Automaticity of Number Perception

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Abstract

In 2 experiments, the authors investigated whether the attributes "small" and "large" associated with individual digits are responsible for the effects of size congruity on judgments of physical size (Tzelgov, Meyer, & Henik, 1992). In Experiment 1, a size congruity effect was observed when participants judged the relative physical sizes of two digits. However, size congruity effects were just as strong when participants judged the relative physical sizes of small digits (i.e., 1-4) paired with letters. In Experiment 2, a similar size congruity effect was observed when participants judged the sizes of squares within which individual small digits were presented. Consistent with memory-based theories of automaticity, these results suggest that associations between the attribute "small" and individual small digits are sufficient to explain many, if not all, size congruity effects.

Automatic Number Perception

A great deal of research on number perception argues that numbers automatically – without intention – activate some form of magnitude representation (Dehaene & Akhavein, 1995; Henik & Tzelgov, 1982; Pansky & Algom, 1999; Tzelgov, et al., 1992; Tzelgov, Yehene, Kotler, & Alon, 2000). One of the strongest pieces of evidence for the automatic activation of magnitude representations is the size congruity effect. In the size congruity effect, participants observe two digits, one of which is presented in a larger font size than the other. Participants then judge which of the two digits is presented in the larger (or the smaller) font size. Only the physical sizes of the digits are relevant for this task; the magnitudes represented by the digits are irrelevant. Nevertheless, a size congruity effect is often observed such that the time needed to identify the relative sizes of the digits is faster when the difference in the quantities represented by the digits is congruent with the difference in font sizes (e.g., 2 8) than when it is incongruent with the difference in font sizes (e.g., 2 8). These size congruity effects also tend to interact with the distance between the quantities represented by the digits such that the congruity effect is larger for pairs that are far away from each other (e.g., 2, 8) than for pairs that are close together (e.g., 2, 4). These effects demonstrate that magnitude representations associated with digits intrude in the judgments even though people are trying to ignore them and pay exclusive attention to physical size. However, the nature of these intruding magnitude representations and of the cognitive processes that operate on them is not well understood. The purpose of the research reported here was to explore the nature of these magnitude representations and processes.

Several views regarding the nature of these representations and processes have been proposed. One view – henceforth, called the algorithmic model – is that participants map the quantities represented by digits onto an analog magnitude representation. The analog magnitude representation is then used to calculate which is the larger and which is the smaller of the two. The result of this calculation is thought to interfere with (or facilitate) size judgments (Tzelgov, et al., 2000; for related arguments see Dehaene & Akhavein, 1995). The interaction between size congruity and distance is often cited as especially strong evidence for this view, because the larger congruity effects for digit pairs that are farther away from each other are believed to reflect faster processing for pairs of digits whose represented values are more discriminable (i.e., farther apart) on the analog magnitude representation (Pansky & Algom, 1999; Tzelgov, et al., 2000).

Previous research suggests, however, that while automatic processing can associate attributes with items (as in one-place predicates like *small[A]*), it cannot handle relational information (as in two-place predicates like *smaller-than[A,B]*). By contrast, attentional processing can handle either attributes or relations (Logan, 1994; Wolfe, Yu, Stewart, Shorter, et al., 1990). For example, using a visual search paradigm, Logan (1994) found that attention was required to identify when a relational target (i.e., a dash above a plus) was present. Searching for this relational target never became automatic even after a great deal of practice. (See also Hummel & Holyoak, 2001, and Hummel & Choplin, 2000, for a model of the differences in magnitude-comparison representation under attentional and automatic processing). This previous research suggests that while digits might be associated with values on an analog magnitude representation under automatic, unintentional, processing, it ought not to be possible to compare values on the analog representation. Without such comparisons, represented magnitudes could not interfere with size judgments.

