for the present purpose because it results from the same mechanism

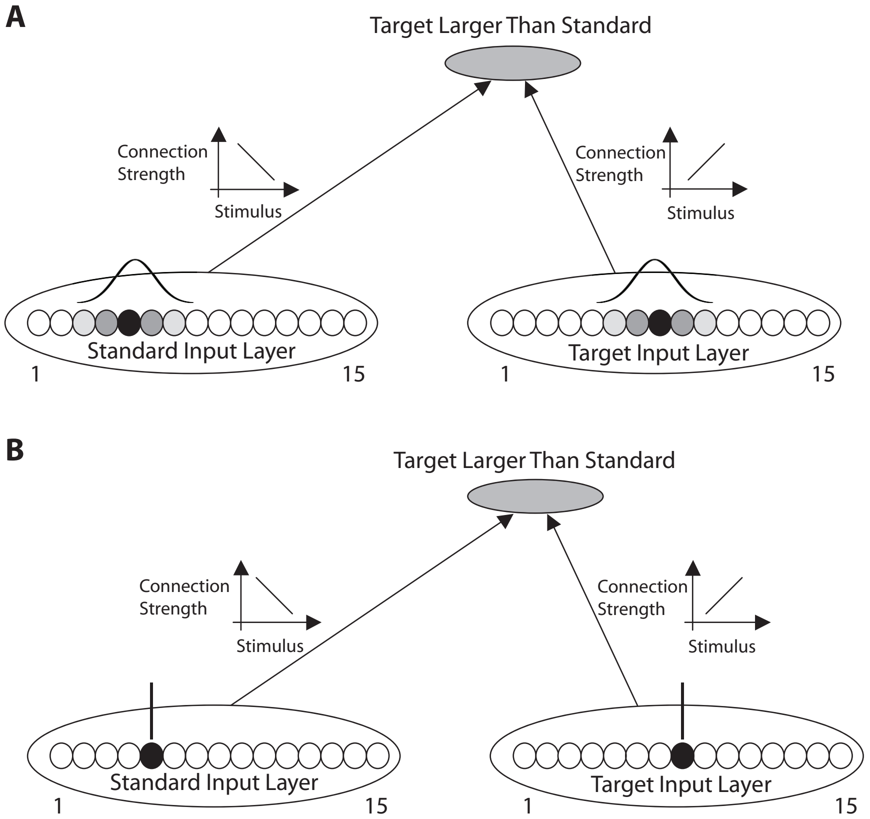

Figure 1. Outline of part of the Verguts, Fias, and Stevens (2005) number comparison model. For simplicity only the *target number larger* output node is shown. Connections to the *standard number larger* output node (or equivalently, *target number smaller*) exhibit the reversed pattern. (A) Model for the number task with representational overlap of the inputs, as indicated by the Gaussian activation function. (B) Model for the letter task: The activation is restricted to a single node (i.e., there is no representational overlap).

as the comparison distance effect according to the representational overlap view, but from a different mechanism according to the monotonic connection view. For example, the Verguts et al. (2005) model, as an instantiation of the monotonic connection view, does not deny the existence of overlapping representations of numbers (cf. Figure 1A) or its causal role in accounting for the priming distance effect; it denies only that the mental number line accounts for the comparison distance effect. Thus, according to the representational overlap view, the presence of a comparison distance effect implies a priming distance effect, whereas the monotonic connection view allows a dissociation between the comparison distance effect and the priming distance effect. To procure this dissociation, we chose letters as stimuli. The alphabet is a highly practiced linear order, and letters form an important part of our memory. The fact that we can recite the alphabet does not in itself imply representational overlap; reciting the alphabet constitutes a type of rote verbal knowledge unrelated to (number or letter) semantic processing. In fact, at least in the number domain, a double dissociation between rote verbal knowledge and semantic processing has been reported (Dehaene & Cohen, 1997).

