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Visual pattern matching: Effects of size ratio, complexity, and similarity in simultaneous and successive matching

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Abstract An experiment on mental transformation of size, in pairwise comparison of simultaneously or successively presented figures with respect to shape, is reported. Regardless of type of presentation (simultaneous vs. successive), figural complexity, and similarity within pairs of different-shaped figures, median latencies of both *same* and *different* responses were approximately linearly increasing functions of the linear size ratio between the patterns to be compared. The slopes of the functions showed significant effects of figural complexity and similarity for simultaneous but not for successive matching. The results suggest that successive matching was done by encoding a subpattern of the first stimulus in a pair as a mental image, transforming the image to the size format of the other stimulus, and then testing for a match; in simultaneous matching the process of encoding, transformation, and comparison appeared to be executed several times for each pair of figures. The interpretation was illustrated by a random walk model, which provided a good fit to the results.

Introduction

Transformations of mental images have been studied extensively in pattern matching tasks (see works collected by Shepard & Cooper, 1982; also see Bundesen & Larsen, 1975; Bundesen, Larsen, & Farrell, 1981; Jolicoeur & Besner, 1987; Larsen, 1985; Larsen & Bundesen, 1978, 1998; Shepard, 1984; Ullman, 1989). In the most widely used paradigm, subjects are asked to decide as

quickly as possible whether two stimulus patterns are the same in shape regardless of any differences in size or orientation. The patterns may be presented side by side at the same time (*simultaneous matching*) or one by one in temporal succession (*successive matching*).

The results obtained for simultaneous and successive matching have been similar in some respects but different in others. For example, consider the findings of Bundesen and Larsen (1975) and Larsen and Bundesen (1978). Bundesen and Larsen (1975, Exp. 2) showed their subjects pairs of simultaneously presented 2-D solid random shapes. The subjects were instructed to determine as quickly as possible whether the two members of a pair were identical except for a parallel displacement and a change of size. Each stimulus pair was presented until the subject responded. Both mean and median reaction times were found to be linearly increasing functions of the linear size ratio, s , between the two members of the pair (measured such that $s \geq 1$). Averaged across subjects, the mean reaction time for a size ratio of 1 was about 750 ms. The slope of the mean reaction time function was 32 ms, which yielded a rise of about 130 ms by a run from a size ratio of 1 to a size ratio of 5.

Larsen and Bundesen (1978, Exp. 1) used exactly the same type of stimuli as Bundesen and Larsen (1975, Exp. 2), but the members of a pair were presented successively and at the same spatial location with a blank interstimulus interval (ISI) of 2 s. The results were similar to those of Bundesen and Larsen, but the mean reaction time for a size ratio of 1 was only about 475 ms, and the slope of the mean reaction time function was only 14 ms, which yielded a rise of about 55 ms by the run from size ratio 1 to size ratio 5.

The common pattern in the results of Bundesen and Larsen (1975) and Larsen and Bundesen (1978) supported the interpretation that performance in both the simultaneous and the successive matching tasks was based on a process of encoding one of the stimulus patterns in a pair as a more or less detailed visual image, gradually transforming this image to the size format of

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the other pattern, and then testing for a match. The differences between the results obtained by simultaneous versus successive matching can be explained by assuming that in simultaneous matching, the process of encoding, transformation, and comparison tends to be executed not only once, but repeatedly, until the participant feels that she or he has sufficient evidence to make a decision (cf. Bundesen & Larsen, 1975, p. 220).

The studies by Bundesen and Larsen (1975, Exp. 2) and Larsen and Bundesen (1978, Exp. 1) may be the only previous studies in which simultaneous and successive matching were directly contrasted. However, other studies appear consistent with the dual hypotheses that (a) the same process of encoding, transformation, and comparison underlies performance in simultaneous and successive matching tasks, but (b) the process normally is executed only once per stimulus pair in successive matching but several times in simultaneous matching. In particular, in Exps. 1 and 3 on simultaneous matching by Bundesen and Larsen, the rates of increase in (positive) mean reaction times as functions of size ratio were about 78 and 48 ms, respectively. Comparable slope constants were found in the simultaneous matching experiments of Larsen (1985). By contrast, in the extensive successive matching experiment of Bundesen et al. (1981), the slope of the mean reaction time function was only 16 ms.