An alternative to the multi-step algorithm advocated by Tzelgov and his colleagues (e.g., Tzelgov, et al., 2000) and Dehaene and his colleagues (e.g., Dehaene & Akhavein, 1995) is suggested by memory-based theories of automaticity. In these theories, automaticity reflects the single-step recollection of formerly observed instances from memory. Memory-based theories seem sufficient to explain the development of automaticity in tasks such as memory

search (Strayer & Kramer, 1990), category learning (e.g., Logan & Etherton, 1994), lexical decisions, (e.g., Logan, 1988), and numerocity judgments (e.g., Lassaline & Logan, 1993; Palmeri, 1997). Postulating changes in the algorithms used to perform those tasks has not appeared necessary to explain the development of automaticity and there is no *a priori* reason to think that the automatic processing of magnitude information in the size congruity effect should somehow be different. A memory-based account of size congruity effects would be more consistent with previous work on automatic processing.

In one such a memory-based account, participants might associate particular responses with particular sets of already-grouped digits. For example, after repeatedly judging that 8 > 2 in contexts in which greater than responses are appropriate, participants might simply recall "8" in response to the set of digits {8, 2} and the feature "greater-than" provided by the context without comparing the quantities represented by the digits (Logan & Etherton, 1994). The memory that "8" is the appropriate response to the set {8, 2} could then interfere with participants' judgment that 2 is physically larger than is 8. However, the results of Tzelgov, et al. (2000) argue against this view. They gave their participants extensive training judging the magnitudes of pairs of arbitrary symbols (i.e., Gibson figures). Importantly, however, participants only viewed a subset of the possible Gibson-figure pairings during the training sessions. Afterwards, participants were asked to judge the relative physical sizes of novel Gibson-figure pairings. Size congruity effects were observed. Directly learned associations between pairings and responses are not sufficient to explain such an effect (but see the General Discussion section for a discussion of this effect).

Another way to reconcile size congruity effects with the previous work on automatic processing is to assume that attributes associated with individual digits interfere with size judgments. Tzelgov, et al. (1992) proposed one such model as a supplement to the algorithmic model described above. In this model (henceforth, called the laterality model), digits representing values less than 5 (i.e., 1, 2, 3, and 4) activate the attribute "small;" and digits representing values more than 5 (i.e., 6, 7, 8, and 9) activate the attribute "large." These associated attributes would facilitate size judgments when subjects are asked to identify digits as small that they already associate with the attribute "small" or identify digits as large that they already associate with the attribute "large." They would interfere with size judgments when subjects are required to identify digits that activate the attribute "small" as physically large or to identify digits that activate the attribute "large" as physically small. Interactions between size congruity and distance would occur because distance is confounded with the laterality of the pairs. Of the pairs that have a distance of two steps between them, only one pair out of seven (14% of pairs) crosses 5 (i.e., {4, 6} cross 5, but {1, 3}, {2, 4}, {3, 5}, {5, 7}, {6, 8}, and {7, 9} do not). Of the pairs that have a distance of three steps between them, two pairs out of six (33% of pairs) cross 5 (i.e., {3, 6} and {4, 7} cross 5, but {1, 4}, {2, 5}, {5, 8}, and {6, 9} do not), and so forth.

Our goal in pursuing the research reported here was to further investigate the laterality model as one possible memory-based account of the size congruity effect. If differences in laterality produce size congruity effects, then the attributes "large" and "small" hypothesized to be associated with each of the compared digits ought to be associated with individual digits as well. These associated attributes, in turn, ought to interfere with size judgments. Reaction times ought to be fast for congruent trials in which size judgments involve small digits (i.e., 1-4) that result in a judgment of "small" or large digits (i.e., 6-9) that result in a judgment of "large" relative to incongruent trials in which size judgments involve small digits (i.e., 1-4) that result in a judgment of "large" or large digits (i.e., 6-9) that result in a judgment of "small." We performed two experiments to test this prediction. In Experiment 1, small (i.e., 1-4) and large (i.e., 6-9) digits were paired with letters in addition to being paired with other digits. One character was larger than the other and participants identified the larger or the smaller member of the pair. In Experiment 2, individual digits were presented alone within either small or large squares and participants identified the sizes of the squares. If attributes associated with individual digits are responsible for size congruity effects in judging the relative sizes of digits presented in pairs, then size congruity effects also ought to be observable in conditions in which individual digits are paired with letters or are presented alone. By contrast, if comparisons between two digits are responsible for size congruity effects, then these effects ought not to occur when individual digits are paired with letters or are presented alone.

