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A size-congruency effect in memory for visual shape

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In five experiments, visual shapes were shown at either a small or a large size for study in the learning phase of a recognition memory experiment. Later, in the test phase, recognition memory was tested in an *old-new* paradigm in which an equal number of new shapes were mixed at random with previously seen shapes. Half of the *old* shapes were shown at the same size as in the learning phase, whereas half were shown at the other size. In every experiment, shapes tested at the same size as shown in the learning phase were recognized more quickly and more accurately than shapes tested at a different size. This size-congruency effect was found for line drawings of natural objects and for unfamiliar shapes (i.e., blobs and stick figures). Furthermore, the magnitude of the size-congruency effect depended on the degree of discrepancy between the learning size and the test size. Together, the results suggest that visual shape memory can be sensitive to the size at which patterns are originally encoded, and that the speed and accuracy of recognition memory is influenced by the size of a shape.

People can often remember having seen a particular visual shape or pattern even when the retinal image of the shape or pattern has undergone a transformation such as translation, rotation, expansion, or contraction. Somehow, the visual system and visual memory must represent shapes in such a way as to make recognition possible despite such transformations of the retinal image. In this paper I focus on the effects of expansion and contraction on memory for visual shapes.

A number of contemporary approaches have been proposed to explain the recognition of shapes despite changes in the size, location, and orientation of the shapes (e.g., see Hinton & Parsons, 1978; Jolicoeur & Kosslyn, 1983; Marr & Nishihara, 1978; Pinker, 1984). Researchers in vision have proposed several alternative ways in which a pattern recognition device could achieve this type of stimulus equivalence. One prominent view is that visual patterns are decomposed into a set of elementary features and that pattern recognition consists of matching a list of features obtained from a visual stimulus with one stored in long-term memory (e.g., Lindsay & Norman, 1972). For this approach to solve the stimulus equivalence problem, some level of representation must involve features that are orientation, size, and location independent.

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Logically, however, there must also be levels of representation and/or processing at which the representations are orientation, size, and location dependent, given that the initial representation (i.e., the retinal image) is vantage-point specific. Marr and Nishihara (1978), for example, proposed that the identification process consists of transforming vantage-point-dependent representations (i.e., the "primal sketch" and the "2½-D sketch") into vantage-point-independent representations (i.e., a "3-D model"; see also Marr, 1982). Similarly, Hinton (1981) proposed a model in which the first level of representation consists of features that are defined with respect to retinal coordinates. At this level, the features are orientation, size, and location specific. The model also includes "mapping units," whose purpose is to translate the retinally defined features into a feature space with a canonical orientation, size, and location. The model also postulates that long-term memory representations of an object are built up from features defined with respect to a canonical orientation, size, and location. These object representations are thus independent of the orientation, size, and location of the stimulus.

These models suggest that long-term memory representations of objects are independent of the size in which visual shapes were originally seen. An issue in these models is whether the initial retinocentric representations are stored in long-term memory, or whether these representations are discarded and only the more abstract object-centered representations are retained for future recognition. In fact, other researchers have proposed explicitly that long-term memory for visual shape includes size-dependent representations. For example, Kosslyn (1980) proposed that a shape is represented explicitly in memory at a particular size, orientation, and location, and as seen from a particular vantage point. Others have postulated that long-term memory representations include information about the processes used to create them, and that differences in the orientation, size, and location of a pattern may result in the involvement of different encoding processes. In this view, long-term memory representations of visual shape should contain information about the particular attributes of a visual shape that had processing consequences at the time of encoding (e.g., Kolers & Roediger, 1984).

Although the effects of the orientation of visual patterns on long-term memory have been studied extensively (e.g., Rock, 1956, 1973, 1974; Rock, Di Vita, & Barbeito, 1981; Rock & Heimer, 1957), less is known about the effects of size. The present experiments investigate whether the size of a visual shape is explicitly represented at some level of representation in long-term visual memory.

EXPERIMENTS 1a, 1b, AND 1c

People usually hold their heads upright, and most objects have a predominant orientation in the environment. Thus, there is good reason to expect that the orientation of a visual shape could be an important aspect of shapes encoded in memory. Is this also true of pattern size? On the one hand, objects are not usually seen at only one predominant size. Given that most people are free to navigate in the environment, they view objects from many different distances, and thus most objects are seen in a large range of sizes. From this point of view, we might expect that pattern size would not be encoded directly in long-term visual memory. On the other hand, pattern size must be represented in the early stages of the recognition process, and it certainly is possible that this information could be incorporated in the long-term memory representation of visual shapes.

The purpose of Experiments 1a, 1b, and 1c was to discover whether the size in which shapes are encoded would influence the subjects' ability to recognize them later. The experiments had two phases: a learning phase and a testing phase. In the learning phase, half of the shapes were presented at a relatively large size and half were presented at a small size. During the testing phase, half of the items studied at a large size were again presented large and half were presented small. Similarly, half of the items shown at a small size during the learning phase were tested small and half were tested large.

If the size of visual patterns is represented in long-term memory and if this aspect of the representation is involved during the recognition process, then patterns tested at the same size as in the learning phase should be recognized more quickly than patterns tested at a different size. If pattern size is not encoded in the representations that are used to recognize previously seen shapes, then pattern size should not affect recognition memory.

This design was repeated three times using different sets of materials. One set consisted of continuous closed curves, or "blobs," and was used in Experiment 1a. Stick figures were used in Experiment 1b. It was thought that perhaps stick figures could be decomposed into discrete features more readily than could the more "integral" blob patterns. If so, then perhaps the size manipulation would affect memory for blobs more than memory for stick figures. Finally, line drawings of natural objects were employed in Experiment 1c to discover whether the effect of pattern size would generalize to shapes that belong to clear-cut categories in long-term memory and have distinct verbal labels.

General Method

All three experiments used identical procedures and differed mainly in the type of visual stimulus subjects had to remember. First I describe those aspects of the method that all three experiments had in common, and then I describe how the experiments differed.

Subjects

The subjects were undergraduates at the University of Saskatchewan who participated in the experiment without pay. All subjects had normal or corrected-to-normal vision. Of the 48 subjects, 16 participated in each experiment.

Procedure

Every experiment involved a set of 40 distinct shapes. These 40 shapes were divided randomly into two sets of 20 shapes each (Set A and Set B). Half of the subjects studied shapes from one of the sets in the learning phase and the other half studied shapes from the other set. All 40 shapes were used in the testing phase. Different random orders of the shapes were used for each subject in both the learning phase and the testing phase, with one constraint: The first three shapes of the testing phase were always *new*. This constraint was adopted to maximize the likelihood of obtaining valid observations on *old* trials, which were of greater theoretical interest than were *new* trials.

In the learning phase, half of the shapes were presented at a relatively large size and half were presented at a relatively small size. The subjects were instructed to study each shape so as to be able to remember it in a later test of memory and were told that the size of the shape was not a relevant factor (i.e., that later memory for the shape involved remembering the shapes at different sizes). Each shape was shown for 6 sec with a 1-sec pause between shapes. The entire set of 20 shapes was shown twice. Thus, each shape was studied for a total of 12 sec.

The testing phase began after a brief pause to instruct the subjects and to change slide trays on the projector. Half of the shapes shown at a small size in the learning phase were tested small and half were tested large. Similarly, half of the shapes seen at the large size in the learning phase were tested large and half were tested small. Across every 8 subjects, each slide was used once in each cell of the design (learned small or large; tested small or large; target or foil). The foils were assigned to counterbalancing cells in the same manner as were targets (for foils the learning size was a dummy variable).