In the present study, both letter and number stimuli were used in a priming experiment. We expected both a comparison distance effect and a priming distance effect in the number stimuli. A dissociation between the two effects in the letter stimuli is possible according to the monotonic connection view, whereas the representational overlap view does not allow a dissociation.

EXPERIMENT 1

Method

Participants. Twenty-three students at Ghent University (age, 18–23 years, 3 of them male) participated for course credit. None was aware of the purpose of the experiment.

Apparatus and Stimuli. A response box was connected to a Pentium 4, 2.8-GHz computer. Stimuli were presented in white on a black background (Courier 32 font), synchronized with the refresh rate (16.67 msec). The task was to compare a target letter or number with a fixed standard. Primes and targets in the number task were the numbers from 1 to 9, except 5, resulting in 64 different prime–target combinations. Serial position effects were minimized by choosing letters from the middle of the alphabet for the letter task (Jou & Aldridge, 1999). Primes and targets were the letters J to R (with standard N) presented in uppercase. Each trial started with a fixation cross (+; 500 msec), followed by a premask (###; 100 msec), a prime (83 msec), a postmask (###; 100 msec), and a target presented until response. The response–stimulus interval was 1,000 msec.

Procedure. The participants took part in two sessions (on 2 consecutive days). Half of the participants performed the number task in the first session and the letter task in the second session; the other half, vice versa.

A practice block of 8 trials with feedback on accuracy and RTs preceded two experimental blocks of 320 trials each. One session (648 trials) lasted about 35 min. Half of the group performing the number task in the first session pressed the left button as quickly as possible when the target was smaller than 5 and the right button when the target was larger than 5. The other half had the reversed mapping. The participants in the letter task were counterbalanced similarly. Half of the participants of each group changed response mappings between sessions. The participants were instructed to respond only to the target and to categorize the target as smaller or larger than the standard in the number task and as coming before or after the standard in the alphabet in the letter task.

Results and Discussion

One participant failed to comply with task instructions and was excluded. One participant was excluded because of exceptionally large RTs [>(median + 7*SD*)]. The mean error rate was 6.9%.[1]

Comparison distance effect. Figure 2A shows a comparison distance effect in both tasks: RTs decreased when the distance between the standard and the target increased. This was confirmed by a 2 (task: letter/number) × 2 (size: before/after the standard) × 4 (comparison distance: 1, 2, 3, or 4) within-subjects ANOVA on median correct RTs. To exclude a confound with priming distance, only trials on which the prime and the target were identical were used in this analysis. There was a significant main effect of task [$F(1,20) = 98.56$, $MS_e = 6{,}628$, $p < .001$] and of comparison distance [$F(3,60) = 12.33$, $MS_e = 1{,}680$, $p < .001$]: RTs were smaller on large-distance trials than on small-distance trials. The interactions between task and comparison distance, between size and comparison distance, and the three-way interaction were also significant (all *p*s < .05). Importantly, planned trend analyses showed significant linear effects of comparison distance in both the letter and the number tasks, both before and after the standard (all *p*s < .05; see Figure 2A and Table 1).

Congruency-priming effect. The participants responded more quickly to trials on which prime and target elicited the same response (congruent trials) than on trials on which they elicited different responses (incongruent trials) in both the number task and the letter task (Figure 2B). For this analysis, trials with identical primes

Table 1
Median Response Times (RTs, in Milliseconds) for Comparison Distances in Experiments 1 and 2, With Error Rates (PE)

	Distance															
	Before Standard								After Standard							
	4		3		2		1		4		3		2		1	
Prime	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE
Experiment 1																
Number	380	3.3	372	2.9	383	3.3	403	9.0	379	1.4	367	0.9	385	2.4	397	10.0
Letter	440	4.3	497	11.4	486	3.8	493	12.8	448	2.9	441	2.4	469	9.0	500	7.6
Experiment 2																
Number	400	1.0	398	2.3	407	2.0	426	6.0	396	1.7	401	1.0	410	3.0	417	4.7
Letter	467	3.0	484	5.0	533	11.7	514	9.7	456	3.0	495	4.7	481	5.3	533	12.7