Experiment 1

The algorithmic model assumes that the comparison algorithm requires two inputs. In this view, size congruity ought only to occur when two digits are presented together. By contrast, the laterality model assumes that retrieval of the attributes "small" and "large" occur in response to individual digits. In this view, size congruity effects require only one digit. To test these hypotheses, digits in Experiment 1 were paired with letters in addition to being paired with other digits. If size congruity effects occur when digits are paired with letters, they cannot be due to a comparison algorithm.

Method

Forty-eight undergraduate students with normal or corrected-to-normal vision participated in partial fulfillment of course requirements. These participants sat approximately 60 cm in front of a 30 x 40 cm computer screen. On each of 2016 trials (plus 4 training trials), a fixation point was presented at the center of the screen for 500 ms followed by two characters. Both characters were presented at the vertical center of the screen. One character was presented approximately 1.2 cm left of the horizontal center of the screen; the other character was presented approximately 1.2 cm right of the horizontal center of the screen. One character was presented in Courier 30-font

script (approximately 1.0 x 1.4 cm) and its counterpart was presented in Courier 40-font script (approximately 1.4 x 2.0 cm). Twenty-four of the participants identified which character was the smaller of the two and the other twenty-four participants identified which character was the larger of the two as accurately and quickly as they could. They did this by pressing the <S> key, which is on the left side of the keyboard, if the character on the left was the smaller (or larger) of the two or the <K> key, which is on the right side of the keyboard, if the character on the right was the smaller (or larger) of the two. The assignment of characters to presentation on the left or right side of the screen as well as presentation in 30 or 40-font script was fully counter balanced. These characters remained on the screen until the student responded.

We created three different character-pair conditions. We created the first condition (henceforth, the NN Condition) by taking all pairwise combinations involving one digit from the set {1, 2, 3, or 4} paired with one digit from the set {6, 7, 8, or 9}. We classified these pairs by the distance (number of steps) between the members. To assess the extent to which attributes associated with the small digits account for size congruity effects, we created the second condition by taking all of the pairs used in the NN condition and substituting the letter H for the number 6, the letter N for the number 7, the letter P for the number 8, and the letter T for the number 9. This condition will be called the NL Condition (for Numbers-Letters) because the letters replaced large numbers. To assess the extent to which attributes associated with the large digits account for size congruity effects, we created the third condition by taking all of the pairs used in the NN condition and substituting the letter J for the number 1, the letter L for the number 2, the letter R for the number 3, and the letter V for the number 4. This condition will be called the LN Condition (for Letters-Numbers) because the letters replaced small numbers. Note that the L's and N's in this notation represent the magnitudes of the numbers that were presented and the magnitude of the numbers that were replaced, not the location in which they were presented on the computer screen. Presentation on the left or the right side of the screen was fully counterbalanced. To allow us to directly compare the NL and LN Conditions to the NN condition, we classified the pairs in the NL and LN Conditions by the distance (number of steps) between the members of the NN Condition out of which they were created. We used this classification scheme to assess the extent to which attributes associated with individual numbers could explain congruity effects found for NN pairs. Note, however, that outside of the context of this experiment it makes little sense to classify distances between numbers and letters (e.g., the number of steps between 4 and H).

Results and Discussion

For each condition, congruity scores were calculated by subtracting the average reaction time on the congruent trials from the average reaction time on incongruent trials. The results are presented in Figure 1.