The subject's task was to decide, as quickly as possible while making as few errors as possible, whether a shape had been seen in the study phase, while ignoring possible size differences between the first and the second presentation. Responses were indicated by pressing one of two buttons. In each trial of the testing phase, an electronic shutter was opened at the beginning of the trial, which allowed the slide to be projected onto a rear-projection screen. Response time was measured from the opening of the shutter to the subject's keypress. Responses and response times were recorded by a computer. The slide remained in view until the subject made a response or until 4 sec had elapsed. The intertrial interval was 1 sec.

Materials

In each experiment the 40 shapes were photographed onto 35-mm slides with each shape photographed at two sizes that differed by roughly a 7:1 ratio (by placing the camera at different distances from the originals).

Experiment 1a (blobs). The shapes were 40 closed curves (blobs) drawn in black ink on white background. The shapes varied in the number of lobes formed by the outline curve from two to six, with

8 shapes having each possible number of lobes. Example blobs can be seen in Figure 1. These shapes were photographed onto 35-mm slides. Each shape was photographed twice, once for presentation in the learning phase and once for presentation in the testing phase of the experiment. These patterns were divided into two sets of 20 shapes such that each set had an equal number of shapes with a particular number of lobes. The average size of the stimuli was 4.7° of visual angle for the small presentation size and 34.4° for the large presentation size.

Experiment 1b (stick figures). Each of the 40 shapes was a stick figure composed of six line segments. The segments were of the length ratios 10:5:3, with one long segment (10 units), two medium segments (5 units), and three short segments (3 units). These figures were drawn with the constraint that the intersection between segments always included an end point of at least one of the segments. Example stick figures can be seen in Figure 1. The patterns were then divided at random into two sets of 20 shapes. The average size of the stimuli was 4.0° of visual angle for the small presentation size and 29.8° for the large presentation size.

Experiment 1c (objects). Forty line drawings of objects were taken from Snodgrass and Vanderwart (1980). Four objects were chosen from each of 10 categories. The names of the objects and categories are listed in the Appendix. Drawings of the objects can be seen in Snodgrass and Vanderwart (1980). Two items from each category were assigned to one set of items (Set A) and the other 2 to the other set (Set B). The average size of the stimuli was 5.8° of visual angle for the small presentation size and 39.7° for the large presentation size.

Results

The analyses reported here focus on trials with *old* patterns, in which the subjects had an opportunity to encode the stimuli at a particular size. An analysis of *new* trials across Experiments 1a–1c showed that *new* trials were responded to more slowly than *old* trials but failed to reveal any other significant effect ($p > .10$ in all cases).

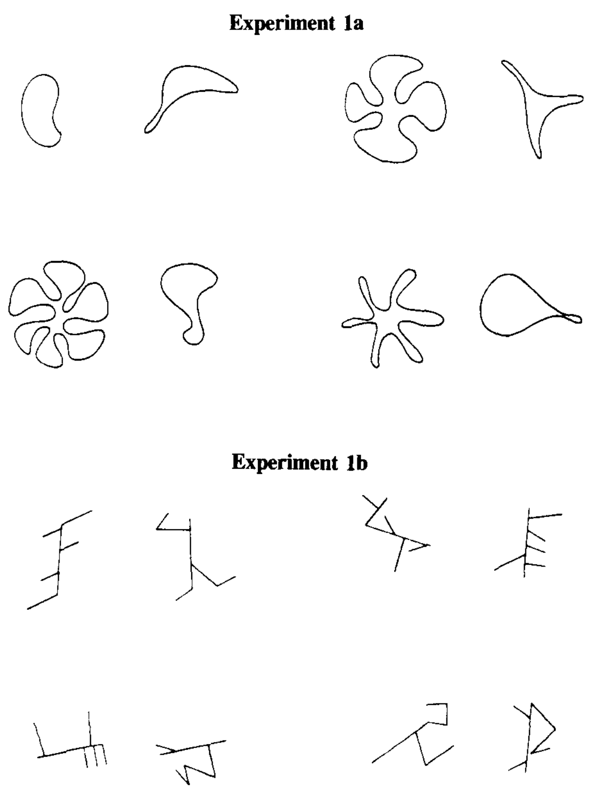

Figure 1. Example blobs and stick figures used in Experiments 1a and 1b, respectively.

Experiment 1a (Blobs)

A number of the subjects in Experiment 1a (blobs) and in Experiment 1b (stick figures) had relatively high error rates. Initially, it was feared that this would obscure the results for correct responses, and several additional subjects were tested to replace the data from those subjects with high error rates. (A subject's data was rejected if any one cell in the experiment had an accuracy level of less than 40%.) After the experiment was almost completed, I analyzed the data and discovered that the rejected subjects showed the same pattern of results as did the subjects who were to be included in the final analyses. At that point, I relaxed the criterion for rejection of subjects. I present the results for the 16 subjects with the lowest error rates in their respective counterbalancing conditions (which ensures that each shape was tested equally often in each condition in the experiment).

Response times. For each subject I averaged the response times for correct responses to slides that had been seen during the learning phase. These means were submitted to a repeated measures analysis of variance in which subjects, learning size, and testing size were considered as factors.

The mean response time for shapes learned at small and large sizes and tested at small and large sizes is displayed in Figure 2 (left panel). Shapes tested small had relatively fast response times if they had been learned at small sizes, and they had relatively slow response times if they had been learned at large sizes. Conversely, shapes tested large yielded fast times if they had been learned large, and yielded slow times if they had been learned small. This pattern of results was reflected in the analysis by an interaction between learning size and testing size [$F(1,15) = 8.97$, $p < .01$, $MSe = 1.655991 \times 10^5$]. Shapes learned and tested at the same size were thus recognized more quickly than shapes learned and tested at different sizes. There were no other significant effects in the analysis ($F < 1$ in all cases).

Errors. The mean number of errors for each subject for shapes learned at each size and tested at each size was submitted to the same type of analysis that was used for the response times. The percent error rate for patterns learned and tested at each size is shown in Figure 2 (right panel). Subjects made more errors when the patterns were learned and tested at different sizes, which resulted in a significant interaction between learning size and testing size [$F(1,15) = 10.7$, $p < .006$, $MSe = 5.83329 \times 10^{-1}$]. This pattern of error rates mirrors what was found for the response times. Thus, the pattern of response times did not result simply from speed–accuracy trade-offs.