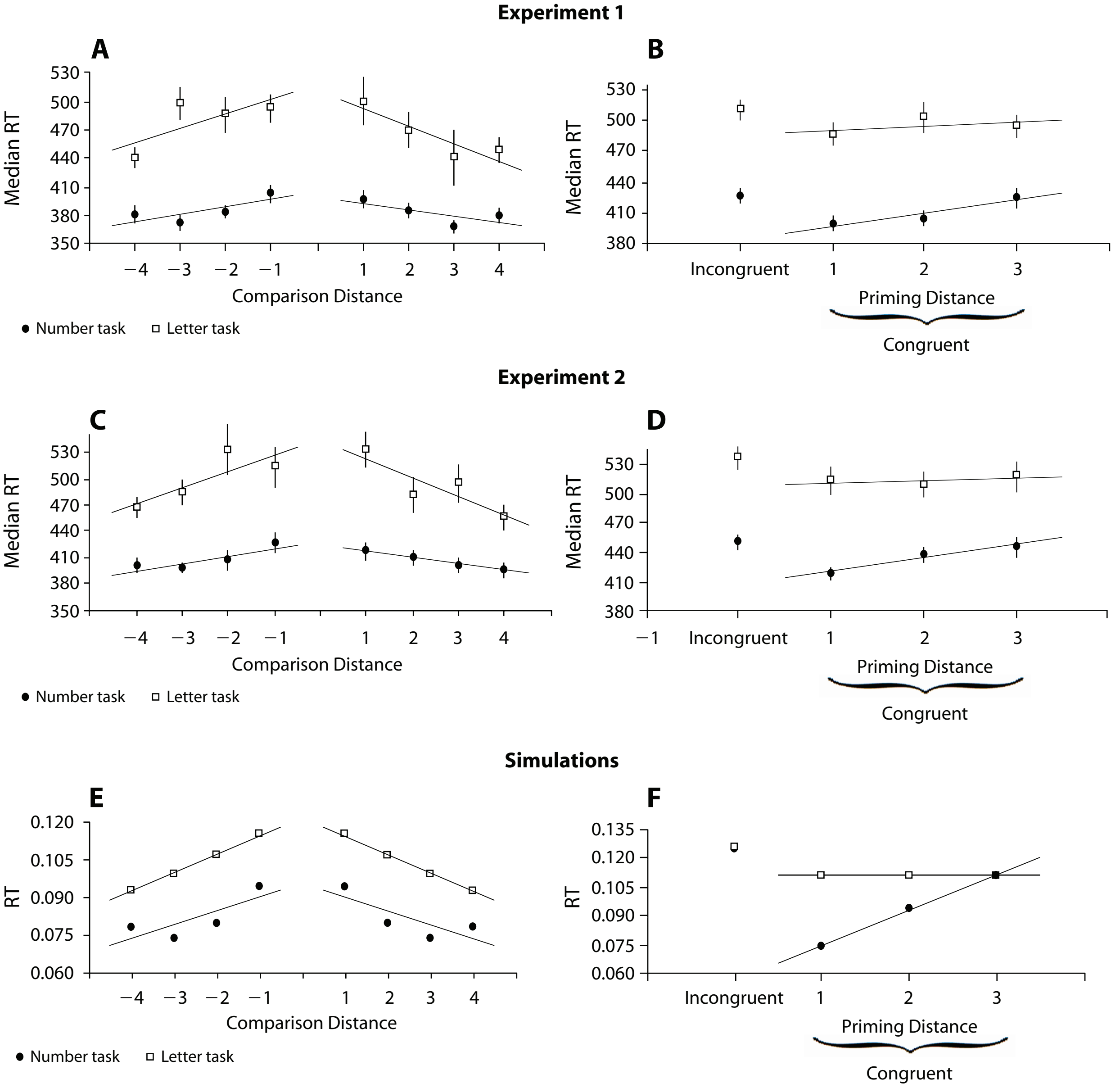

Figure 2. Median response times (RTs, in milliseconds) for the comparison distance effect in Experiment 1 (A) and Experiment 2 (C) and the congruency and priming distance effect for targets before the standard in Experiment 1 (B) and Experiment 2 (D). Confidence intervals are calculated according to Loftus and Masson (1994). Model simulations of the comparison distance effect and the congruency and priming distance effect are shown in panels E and F, respectively. Simulated RTs are in arbitrary time units.