A 3 (character-pair type: NN, NL, and LN) x 7 (steps: 2 through 8) Within-Subjects Analysis of Variance (ANOVA) was performed on these congruity scores. This analysis revealed a significant main effect of character-pair type, $\underline{F}(2,92) = 79.0$, $\underline{MSE} = 1853.1$, $\underline{p} < .001$. A least significant difference analysis revealed that the congruity effects were lower in the LN Condition than in either the NN or NL Conditions and that the congruity effects in the NN and NL Conditions were not significantly different from each other. The congruity effects in the NN and NL conditions were significantly greater than zero, but the congruity effects in the LN condition were not. The fact that we found congruity effects in the NL Condition, but not the LN Condition suggest that the attribute "small" associated with the digits 1-4 is sufficient to explain size congruity effects—with little or no influence from the attribute "large." Separate trend analyses for each of the three character-pair type conditions revealed significant linearly increasing trends across steps for the NL Condition [$F(1,47) = 8.79$, $MSE = 1454.36$, $p < .01$] and NN Condition [$F(1,47) = 6.68$, $MSE = 883.91$, $p < .05$] respectively and a significant linearly decreasing trend across steps for the LN Condition [$F(1,47) = 7.97$, $MSE = 696.75$, $p < .01$]. The fact that we found step effects in the NL Condition—even though it makes little sense to talk about the number of steps between numbers and letters—suggests that these step effects are not due to discriminability on an analog magnitude representation. Rather, they appear to be due to associations between small digits and the attribute "small." The fact that we found linearly increasing trends across steps in the NL and NN Conditions suggests that the associations between each of the small digits and the attribute "small" are not of equal strength. It is not immediately clear why we found a linearly decreasing trend in the LN Condition. Perhaps it is a statistical aberration.

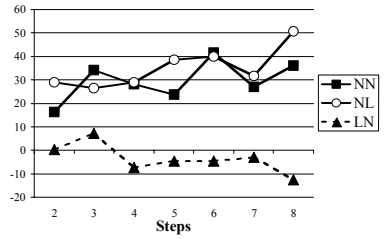

Figure 1. Results of Experiment 1. Congruity effects were just as large when the digits 1-4 were paired with letters (NL Condition) as when the digits 1-4 were paired with the digits 6-9 (NN Condition). Congruity effects were not significantly greater than zero when the digits 6-9 were paired with letters (LN Condition).

To make the results of Experiment 1 comparable to the results of Experiment 2, reaction times for conditions in which each of the 8 digits were paired with letters (i.e., 1-4 in the NL Condition and 6-9 in the LN Condition) were analyzed separately. These data are presented in Figure 2.

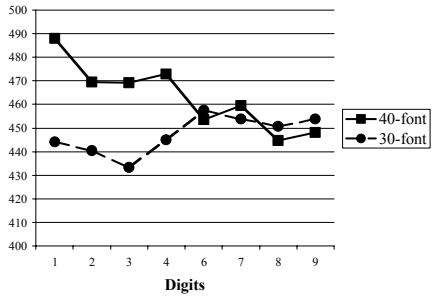

Figure 2. Results of Experiment 1 NL and LN Conditions. Reaction times to identify the relative sizes of the characters when the digits were presented in 40-point font was greater than the time needed to identify the relative sizes of the characters when the digits were presented in 30-point font for the digits 1-4, but not for the digits 6-9.

As suggested by Figure 2, a contrast analysis on these reaction time data revealed that the time needed to identify the relative sizes of the characters when the digits were presented in 40-point font was greater than the time needed to identify the relative sizes of the characters when the digits were presented in 30-point font for the digits 1-4, but not for the digits 6-9, $F(1,47) = 162.06$, $MSE = 398.35$, $p < .01$. Posthoc t-tests with Bonferroni adjustments ($\alpha = .05/8 = .006$) revealed that reaction times were significantly faster in response to digits printed in 30-point font than in response to digits printed in 40-point font for the digits 1-4 [*t*'s (47) = 9.37, 6.63, 7.24, and 6.79, respectively], but were not significantly different for the digits 6-9 [*t*'s (47) = 1.11, 1.58, 1.31, and 1.99, respectively]. A linearly increasing trend in reaction times across the 8 presented digits was revealed for pairs in which the digits were presented in 30-point font, $F(1,47) = 33.24$, $MSE = 368.13$, $p < .01$; while a linearly decreasing trend in reaction times across the 8 presented digits was revealed for pairs in which the digits were presented in 40-point font, $F(1,47) = 126.47$, $MSE = 469.52$, $p < .01$.

Consistent with the laterality model (Tzelgov, et al., 1992), these results suggest that the digits 1-4 are associated with the attribute "small," but inconsistent with the laterality model these results suggest that the digits 6-9 are not associated with the attribute "large." This finding was unexpected. We speculate that the reason for this asymmetry is that the small digits 1-4 are always small (i.e., always close to zero). By contrast, the large digits 6-9 are large in the context of the single digits, but they are not large in other contexts, such as the numbers 1-100. Notice, however, that although these results are partially inconsistent with the laterality model, they are consistent with the spirit of memory-based models of automaticity in that the association between the digits 1-4 and the attribute "small" seems sufficient to explain size congruity effects.