As can be seen in Figure 2, more recognition errors were made when the patterns had been studied at a small size (26%) than when they had been studied at a large

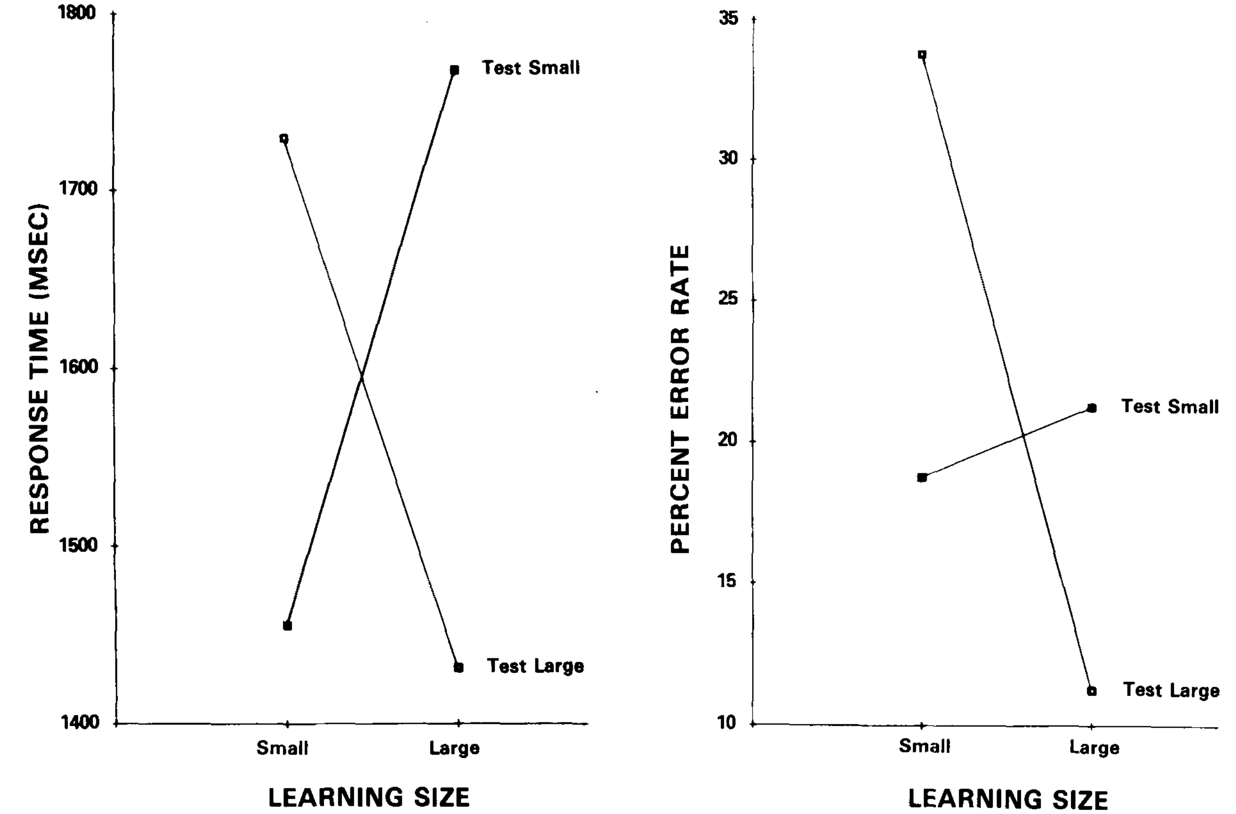

Figure 2. Mean recognition time (left panel) and mean percent error rate (right panel) for blobs learned small and large and tested small and large in Experiment 1a.

size (16%) [$F(1,15) = 10.00, p < .007, MSe = 3.999985 \times 10^{-1}$]. This particular difference in error rates was not replicated in Experiments 1b or 1c, and thus it may have been spurious. For this reason, it is not discussed further.

Experiment 1b (Stick Figures)

Response times. The response times were analyzed as in Experiment 1a. Figure 3 (left panel) displays the mean response time for *old* shapes learned and tested at a small and large size. Again, patterns tested at the size at which they were learned resulted in faster recognition than patterns tested at a different size [$F(1,15) = 7.73, p < .015, MSe = 4.203517 \times 10^4$]. The tendency for patterns shown at a small size during the test phase to result in longer recognition times than patterns tested large did not reach statistical significance [$F(1,15) = 3.45, p > .08, MSe = 7.29575 \times 10^4$].

Errors. The error data were also analyzed as in Experiment 1a, and Figure 3 (right panel) displays the mean percent error rate for shapes learned and tested at small and large sizes. Again, there were fewer recognition errors when the shapes were tested at the same size at which they had been learned [$F(1,15) = 8.77, p < .01, MSe = 8.6252 \times 10^{-1}$]. There were no other significant effects in the error analysis ($p > .10$ in all cases).

Experiment 1c (Objects)

Response times. The response times were analyzed as in Experiment 1a. Figure 4 (left panel) displays the mean recognition time for objects learned and tested at small and large sizes. Again, recognition time was faster when the size of the test pattern matched the size of the pattern shown during the learning phase [$F(1,15) = 6.45, p < .023, MSe = 2.441854 \times 10^4$]. In addition, patterns tested at the large size were recognized faster overall than patterns tested small [$F(1,15) = 6.26, p < .024, MSe = 1.878309 \times 10^4$].

Errors. The error data were analyzed as in Experiment 1a. Figure 4 (right panel) shows the mean percent error for objects learned and tested at small and large sizes. Again we replicated the pattern of errors found in Experiments 1a and 1b: There were more recognition failures when objects were tested at a size different from that used during the study phase of the experiment [$F(1,15) = 7.35, p < .017, MSe = 2.572852 \times 10^{-1}$]. There were no other significant effects in this analysis ($p > .45$ in all cases).

Note that the error rate in Experiment 1c was substantially lower than the rates in Experiments 1a and 1b. Thus, we can be confident that the results in Experiments 1a and 1b were not caused by the relatively poor performance,