and targets were removed to exclude perceptual priming. A 2 (task) × 2 (size) × 2 (congruency) within-subjects ANOVA was performed on median correct RTs. This revealed an effect of task [$F(1,20) = 125.79$, $MS_e = 2{,}185$, $p < .001$] and of congruency [$F(1,20) = 49.31$, $MS_e = 305$, $p < .001$]: RTs were smaller on congruent trials (446 msec) than on incongruent trials (465 msec). There was a significant interaction between task and congruency [$F(1,20) = 8.32$, $MS_e = 224$, $p < .01$]: Congruency priming was significant in both the number task [$F(1,20) = 99.31$, $MS_e = 138$, $p < .001$; effect size = 26 msec] and the letter task [$F(1,20) = 8.09$, $MS_e = 391$, $p < .05$; effect size = 12 msec]. Furthermore, there was a significant three-way interaction [$F(1,20) = 7.04$, $MS_e = 112$, $p < .05$]. Interaction analyses revealed a significant difference in the congruency priming effect between letters and numbers after the standard [$F(1,20) = 12.19$, $MS_e = 208$, $p < .005$]. There was no significant difference of congruency between numbers and letters before the standard ($F < 1$). Detailed results are shown in Table 2.

Priming distance effect. The congruency-priming effect, which indexes the extent of prime processing, was of similar size for stimuli before the standard, but not after the standard. A reasonable interpretation is that number and letter primes before the standard were processed equally deeply. In contrast, differences in the

Table 2
Median Response Times (RTs, in Milliseconds) for Congruency Priming in Experiments 1 and 2, With Error Rates (PE)

	Before Standard				After Standard			
	Congruent		Incongruent		Congruent		Incongruent	
Prime	RT	PE	RT	PE	RT	PE	RT	PE
Experiment 1								
Number	405	5.9	427	5.1	399	4.5	429	7.3
Letter	493	8.0	510	9.4	486	7.9	494	7.6
Experiment 2								
Number	430	5.4	451	5.7	428	4.8	456	5.6
Letter	513	4.7	537	9.7	522	7.6	528	8.4

Table 3
Median Response Times (RTs, in Milliseconds) for Priming Distances in Experiments 1 and 2, With Error Rates (PE)

	Distance Before Standard					
	1		2		3	
Prime	RT	PE	RT	PE	RT	PE
Experiment 1						
Number	399	4.0	404	6.2	425	10.9
Letter	486	7.1	503	8.1	494	10.2
Experiment 2						
Number	419	3.6	438	5.0	446	7.3
Letter	514	7.5	509	6.2	518	8.2

congruency-priming effect for letters and numbers after the standard may indicate shallower processing of letter primes. Therefore, analysis of the priming distance effect is focused on stimuli before the standard. A 2 (task) $\times$ 3 (priming distance: 1, 2, or 3) within-subjects ANOVA was performed on the correct, congruent median RTs for targets before the standard. There were main effects of task [$F(1,20) = 79.77$, $MS_e = 2{,}866$, $p < .001$] and distance [$F(2,40) = 6.07$, $MS_e = 503$, $p < .005$]. Importantly, there was a significant interaction between task and priming distance [$F(2,40) = 5.40$, $MS_e = 443$, $p < .01$], with a significant priming distance effect in the number condition [$F(1,20) = 14.99$, $MS_e = 455$, $p < .001$] but not in the letter condition [$F(1,20) = 1.67$, $MS_e = 414$, $p = .21$; see Table 3 and Figure 2B]. A significant interaction between task and priming distance is also observed ($p < .05$) if we include all the stimuli in the analysis (i.e., the primes both before and after the standard).