Experiment 2

The purpose of Experiment 2 was to test whether individually presented digits can produce size congruity effects. The algorithm model predicts no size congruity effects for individually presented digits because the comparison algorithm requires two digits. By contrast, the laterality model predicts a size congruity effect for individually presented digits because only one digit is required to instigate retrieval of attributes associated with that digit. To further investigate associations between individual digits and the attributes "small" and "large," the digits in Experiment 2 were individually presented within a small or a large square. Participants judged the square size.

Method

Twenty-four undergraduate students with normal or corrected-to-normal vision participated in partial fulfillment of course requirements. These participants sat in front of the same computer screen as that described in Experiment 1. On each of 1440 trials (plus 6 training trials), a fixation point was presented at the center of the screen for 500 ms followed by one character from the digits {1, 2, 3, 4, 6, 7, 8, and 9} or the letters {G, K, M, R, S, V, W, and X} presented in Courier 30-font script (approximately 1.0 x 1.4 cm). This character was either presented inside a small or a large square. The small square was 3.0 x 3.0 cm; and the large square was 4.0 x 4.0 cm. Participants pressed the <Q> key to identify that the square was small and the <P> key to identify that the square was large or vice versa. The character and the square remained on the screen until the student responded.

Results and Discussion

Response times for each of the 8 digits printed within either a 3.0-cm square or 4.0-cm square are presented in Figure 3.

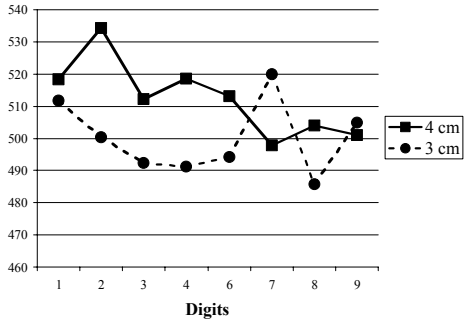

Figure 3. Results of Experiment 2. Reaction times to identify 4.0-cm squares was greater than reaction times to identify 3.0-cm squares when the digits 1-4 were printed within them as compared to when the digits 6-9 were printed within them.

As suggested by Figure 3, a contrast analysis on these reaction time data revealed that the time needed to identify 4.0-cm squares was greater than the time needed to identify 3.0-cm squares when the digits 1-4 were printed within them as compared to when the digits 6-9 were printed within them, $F(1,23) = 10.13$, $MSe = 875.08$, $p < .01$. A linearly decreasing trend in reaction times was revealed

across the 8 digits presented within 4.0-cm squares, $F(1,47) = 15.57$, $MSE = 972.48$, $p < .01$. However, contrary to our predictions no significant linear trend was revealed across the 8 digits presented within 3.0-cm squares, $F < 1$. Nevertheless, these results, along with the results of Experiment 1, are generally consistent with the view that the digits 1-4 are associated with the attribute "small," but the digits 6-9 are not associated with the attribute "large."

General Discussion

In 2 experiments, we investigated the laterality model as one possible memory-based account of size congruity effects. The reasoning behind these experiments was that if associations between digits and size attributes (i.e., "small," "large") were responsible for the size congruity effects observed in pairs of digits as suggested by Tzelgov, et al., (1992), then analogous size congruity effects ought to be observable for individually presented digits. By contrast, if comparisons between the values represented by the digits were responsible for the size congruity effects observed in pairs of digits, then size congruity effects ought not to occur for individually presented digits. In Experiment 1, participants judged the relative physical sizes of two characters. Three character-pair types were presented: small digits {1-4} paired with large digits {6-9}, small digits {1-4} paired with letters, or large digits {6-9} paired with letters. Size congruity effects were just as large for small digits {1-4} paired with letters as they were for digits paired with other digits, but were not reliably greater than zero for large digits {6-9} paired with letters. In Experiment 2, each of the 8 digits used in Experiment 1 (i.e., 1, 2, 3, 4, 6, 7, 8, and 9) was presented individually within small and large squares. Participants judged the sizes of the squares. Reaction times to identify 4.0-cm squares were greater than reaction times to identify 3.0-cm squares when the digits 1-4 were printed within them as compared to when the digits 6-9 were printed within them. Contrary to the laterality model but consistent with memory-based models of automaticity generally, these results suggest that the associations between the small digits {1-4} and the attribute "small" are sufficient to explain size congruity effects. Apparently, associations between the large digits {6-9} and the attribute "large" play little or no role in size congruity effects (although the observed linearly decreasing trend across steps for the LN Condition in Experiment 1 are intriguing).