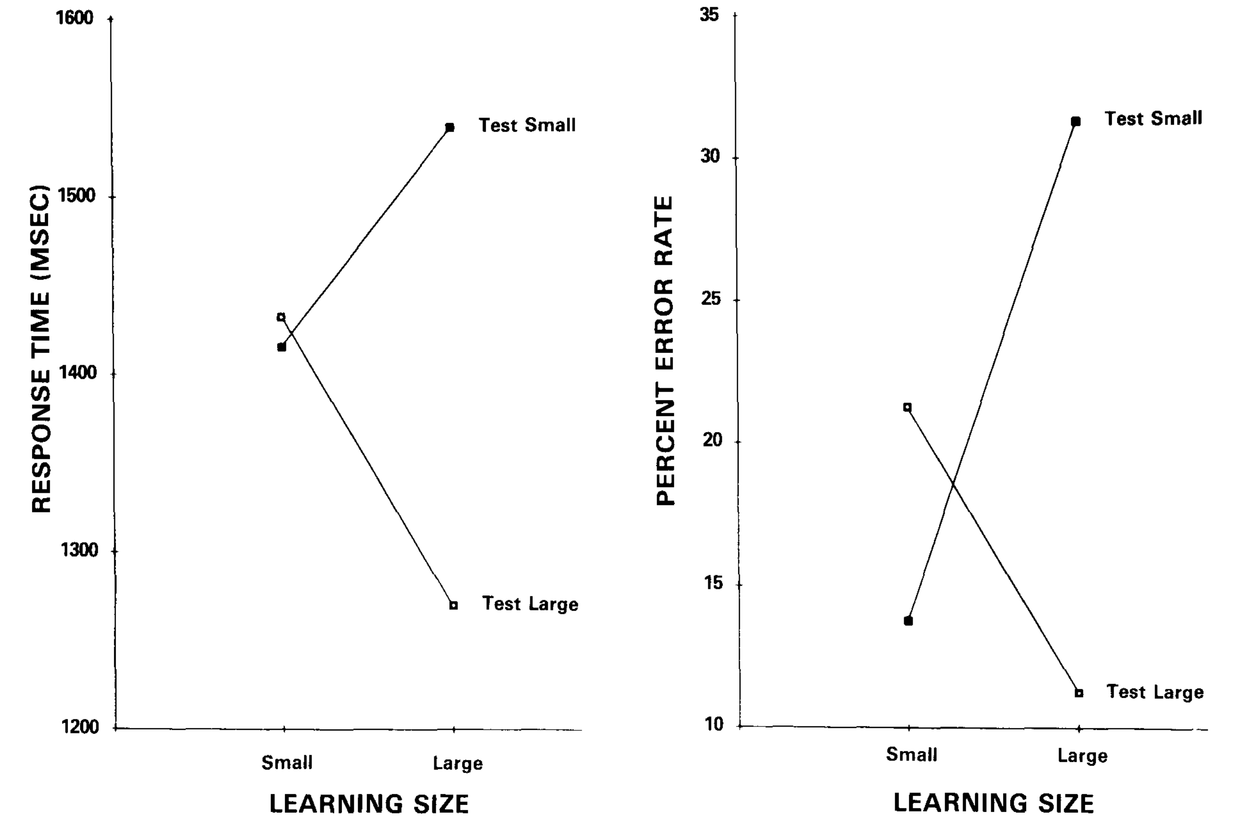

Figure 3. Mean recognition time (left panel) and mean percent error rate (right panel) for stick figures learned small and large and tested small and large in Experiment 1b.

because we found the same general pattern of results in all three experiments (better performance when the size of the pattern at testing was the same as that seen in the learning phase).

Comparison Across Experiments

Performance on *old* trials was compared across the three experiments, which was possible given that the same number of subjects and the same design was used in all three cases. In these analyses, experiments was a between-subjects factor, and learning size and testing size were within-subjects factors.

Response times. As we would expect from the above analyses, there was a strong interaction between learning size and testing size [$F(1,45) = 20.58, p < .0001$, $MSe = 7.735094 \times 10^4$]. However, the magnitude of this interaction did not differ significantly between experiments [$F(2,45) = 2.43, p > .099, MSe = 7.735094 \times 10^4$]. There were only two other significant effects in the analysis. First, the overall mean response time was different in different experiments (blobs, 1,596 msec; stick figures, 1,414 msec; objects, 877 msec) [$F(2,45) = 16.23$, $p < .0001$, $MSe = 5.511319 \times 10^5$]. Further analyses (using contrasts) found that the overall mean response time did not differ between blobs and stick figures [$F(1,45) = 1.92, p > .17, MSe = 5.511318 \times 10^5$]. However, the mean recognition time was faster for objects than for the time averaged across blobs and stick figures [$F(1,45) = 30.55, p < .0001, MSe = 5.511318 \times 10^5$]. Second, there was a marginal tendency for shapes tested small to result in slower times than shapes tested large [$F(1,45) = 3.83, p < .057, MSe = 8.160499 \times 10^4$].

Errors. Again, the analysis reflected the fact that patterns tested at the same size as they were learned were recognized more often [$F(1,45) = 25.77, p < .0001$, $MSe = 5.677114 \times 10^{-1}$]. There was no tendency for this effect to differ across experiments ($F < 1$). As in the results for recognition time, there were substantial differences in the overall level of performance across the three experiments (blobs, 21%; stick figures, 19%; objects, 6%) [$F(2,45) = 12.16$, $p < .0001$, $MSe = 9.177421 \times 10^{-1}$]. There was only one other significant effect in the analysis: the effect of learning size of the patterns was different across experiments [$F(2,45) = 4.87, p < .013, MSe = 4.566258 \times 10^{-1}$]. In Experiment 1a (blobs) patterns learned small were recognized more poorly than patterns learned large (learned small, 26%; learned large, 16%), whereas in Experiments 1b (stick figures) and 1c (objects) the opposite pattern of results was found (stick figures learned small, 18%; learned large, 21%; objects learned small, 5%; learned large, 7%).

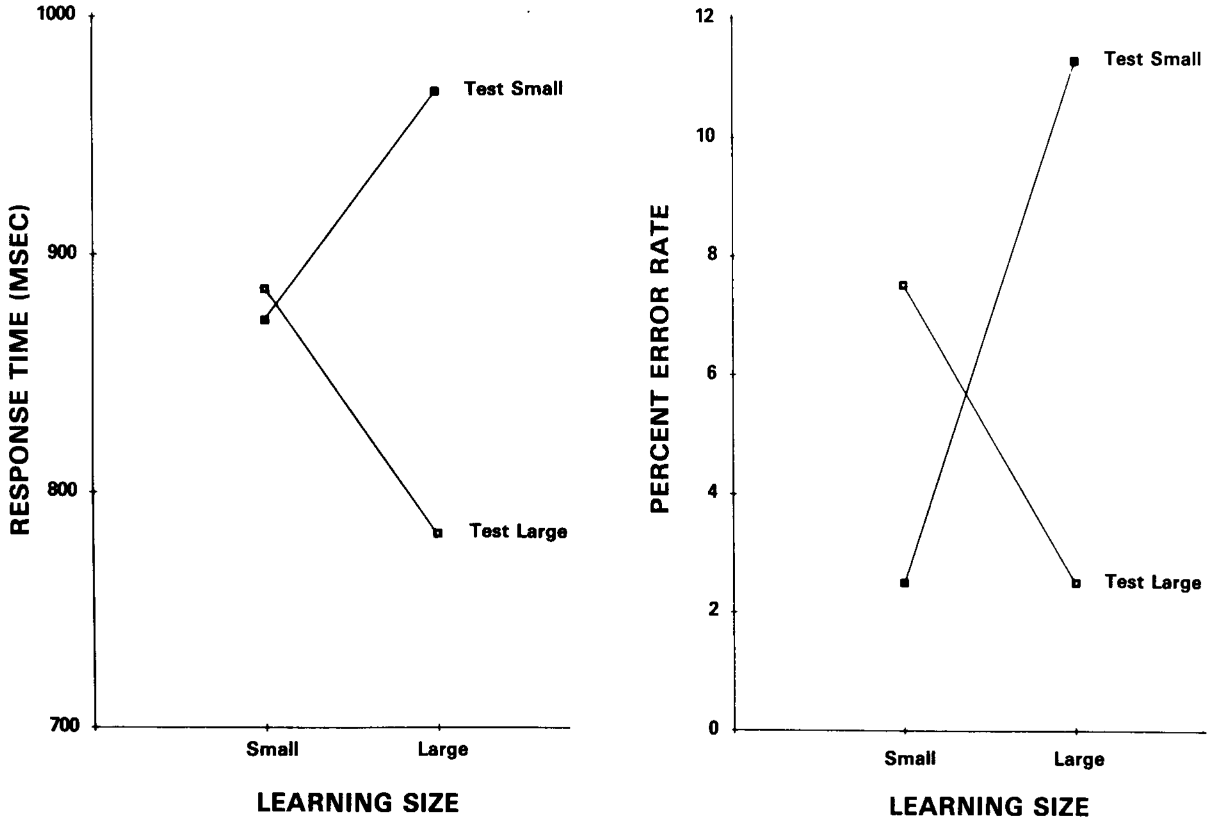

Figure 4. Mean recognition time (left panel) and mean percent error rate (right panel) for objects learned small and large and tested small and large in Experiment 1c.

Discussion

The main results were clear-cut: Recognition was faster and more accurate when the size of the test shape was the same as the size at which the shape had been learned than when the size was different. This size-congruency effect was evident in all three experiments, which suggests that the effect is quite general across a number of different stimulus materials. Further discussion of the size-congruency effect is left for the General Discussion.