These results favor the monotonic connection view: Both number and letter comparison elicit a comparison distance effect and a congruency-priming effect. The priming distance effect is, however, limited to the number task. To ensure that these effects are not due to the specific letter set used in the experiment, Experiment 1 was replicated, using a different set of letters in Experiment 2. Again, letters from the middle of the alphabet were selected to exclude confounds with the serial position effect.

EXPERIMENT 2

Method

Participants. Thirty university students (age, 18–23 years; 10 of them male) participated for a payment of €20 or course credit.

Apparatus and Stimuli. As in Experiment 1, except for the letter stimuli. Letters I to Q (standard, M) were used.

Procedure. The procedure was identical to that in Experiment 1.

Results and Discussion

The mean error rate was 6.5% (see note 1).

Comparison distance effect. As in Experiment 1, there was a main effect of task and of distance (both *p*s < .001; see Figure 2C). There was a significant interaction between task, size, and comparison distance [$F(3,87) = 3.39$, $MS_e = 3{,}156$, $p < .05$]. Planned linear trend analysis revealed a significant comparison distance effect for letters and numbers before and after the standard (all *p*s < .01; see Table 1).

Congruency-priming effect. Besides main effects of task and congruency (both *p*s < .001), there were significant interactions between task and congruency [$F(1,29) = 6.01$, $MS_e = 185$, $p < .05$] and between task, congruency, and size [$F(1,29) = 16.73$, $MS_e = 135$, $p < .005$]. Planned comparisons showed that the three-way interaction was caused by a significant difference in congruency-priming effect between numbers and letters after the standard [$F(1,29) = 16.73$, $MS_e = 214$, $p < .001$] but no significant difference of congruency between numbers and letters before the standard ($F < 1$; see Table 2).

Priming distance effect. Analysis focused on trials on which the priming effect was equally strong in the number and letter tasks—that is, on trials with targets before the standard (see the previous section). Besides main effects of task and distance (*p*s < .05) and a significant interaction between task and priming distance [$F(2,58) = 4.43$, $MS_e = 608$, $p < .05$], planned comparisons showed a significant priming distance effect in the number task ($p < .001$), but not in the letter task ($p = .68$; see Table 3 and Figure 2D). If we include all the stimuli in the analysis (i.e., the primes both before and after the standard), a marginally significant interaction between task and priming distance ($p = .071$) was still observed.

SIMULATION STUDY

The two tasks were simulated using a simplified steady state version of the Verguts et al. (2005) comparison model. We assume that a learning process akin to the one in number comparison has taken place in letter comparison also. In this case, a monotonic weight pattern is predicted for both the number and the letter tasks. The activation of the *target larger than standard* and *target smaller than standard* output nodes is the summed activation from the standard and the target input layer. Activation of the target input layer is the sum of prime activation and target activation. Simulated RT was an inverse function of activity of the correct output node (see the Appendix for details).

The number task was modeled with high representational overlap (a large value of σ; see Figure 1A); the letter task was modeled without representational overlap (a very small value of σ; see Figure 1B). For simplicity, both tasks have identical connection weights (see insets in Figure 1). The simulation results closely match those from Experiments 1 and 2: In both number and letter simulations, a comparison distance effect (Figure 2E) and a congruency-priming effect (Figure 2F) are present, whereas the priming distance effect appears only in the number simulation (Figure 2F).

The comparison distance effect in both the number and the letter simulations originates from the monotonicity in the connection weights, independently of representational overlap. There is also a congruency effect in both models, because activation of the prime is cascaded to the output: If the prime and the target are on the same side of the standard (i.e., congruent trial), activation of the correct output node is higher than if the prime and the target are on a different side of the standard (i.e., incongruent trial). This leads to shorter RTs in the congruent case.