Similar results have been obtained in studies of mental rotation. The increase in reaction time with increased difference in angular orientation between the patterns to be compared tends to be higher for simultaneous than successive matching (see, e.g., Bundesen et al., 1981; Shepard & Cooper, 1982). Furthermore, by analysis of eye movements in a replication of the classic simultaneous matching experiment of Shepard and Metzler (1971), Just and Carpenter (1976) showed that subjects looked back and forth between the two patterns to be compared. Such results lend some support to the hypothesis that simultaneous matching can be based on repeated execution of a process of encoding, transformation, and comparison.

In this paper we report a new study of mental transformation of random shapes with respect to size. The study was designed to test and further develop the above analysis of the relationship between processing in simultaneous and successive matching tasks. Our stimuli varied systematically in complexity and in the level of similarity between the members of a negative pair. The levels of similarity (*high* and *low*) were chosen so that discrimination between the two members of a negative pair was quite difficult even at the so-called low level of similarity. Previous studies suggest that when members of negative pairs are grossly different in shape, negative responses may be based on differences detected without use of mental transformation of size (cf. Besner & Coltheart, 1976; Larsen, 1985; also see Bundesen & Larsen, 1975; Jolicoeur & Besner, 1987).

For successive matching we expected that decisions would be based on a process of encoding the first stim-

ulus in a pair as a more or less detailed mental image, transforming the image to the size format of the second stimulus, and then testing for a match. Assuming that the process would be executed just once for each pair of stimuli, we conjectured that the increase in reaction time with increase in the linear size ratio between the patterns to be compared would be constant across variations in stimulus complexity and variations in the level of similarity between the two members of a negative pair.

For simultaneous matching we expected that the process of encoding, transformation, and comparison would be executed several times for each pair of stimuli. Both slopes and intercepts at size ratio 1 of functions relating reaction time to the linear size ratio between the patterns to be compared were therefore expected to be higher for simultaneous than for successive matching. In addition to testing this qualitative prediction, we hoped to be able to provide a more detailed, quantitative account of both speed and accuracy of performance.

Method

Participants. One female and three males, aged 22–27 years, participated in the study. All had normal or corrected-to-normal vision.

Stimuli. A random polygon with n vertices and $n - 1$ sides was generated by first selecting $2n$ random numbers from a uniform distribution between 0 and 1. The numbers were taken to be the coordinates of n points in the unit square, which were then joined by $n - 1$ lines: from the first to the second point, from the second to the third, and so on. This yielded a random polygon somewhere in the unit square. The polygon was then stretched in the x and y directions to completely fill the unit square. Figural *complexity* was defined as the number of sides in the polygon. Simple polygons had six sides, complex polygons had ten (see Fig. 1).

The polygons were generated in pairs. The first polygon of a pair was created as above. For a positive pair, the second polygon was identical to the first one. For a negative pair, the second polygon was created from the first polygon of the pair by adding independent random perturbations to all of the x and y coordinates of the n vertices. The perturbations were drawn from a gaussian distribution with a mean of 0 and standard deviation σ . Two levels of figural *similarity*, high and low, were defined by setting $\sigma = 0.05$ and $\sigma = 0.1$, respectively (recalling that the first polygon was exactly 1 unit wide and 1 unit high).

Finally, each of the polygons in the pair were scaled one last time to appear on the computer screen. This final scaling determined the size of the polygon. Three sizes were available: small (S), medium (M), and large (L) in the ratio 1:1.54:6. These sizes gave four different size ratios for the polygon pairs: 1 (S:S, M:M, L:L), 1.54 (M:S), 3.90 (L:M), and 6 (L:S). The smallest polygons fitted into a square 50 pixels wide, corresponding to 2.1 cm on the screen. The polygons were rendered by 1-pixel white lines on a black background. They were not antialiased.

Procedure. The participants were tested individually. They were seated in front of the display screen at a viewing distance of 60 cm in a semi-darkened room. Their task was to decide whether or not the two members of a pair of stimulus polygons were the same in shape regardless of any difference in size. Viewing was binocular and fixation was free.

Each subject participated in ten experimental sessions over a few days. In each session, trials were blocked according to a