Tzelgov, et al. (1992) proposed the laterality model as a supplement to the algorithmic model. In their view, both processes operate to produce size congruity effects. The results of Experiment 1, however, argue against this dual-process model. If both processes were operating, then, presumably, both processes would affect reaction times. However, the size congruity effects in Experiment 1 were just as large for small digits (i.e., 1-4) paired with letters as they were for pairs of digits suggesting that associations between the small digits {1-4} and the attribute "small" are sufficient to explain size congruity effects. Postulating effects of algorithmic comparison processes appears to be entirely unnecessary.

Tzelgov, et al.'s (1992) argument for a dual-process model was highly dependent upon finding size congruity effects for pairs of which both members were smaller than or larger than 5. The laterality model as originally articulated by Tzelgov et al. predicted no size congruity effects for such pairs because the associations between each of the small digits (i.e., 1, 2, 3, and 4) and the attribute "small" as well as between each of the large digits (i.e., 6, 7, 8, and 9) and the attribute "large" were supposed to be equally strong. However, the linear trends observed in Experiments 1 and 2 across the 8 presented digits do not support this prediction of the laterality model as it was originally articulated. On the contrary, these linear trends suggest that the associations between digits and the attribute "small" are not equally strong. It is conceivable, therefore, that differences in the strengths of the associations between digits and the attribute "small" could produce size congruity effects for pairs of which both members were smaller than 5. We should point out, however, that consistently reliable size congruity effects for pairs of which both members were smaller than or larger than 5 have rarely been reported in the literature. Most studies have primarily investigated pairs of which one member was smaller than 5 and the other member was larger than 5, failed to find size congruity effects for pairs of which both members were smaller than or larger than 5, or reported distance effects that were confounded with the percentage of pairs that crossed 5 such that it is impossible to tell whether there were significant size congruity effects in pairs of which both members were smaller than or larger than 5 (Algom, et al., 1996; Dehaene & Akhavein, 1995; Henik & Tzelgov, 1982). Tzelgov, et al. (1992) themselves only reported size congruity effects for two pairs of which both members were smaller than or larger than 5 (i.e., 2, 4 and 6, 8) and failed to report the significance level of these pairs. In fact, the major finding they reported with respect to these pairs was that the size congruity effects for these pairs were significantly smaller than those observed for pairs of which one member was smaller than 5 and the other member was larger than 5. Further research is needed to determine whether size congruity effects are real for pairs of which both members are smaller than or larger than 5, and if so, the extent to which differences in the strengths of the associations between individual digits and the attribute "small" can account for them.

Associations between the small digits {1-4} and the attribute "small" are only one of several memory-based factors that could produce congruity effects on judgments of physical size. As mentioned earlier, learned associations between sets of features (e.g., {8, 2, and greater-than}) and responses (e.g., "8") could also interfere with participants' judgments of physical size (e.g., that 2 is physically larger than is 8). Tzelgov, et al. (2000) argued against this possibility by training participants to judge the relative magnitudes represented by arbitrary symbols (i.e., Gibson figures). During training, participants only saw a subset of Gibson-figure pairings. Later, participants judged the