The priming distance effect is present only in the number simulation (Figure 2F): A stimulus activates not only its own input unit, but also the neighboring input units, according to a Gaussian function. Therefore, the influence of prime activation on target processing will be larger when the prime and the target are closer to each other.

GENERAL DISCUSSION

We pitted opposite predictions from two views on the comparison distance effect against one another. The results support the monotonic connection view: When matched on congruency priming effects, there was a comparison distance effect in numbers and letters, but a priming distance effect was restricted to the number task.

In earlier studies, the distance effect referred to any effect of semantic distance between two stimuli, in comparison tasks (e.g., Moyer & Landauer, 1967), in Stroop-like tasks (e.g., Pavese & Umiltà, 1998), and in priming tasks (e.g., Dehaene et al., 1998). Our results point toward the necessity for dissecting the distance effect into at least a comparison distance effect and a priming distance effect. This results in some conceptual clarification. For example, Pavese and Umiltà criticized the symbolic-coding model of Banks (1977) for ascribing the distance effect to a comparison process, because they obtained (priming) distance effects in other tasks also. Dissecting the two effects leads to the conclusion that the comparison distance effect originates only in comparison tasks (as Banks, 1977, had postulated), whereas the priming distance effect can appear in other tasks also (as Pavese & Umiltà, 1998, argued). More generally, distance effects in tasks that cannot be solved by a simple comparison network such as the one presented here (e.g., the *same/different* task; Verguts & Van Opstal, 2005) could still be caused by representational overlap (Dehaene & Changeux, 1993).

The comparison distance effect is very robust, since it is obtained in any type of material in which a comparison task has been studied, whereas the priming distance effect is not. From the model point of view outlined above, this is not surprising: Solving the task correctly actually *implies* a comparison distance effect. Of course, there may be alternative strategies for solving the comparison task (e.g., exemplar-based strategies) that work against or even reverse the comparison distance effect. For example, Turconi et al. (2006) found a reversed distance effect in an order task: When participants had to judge whether two numbers were in ascending order, a reversed distance effect was found for ascending pairs. Because this effect was limited for distance 1, as compared with distance 2, 3, or 4 (the distance effect was normal between distances 2, 3, and 4) in ascending order, these results may have been caused by an exemplar-based strategy adopted by the participants. We argue, however, that as long as the comparison network is used, a comparison distance effect follows. In contrast, the priming distance effect is not needed in any task, so the absence of this effect in some stimulus materials (e.g., letters) is not surprising.

AUTHOR NOTE

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NOTE

1. Because analyses on the error rates revealed results similar to those for the RT analyses, the error rates are only reported in Tables 1–3, but statistical analyses are not described explicitly.

APPENDIX

Only one output node (*target larger than standard*) will be discussed. For simplicity, we used linearly increasing and decreasing weights. Changing the weights to those from the trained comparison model (Verguts et al., 2005) does not change the results qualitatively. The output function of *target smaller than standard* is identical, except for the linear weight factors $(c - i)$ and i, which are exchanged.

Formally, the activation received by the output node can be written as

$$\sum_{i=1}^{15}(c-i)\left[e^{-\frac{1}{\sigma}|i-s|^2}-\theta\right]^+ + \sum_{i=1}^{15} i\left[\left(e^{-\frac{1}{\sigma}|i-t|^2}+\alpha e^{-\frac{1}{\sigma}|i-p|^2}\right)-\theta\right]^+,$$

where s, t, and p indicate the standard, target, and prime, respectively, and the summation runs over the 15 number nodes in the standard and the target input layer, respectively. $[A]^+$ denotes the maximum of zero and A. The first summation term represents the amount of activation received by the output node from the standard input layer. The second term is the amount of activation received from the target input layer (i.e., the activation of the prime and the target). Because of the brief prime presentation, its contribution is multiplied by $\alpha = .2$. Threshold θ was set to .8; the weight intercept c was set to 9. The Gaussian width is defined by σ. See Verguts et al. (2005) for a full explanation.

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