EXPERIMENT 2

The size-congruency effect found in Experiments 1a, 1b, and 1c may remind some readers of the size-ratio effect in experiments in which pairs of shapes must be judged as same or different (Besner, 1983; Besner & Coltheart, 1975, 1976; Bundesen & Larsen, 1975; Bundesen, Larsen, & Farrell, 1981; Corcoran & Besner, 1975; Jolicoeur & Besner, 1987; Kubovy & Toth, 1985; Larsen, 1985; Larsen & Bundesen, 1978; Posner & Mitchell, 1967; Sekuler & Nash, 1972). The time to decide whether two shapes are the same, except for a possible irrelevant difference in size, increases linearly as the ratio of sizes of the shapes increases. It is possible that the same mechanism involved in the shape matching paradigm may be involved in the size-congruency effect found in Experiments 1a, 1b, and 1c. If so, one would expect that the magnitude of the size-congruency effect would depend on the ratio of sizes of the shapes seen in the learning phase and in the testing phase. To investigate this possibility, the present experiment included two different size ratios: 1:2 and 1:4. Larger size-congruency effects should occur in the 1:4 condition than in the 1:2 condition if scaling processes are involved. In addition, if the size-congruency effect is found with both of these size ratios, then we will have evidence that the size congruency is not confined to the rather large ratio used in Experiments 1a, 1b, and 1c, which was 1:7. Finally, the absolute size of the larger stimuli was smaller in the present experiment (8° of visual angle in the 1:2 condition and 16° in the 1:4 condition) than in the first three experiments (30° to 40° of visual angle). If the size-congruency effect is replicated, then we will have evidence that the effect is not confined to the rather large absolute sizes used in these experiments.

Method

Subjects

The subjects were 32 undergraduates at the University of Waterloo with normal or corrected-to-normal vision who participated in the experiment for pay. None of these subjects participated in any other experiments reported in the present paper.

Stimuli

The stimuli were the 40 blobs used in Experiment 1a and the 40 stick figures used in Experiment 1b. The slides used for the large

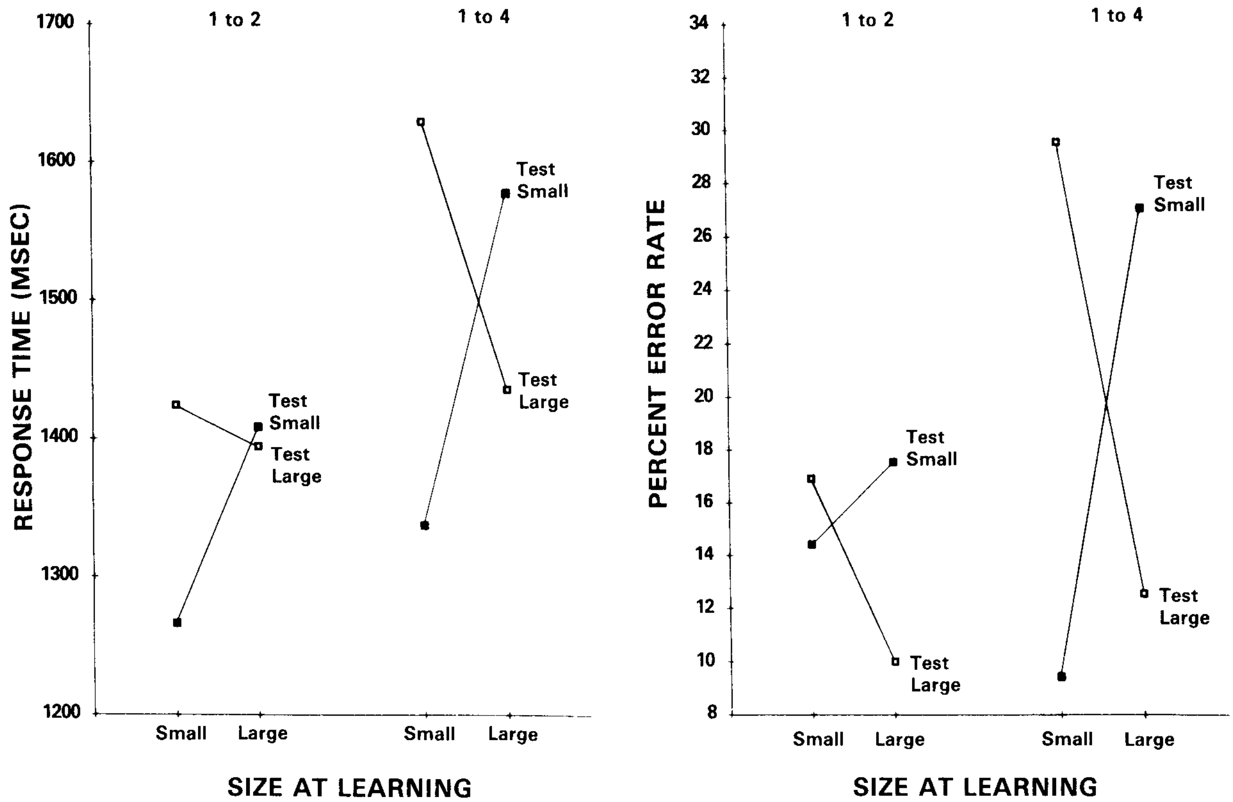

Figure 5. Mean recognition time (left panel) and mean percent error rate (right panel) for shapes learned small and large and tested small and large in the 1:2 and the 1:4 size-ratio conditions in Experiment 2.

condition in Experiments 1a and 1b were used. These slides were displayed by two Kodak carousel slide projectors onto a rear-projection screen. One projector displayed the small stimuli, which were shown at an average visual angle of 4° for both the blobs and stick figures. The second projector was used for the larger size by placing this projector further from the screen. The size of the displayed shapes was changed further by adjusting a zoom lens to achieve either a 1:2 size ratio or a 1:4 size ratio. Using this arrangement, the slides displayed at the smaller size were also noticeably brighter than those shown at the larger size. To compensate for this brightness difference, a neutral-density filter was placed in front of the lens of the projector used for the smaller size. The brightness was set so as to be about equal for both sizes, as judged by two assistants in the laboratory and by the author.

Procedure

The procedure was similar to that used in the first three experiments. The main differences were as follows. First, every subject participated in two sessions, back-to-back. One of these sessions was essentially identical to Experiment 1a and the other one was identical to Experiment 1b, except for the difference in size ratio. One of the sessions involved a 1:2 size ratio between the small and large presentation sizes, whereas the other session involved a 1:4 size ratio. Every possible order and combination of stimulus type (blobs, stick figures) and size ratio (1:2, 1:4) was used once. Thus, half of the subjects performed the recognition memory task with the blob stimuli first and then with the stick figures, whereas the other half performed the tasks in the other order. Furthermore, half of each of the above groups performed the first memory task with a 1:2 size ratio first and then they did the task again with different stimuli and with the 1:4 size ratio. The other half had the opposite order of size ratios.