relative physical sizes of Gibson-figure pairs. Size congruity effects were observed even for pairs that participants had not seen during training. Because participants had never before seen these pairs, Tzelgov, et al. argued that the associations between these pairs (e.g., {Gibson figure8, Gibson figure2, and greater-than}) and appropriate magnitude responses (e.g., "Gibson figure8") could never have developed and, therefore, could not be responsible for the observed interference. We might point out, however, that exemplar-based memory theories, like Instance Theory, do not claim that the perception of novel exemplars only initiates retrieval of self-identical exemplars from memory (Palmeri, 1997). On the contrary, the perception of novel exemplars tends to initiate retrieval of similar exemplars from memory. It is, therefore, possible that the perception of a novel exemplar with features such as {Gibson figure8, Gibson figure2, and greater-than} could initiate retrieval of similar exemplars from memory (e.g., {Gibson figure8, Gibson figure1, and greater-than}, {Gibson figure8, Gibson figure3, and greater-than}, {Gibson figure8, Gibson figure4, and greater-than}, etc.). To the extent that these similar exemplars in memory have been associated with appropriate responses such as "Gibson figure8," retrieval of such responses could, in theory, interfere with judgments of physical size (e.g., that Gibson figure2 is physically larger than is Gibson figure8). Algorithmic comparison processes, therefore, are not the only type of process that can account for the results observed by Tzelgov, et al. In fact, preliminary results with a connectionist simulation of Tzelgov, et al.'s experiment suggest that memory-based automaticity can produce the transfer to novel pairs that Tzelgov et al. observed.

Conclusion

Along with previous research, the research we report here suggests that numbers automatically – without intention – activate some form of magnitude representation and, thereby, interfere with judgments of physical size. However, the magnitude representations that intrude in these judgments need not involve analog magnitude representation scales or algorithmic comparisons on these scales (Dehaene & Akhavein, 1995; Pansky & Algom, 1999; Tzelgov, et al., 2000). Rather, a model based upon single-stage retrieval of attributes from memory is likely to prove sufficient to explain size congruity effects as well as other forms of unintentional semantic interference and facilitation.

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References

Algom, D., Dekel, A., & Pansky, A. (1996). The perception of number from the separability of the stimulus: The Stroop effect revisited. *Memory & Cognition*, 24, 557-572.

Dehaene, S., & Akhavein, R. (1995). Attention, automaticity, and level of representation in number processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 21, 314-326.

Henik, A., & Tzelgov, J. (1982). Is three greater than five: The relation between physical and semantic size in comparison tasks. *Memory & Cognition*, 10, 389-395.

Hummel, J. E. & Choplin, J. M. (2000). Toward an integrated account of reflexive and reflective reasoning. In L. R. Gleitman and A. K. Joshi (eds.), *Proceedings of the Twenty-second Annual Conference of the Cognitive Science Society*, 232-237.

Hummel, J. E. & Holyoak, K. J. (2001). A process model of human transitive inference. In M. Gattis (Ed.). *Spatial Schemas and Abstract Thought*, Cambridge, MA:MIT Press.

Lassaline, M.E., & Logan, G.D. (1993). Memory-based automaticity in the discrimination of visual numerocity. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 19, 561-581.

Logan, G.D. (1988). Toward an instance theory of automatization. *Psychological Review*, 95(4), 492-527.

Logan, G.D. (1994). Spatial attention and the apprehension of spatial relations. *Journal of Experimental Psychology: Human Perception and Performance*, 20(5), 1015-1036.

Logan, G. D. & Etherton, J. L. (1994). What is learned in automatization? The role of attention in constructing an instance. *Journal of Experimental Psychology: Learning, Memory and Cognition, 20,* 1022-1050.

Palmeri, T.J. (1997). Exemplar similarity and the development of automaticity. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 23, 324-354.

Strayer, D. L., & Kramer, A. F. (1990). An analysis of memory-based theories of automaticity. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 16, 291-304.

Tzelgov, J., Meyer, J., & Henik, A. (1992). Automatic and intentional processing of numerical information. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 18, 166-179.

Tzelgov, J., Yehene, V., Kotler, L., & Alon, A. (2000). Automatic comparisons of artificial digits never compared: Learning linear ordering relations. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 26, 103-120.

Wolfe, J.M., Yu, K.P., Stewart, M.I., Shorter, A.D., Friedman-Hill, S.R., & Cave, K.R. (1990). Limitations on the parallel guidance of visual search: Color x color and orientation x orientation conjunctions. *Journal of Experimental Psychology: Human Perception and Performance*, 16, 879-892.