Results

Response Times

As in Experiments 1a, 1b, and 1c, the analyses focused on *old* trials, in which the effects of size congruency could be examined. Given that the results from Experiments 1a and 1b were so similar (see Figures 2 and 3), the results were collapsed across stimulus type. The response times for correct responses were averaged for each subject, in each condition of learning size, testing size, and size ratio. These means were submitted to a repeated measures analysis of variance in which size ratio, learning size, and testing size were within-subjects variables. The results can be seen in Figure 5 (left panel). The size-congruency effect found in Experiment 1a, 1b, and 1c was found in the present experiment as well; shapes tested at the same size as seen in the learning phase of the experiment were recognized faster than shapes tested at a different size [$F(1,31) = 13.66, p < .0009, MSe = 1.06685 \times 10^5$]. The only other effect in the analysis that approached statistical significance is the three-way interaction between size ratio, learning size, and testing size [$F(1,31) = 2.73, p < .109, MSe = 9.848052 \times 10^4$]. As can be seen in Figure 5 (left panel), this interaction reflects the fact that the magnitude of the size-congruency effect was larger in the 1:4 condition than in the 1:2 condition. There were no other significant effects in the analysis ($p > .12$ in all cases).

Errors

The mean number of errors in each condition of the experiment was computed for each subject. These error rates, which can be seen as percentages in Figure 5 (right panel), were submitted to the same type of analysis as were the response times. As for the response times, the size-congruency effect was highly significant [$F(1,31) = 25.70$, $p < .0001$, $MSe = 7.661538 \times 10^{-1}$]. Furthermore, the magnitude of the effect was larger in the 1:4 condition than in the 1:2 condition [$F(1,31) = 7.36$, $p < .011$, $MSe = 8.077935 \times 10^{-1}$]. There was only one other significant effect in the analysis, due to a higher error rate overall in the 1:4 condition (19.5%) than in the 1:2 condition (14.7%) [$F(1,31) = 7.18$, $p < .012$, $MSe = 5.229358 \times 10^{-1}$]. All other effects had $p > .14$. Clearly, the size-congruency effects found in the mean response times were not caused by speed-accuracy tradeoffs. In fact, it seems likely that the opposite situation may have arisen. That is, the marginal three-way interaction between size ratio, learning size, and testing size in the analysis of response times is likely due to the fact that this effect appeared in the error rates instead. Had subjects taken enough care to properly recognize the *old* size-discrepant shapes in the 1:4 condition, it is likely that they would have taken much more time than they did, and the interaction with size ratio would have been significant rather than only marginal.

Discussion

A strong size-congruency effect was found in both size-ratio conditions in both recognition times and recognition accuracy. Thus, the congruency effects found in Experiments 1a, 1b, and, in all likelihood, 1c were not due only to the large size ratio or to the large absolute size of the larger stimuli. Furthermore, the size-congruency effect was larger in the 1:4 size ratio condition than in the 1:2 condition in the analysis of error rates, with a trend in this direction in the analysis of response times. These results suggest that the size-congruency effect is sensitive to the magnitude of the size difference between shapes shown in the learning phase and in the testing phase. Thus, the results are consistent with the notion that size-scaling operations first discovered in the context of shape matching experiments (e.g., Posner & Mitchell, 1967; Sekuler & Nash, 1972) may be involved in the recognition process and may be at the root of the size-congruency effect.

EXPERIMENT 3

In Experiment 3, which was essentially a replication of Experiment 2, the stimuli were displayed on a computer screen rather than with slides on a rear-projection screen. While running this series of experiments, I became concerned that the size manipulation could have been confounded with other aspects of the displayed patterns, when the size manipulation was achieved using slides and projectors. For example, in Experiments 1a, 1b, and 1c, patterns shown in the smaller size also had thinner lines, given that the entire pattern had been scaled down proportionally by a factor of about 7:1 in the original photographic process. The smaller patterns were more sensitive to the quality of focus than were the larger patterns, since slightly moving the focus mechanism affected the appearance of the small patterns more than the appearance of the larger patterns. Although the experimenters always took great care to set the focus on the projector using a small pattern, I remained concerned that the size effect might have been due to a differential quality of the slides for small and large patterns, despite our careful attempts to avoid such differences. In Experiment 2, because of the smaller size ratios used, and because of the method used to change projection size (the same slides were used always, and different sizes were obtained by moving the projector closer to or farther from the screen), the focus issue was not a problem. On the other hand, the different presentation sizes in Experiment 2 were associated with different brightness levels. Although I compensated for the brightness differences using neutral density filters, I was concerned that a residual brightness difference might have confounded the results despite the attempts to avoid this problem.

Both of these potential problems were avoided in Experiment 3. The stimuli were displayed on a computer monitor such that the intensity of the outline of the shapes (and the contrast with respect to the background) was the same at all sizes. Also, the lines were equally thick at all sizes, and thus they should have been equally visible across all conditions (although this changes the width of the line relative to the total pattern size).

Finally, smaller absolute sizes than those used in the previous four experiments were used in the present experiment. This change was introduced to reduce further the possibility that the absolute size of the stimuli was the cause of the size-congruency effect. A possible mechanism that could mediate this type of effect would be a differential need for eye movements to encode the shapes when they are presented at different sizes. Another possibility is that the representations of the larger shapes may have been influenced more by the proximity of the frame of the rear-projection screen than were those of the smaller shapes. These sorts of explanations are plausible in the context of Experiments 1a, 1b, and 1c, in which the absolute size of the large presentation size was between 30° and 40° of visual angle. However, these accounts are less plausible in Experiment 2, in which the maximum visual angle was 8° in the 1:2 size ratio condition, which nonetheless produced a strong size-congruency effect. In the present experiment, the maximum visual angle was 2.6° in the 1:2 size ratio condition. If the size-congruency effect is found once more, accounts hinging on the absolute size of the larger stimuli will be even less plausible.

Method

Subjects

The subjects were 32 undergraduates at the University of Waterloo with normal or corrected-to-normal vision who participated in the experiment for pay. None of these subjects participated in any other experiments reported in the present paper.

Stimuli

The stimuli were similar to those used in Experiment 2, but they were adapted for presentation on an Apple II microcomputer. The blobs were replaced with 40 closed polygons whose edges were always horizontal or vertical, and thus all vertices had 90° angles. The stick figures were replaced with 40 stick figures in which the segments were always horizontal or vertical. All stimuli, at the smallest size, subtended about 1.3° in height and 1.2° in width. In the 1:2 condition large stimuli were 2.6° high by 2.4° wide, and in the 1:4 condition they were 5.2° high and 4.6°wide.

Procedure

The procedure was identical to that used in Experiment 2 except for the differences in shapes, the absolute size of the shapes, and the method of presentation. The stimuli were displayed using an Apple II computer, which also performed all timing operations and recorded responses.

Results

Response Times

The data were analyzed as in Experiment 2. The mean recognition time for *old* shapes in each condition can be seen in Figure 6 (left panel). As in the first four experiments, the results exhibited a strong size-congruency effect; shapes tested at the same size as seen in the learning phase of the experiment were recognized faster than shapes tested at a different size [$F(1,31) = 27.99$, $p < .0001$, $MSe = 1.433822 \times 10^5$]. Overall, shapes tested at the small presentation size tended to be recognized faster than shapes tested at the larger size, which resulted in a marginal effect of test size [$F(1,31) = 3.90$, $p < .058$, $MSe = 1.259296 \times 10^5$]. There were no other significant effects in the analysis ($p > .07$ in all cases). In particular, the three-way interaction between size ratio, learning size, and testing size was not significant ($F < 1$). As in Experiment 2, however, this expected interaction was found in the error rates.

Errors

The mean number of errors in each condition of the experiment was computed for each subject. These error rates, which can be seen in percentage form in Figure 6 (right panel), were submitted to the same type of analysis as were the response times. As for the response times, the size-congruency effect was highly significant [$F(1,31) = 40.77$, $p < .0001$, $MSe = 5.979974 \times 10^{-1}$]. Furthermore, the magnitude of the effect was larger in the 1:4 condition than in the 1:2 condition [$F(1,31) = 10.74$, $p < .003$, $MSe = 3.496673 \times 10^{-1}$]. There was only one other significant effect in the analysis, due to a higher er-

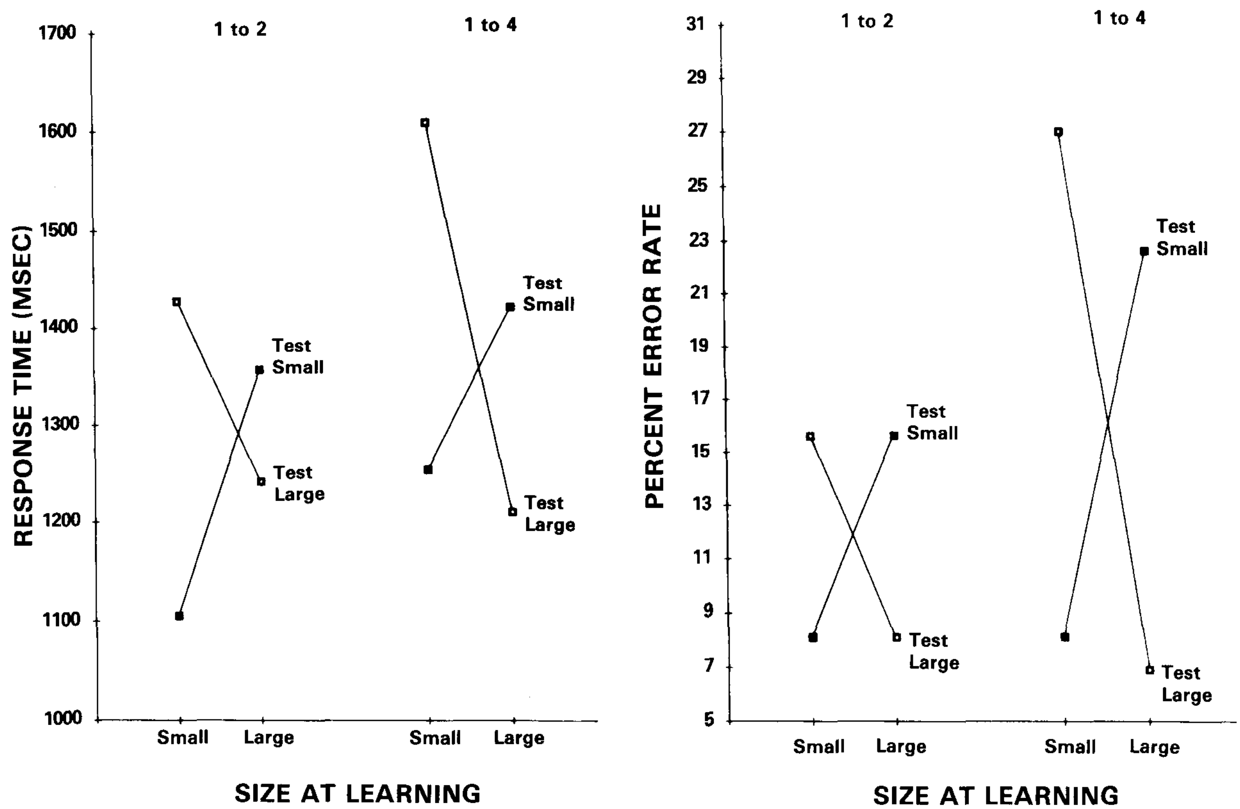

Figure 6. Mean recognition time (left panel) and mean percent error rate (right panel) for shapes learned small and large and tested small and large in the 1:2 and the 1:4 size-ratio conditions in Experiment 3.

ror rate overall in the 1:4 condition (16.1%) than in the 1:2 condition (11.9%) [$F(1,31) = 5.03$, $p < .033$, $MSe = 5.658455 \times 10^{-1}$]. All other effects had $p > .38$. Clearly, the size-congruency effects found in the mean response times were not caused by speed–accuracy trade-offs.

Discussion

A strong size-congruency effect on recognition speed and on accuracy was found in both size-ratio conditions. We can be confident that the size-congruency effects found in the first four experiments were not due to experimental artifacts such as the large absolute size of the larger stimuli, or in systematic differences between patterns shown in the different size conditions other than their size.

As in Experiment 2, the size-ratio manipulation had a larger effect on recognition accuracy than on recognition time. The reason for this finding is not clear. One possibility is that subjects adopted a deadline for responding "old." In this view, if the shape was not recognized as previously seen before this deadline, then subjects responded "new." On the assumption that a size-scaling operation is involved in the recognition process, we would expect longer recognition time in the 1:4 size-ratio condition. With a fixed deadline, more recognition failures would be expected in this condition than in the 1:2 size-ratio condition, as was found. This account will remain tentative until more research is carried out, however.

GENERAL DISCUSSION

The results of these experiments demonstrate the generality of the size-congruency effect across a wide variety of visual stimuli and presentation conditions. The stimuli ranged from unfamiliar stimuli that presumably could not be categorized into existing categories in the subjects' memories (blobs and stick figures) to more familiar ones (depictions of natural objects) that could be named and categorized easily. They included shapes that seem difficult to analyze into discrete features (blobs) to shapes that could be decomposed easily into discrete features (simple stick figures). The shapes were displayed using either slides or computer displays, and over a wide range of sizes.

In general, the results of these experiments demonstrate that the representation of visual shapes in memory is influenced by the size in which the pattern is seen during encoding. Two theoretical interpretations of the main findings are discussed next. I will refer to them as the "representation hypothesis" and the "encoding hypothesis." According to both hypotheses, the size-congruency effect results from a mismatch between the representation stored in memory and the representation produced at the time of recognition. However, the hypotheses differ in the nature of representational difference.

The Encoding Hypothesis

According to the encoding hypothesis, the differences between memory representations of shapes seen at different sizes reflect accidental by-products of encoding processes rather than fundamental properties of the representation of visual shape. In this view, the representation of visual shape is achieved in a representational format that is essentially size invariant. However, shapes shown in different sizes lead to differences in the way in which the shapes are encoded. For example, larger shapes may require a larger number of eye movements than do smaller shapes, which could result in different features being encoded, even if we postulate a model in which shapes are represented using size-invariant features. Although the encoding hypothesis is plausible in the context of Experiments 1a, 1b, and 1c, in which the stimuli were rather large in the large presentation size condition, it seems much less attractive as an account of the results in Experiment 2 and especially in Experiment 3. In Experiment 3, a large size-congruency effect was found in the 1:2 size-ratio condition in which the largest stimuli subtended only 2.6° of visual angle. Although the present results do not completely discredit the encoding hypothesis, in my view the results provide more support for the representation hypothesis, which is presented next.

The Representation Hypothesis

According to the representation hypothesis, the size of a shape is an important part of the representation of the shape in long-term memory. One view is that the representation of a shape *has a size*—in the functional sense—rather than that it merely represents the size of the shape. Template models of pattern recognition, as outlined in many textbooks of cognitive psychology, postulate this property (e.g., Lindsay & Norman, 1972). Kosslyn's (1980) model of mental imagery also postulates that images have a size rather than that they merely represent size. According to Kosslyn, images are active structures in visual short-term memory. The structures are patterns of activated cells in a functional array called the visual buffer. The visual buffer has a finite size, and the activity in the buffer can be confined to a small number of nearby cells, in which case the image *is small*, or the activity can extend over a large area within the buffer, in which case the image *is large*. Another view is that visual shapes are represented in a multidimensional space in which different regions of the space correspond with different attributes of visual shapes, one of which is size (Shepard, 1981). Furthermore, the regions of the space between these two regions representing different sizes themselves represent intermediate sizes. The representations do not have a size, but the representation of patterns at different sizes leads to distinct representations in the multidimensional space. Therefore, these representations are not size invariant. Mental transformations of the size of a shape, in this approach, correspond with moving through the space in such a way as to alter only the size of the shape while leaving the other attributes unchanged. According to the model, however, one cannot instantaneously change the represented size from small to large. Rather, the represented size must change gradually as a path is traversed in the space, and larger transformations (i.e., larger size ratios) correspond with longer paths through the space.

In all of the above representational accounts, one would expect that larger changes in the size of the shapes between learning and testing should result in longer recognition times and/or less accurate recognition, as was found in every experiment reported in the present paper. This prediction derives from the assumption that shapes differing only in size have systematically different representations, and that transformations along the size dimension are achieved by analog processes that take longer to run to completion when a larger transformation is required. The continuous/analog nature of the postulated transformation either of the memory trace or of the encoded test shape is similar to the size-scaling mechanism discussed in the shape matching literature (e.g., Bundesen & Larsen, 1975; Jolicoeur & Besner, 1987; Larsen, 1985; Larsen & Bundesen, 1978; Posner & Mitchell, 1967; Sekuler & Nash, 1972). The present results are consistent with this earlier work and suggest extensions to situations in which shapes must be matched with memory representations of previously seen shapes.

Encoding Specificity for Visual Shapes

The size-congruency effect found in the present study can be thought of also in the theoretical context of encoding specificity (Tulving & Thomson, 1973). In this view, recognition memory will be superior to the extent that the test stimulus approximates the stimulus conditions during the encoding of the memory trace. Memory should be superior, therefore, to the extent that the test shape is in the same size as the encoded shape. Although this is a reasonable *description* of our results, it does not provide an *explanation*, given that the encoding specificity principle, by itself, is not a process model of visual memory or of pattern recognition. The general notion of encoding specificity does not allow us to predict which attributes of visual shapes are represented and, thus, which attributes are likely to produce a specificity effect. Therefore, we must determine empirically what dimensions or attributes of visual shapes are represented in visual memory and involved in visual recognition processes. The present results suggest that pattern size is an important dimension along which shapes can vary in that variations in pattern size have substantial consequences for recognition speed and accuracy.

Levels of Representation

Although the present results suggest that some level of representation in the human visual system preserves size-specific information, they do not, of course, preclude the possibility that other levels of representation could represent visual shape information independently of the input size. For example, it is possible that the visual system represents shapes at a variety of levels of abstraction and that the more abstract levels do not retain specific aspects of visual shapes such as size, location, or orientation (e.g., Hinton, 1981; Marr, 1982; Marr & Nishihara, 1978). What the results suggest within the context of these models (e.g., Marr, 1982), however, is that not only the most abstract levels of representation are retained in long-term memory and that visual recognition can involve the less abstract levels of representation. In this light, the results are consistent with views of memory in which information about specific exemplars is thought to play an important role (e.g., Brooks, 1987).

A related issue is whether the results in the present study, in which a recognition memory paradigm was used, have any direct significance for theories of pattern recognition. It could be suggested that our experiments do not actually address the problem of pattern recognition per se, but rather address the problem of the recognition of episodic traces. According to this account, the subjects could have tried to match test shapes with specific prior visual episodes rather than with abstract representations of shapes, even though these abstract representations were available and even though "normal" pattern recognition involves matching test shapes with these more abstract representations. The present results cannot reject this notion. However, it should be noted that the instructions given to subjects explicitly required them to ignore size as a relevant dimension in the task. Given these instructions, it is not clear why subjects would not have used abstract size-invariant shape representations if such representations had been readily available. Even if we suppose that somehow subjects interpreted the task as suggesting a match with specific episodic traces, it is not clear why alternative size-invariant representations would not be used when a specific episodic trace could not be found (as in the 1:4 size-ratio conditions in Experiments 2 and 3, in which the error rates were high in the incongruent trials). That is, one might expect slower response times in this case (i.e., in the 1:4 ratio condition), rather than especially high error rates. Instead, the response times did not increase very much and the error rates jumped up, as though subjects could not find *any* match in memory corresponding with the test shape. Furthermore, the fact that the results parallel those found in shape matching studies in which pattern size has been manipulated suggests that the size-congruency effects found in the present study are not due to the recognition memory procedure employed in the experiments. Nonetheless, this is an empirical issue, one that will have to be resolved in future work.

Open Questions and Future Directions

A number of other issues concerning the suggested size-dependent representations of visual shapes are raised by the results. For example, would the size-congruency effect be observed at longer lags between learning and testing? If size-dependent representations are only intermediate representations used by the visual system at early stages of information processing, and if they are used to compute more general or abstract object-centered representations, then it is possible that these representations are relatively short lived. Perhaps less evidence for size congruency would be observed after longer delays between learning and testing. This possibility suggests that the memory procedure used in the present study should be carried out using a number of different retention intervals, so as to map out the time course of the congruency effect.

Another issue raised by the present experiments is whether shape representations are influenced by retinal size or by perceived size. Experiments manipulating both the distance of the shapes from the subject and their sizes could resolve this interesting issue.

Finally, it may be worth investigating conditions under which specificity effects can be attenuated or eliminated. For example, Jolicoeur (1985) asked subjects to name disoriented line drawings of natural objects as quickly as possible. In the first block of testing with drawings seen for the first time, mean naming time across orientation was similar to that found in a mental rotation task with the same stimuli (naming time increased sharply with increasing disorientation). However, in subsequent blocks of testing using the same materials, the size of the orientation effect was reduced significantly. With respect to the present discussion, it is possible that repeated exposure to a given shape in different sizes would reduce the magnitude of the congruency effects observed in our experiments. Whether such possible reductions in the magnitude of the congruency effects would be due to the storage of multiple size-dependent representations, or due to the formation of more abstract and size-invariant representations, is a matter for further study.

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APPENDIX

This appendix lists the names of the items used in Experiment 1c. The objects are listed by set (A or B) and by the category label in Snodgrass and Vanderwart (1980). The number in parentheses is the stimulus number in Snodgrass and Vanderwart (1980).

Category	Set A	Set B
Weapon	Airplane (2)	Cannon (45)
	Gun (112)	Hand (115)
Article of clothing	Hat (118)	Dress (78)
	Tie (232)	Watch (250)
Part of human body	Leg (134)	Ear (83)
	Lips (141)	Nose (156)

Category	Set A	Set B
Furniture	Rocking chair (188)	Couch (67)
	TV (228)	Piano (171)
Carpenter's tool	Axe (12)	Ladder (131)
	Saw (196)	Scissors (197)
Musical Instrument	Guitar (111)	Accordion (1)
	Harp (117)	French horn (99)
Vehicle	Bicycle (27)	Helicopter (120)
	Train (240)	Truck (242)
Toy	Doll (74)	Baby carriage (13)
	Kite (129)	Football (95)
Vegetable	Lettuce (137)	Corn (66)
	Mushroom (150)	Peanut (165)
Insect	Butterfly (40)	Fly (93)
	Caterpillar (50)	Spider (212)

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