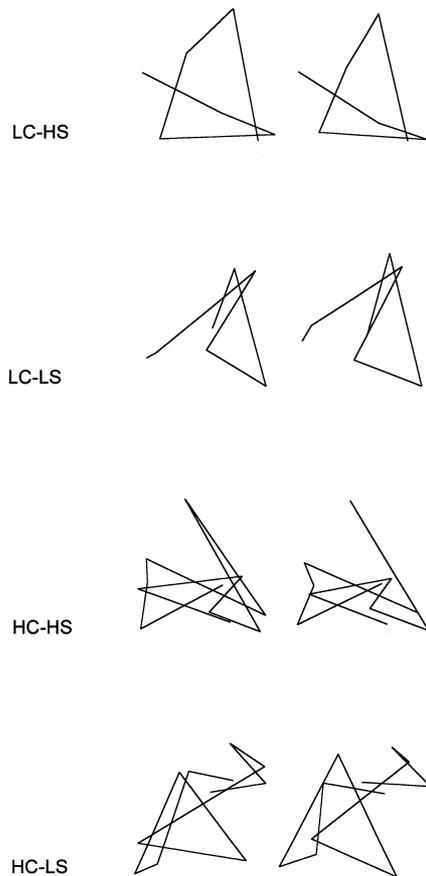


Fig. 1 Examples of negative stimulus pairs. LC = low complexity; HC = high complexity; HS = high similarity; LS = low similarity

combination of three factors: presentation (successive or simultaneous matching), figural complexity (six or ten sides), and figural similarity (high or low). All eight possible blocks were done in random order in each session. The subject was informed which block was to be done at the start of each block.

Each block consisted of 90 trials, preceded by 5 practice trials. On each trial, a new pair of random polygons was displayed. Trials were defined by a combination of three factors: same-pair or different-pair, size of the first polygon (S, M, or L), and size of the second polygon (S, M, or L). In each block, there were 5 trials for each possible combination of these factors, presented in random order. Excluding practice, each subject ran 7,200 experimental trials. The subject was allowed to rest between blocks and could take a pause in the experiment at any time. Otherwise, trial pacing was controlled by computer.

On trials in simultaneous-matching blocks, the subject was shown two polygons side by side. The polygons were centered symmetrically around a fixation mark in the middle of the screen. The center-to-center distance between the polygons was 15 cm. They remained on screen until the subject responded. The next trial commenced 700 ms after the response.

On trials in successive-matching blocks, the subject was shown two polygons at the same locations as those that were used in simultaneous matching, but the polygons were presented one by one. The first polygon in a pair was shown at the left-hand location for 500 ms. After a blank ISI of 1,000 ms, the second polygon was displayed at the right-hand location until the subject responded. Again, the next trial commenced 700 ms after the response. A central fixation mark was shown whenever the screen was blank.

On all trials, the subject responded by clicking a mouse button: left for same-pair and right for different-pair, or vice versa, depending on subject preference. Feedback was not given.

Equipment. The experiment was implemented as a Tcl program running under Windows 95 on a 166 MHz (or faster) Pentium computer. Reaction time from the onset of the stimulus display to the mouse response was measured to the nearest 16 ms (average precision 8 ms) by a Tcl module, which accessed the "multimedia" timer in Windows 95.

Results

Reaction times

Our analyses of reaction times were based on medians rather than means. This was done to avoid an arbitrary cut-off of long reaction times and because our modeling of a subject's performance was more conveniently done on medians. If a participant committed an error in a certain trial, the latency of his or her response on the next trial was not analyzed.

Figures 2 and 3 show group means of median reaction times for correct responses to positive (*same*) and negative (*different*) stimulus pairs as functions of size ratio in each of the eight experimental conditions (types of blocks) formed by the factorial combinations of two types of presentation (simultaneous vs. successive), two levels of figural complexity, and two levels of figural similarity. Considering that exactly the same type of stimulus patterns was used in the simultaneous and the successive presentation conditions, the most striking feature of the data is the huge difference between the reaction times for simultaneous versus successive matching.

For successive matching, the median reaction time functions for each of the four different combinations of figural complexity and similarity (four types of blocks) were approximately linear and parallel, with the same slope constant for positive as for negative responses. For simultaneous matching, the corresponding median reaction time functions were also approximately linear, but the slopes were much steeper and widely different between the four combinations of figural complexity and similarity and between the two types of responses (positive vs. negative). The contrast in slopes between the successive and the simultaneous matching reaction time functions was accompanied by a contrast in intercepts at size ratio 1, so that for all values of size ratio, simultaneous matching was much slower than successive matching.

In the successive matching condition, the mean slope and intercept across positive and negative median reaction time functions were 22 ms and 714 ms, respectively. The corresponding values in the simultaneous matching condition were 174 ms and 1,607 ms. The differences were highly significant, $t(31) = 8.46$, $p < .001$ (slopes); $t(31) = 12.35$, $p < .001$ (intercepts).

Intercepts at size ratio 1 of reaction time functions for simultaneous versus successive matching showed positive correlations across the four different combinations of figural complexity and similarity. Consider correlations based on estimates of intercepts obtained by

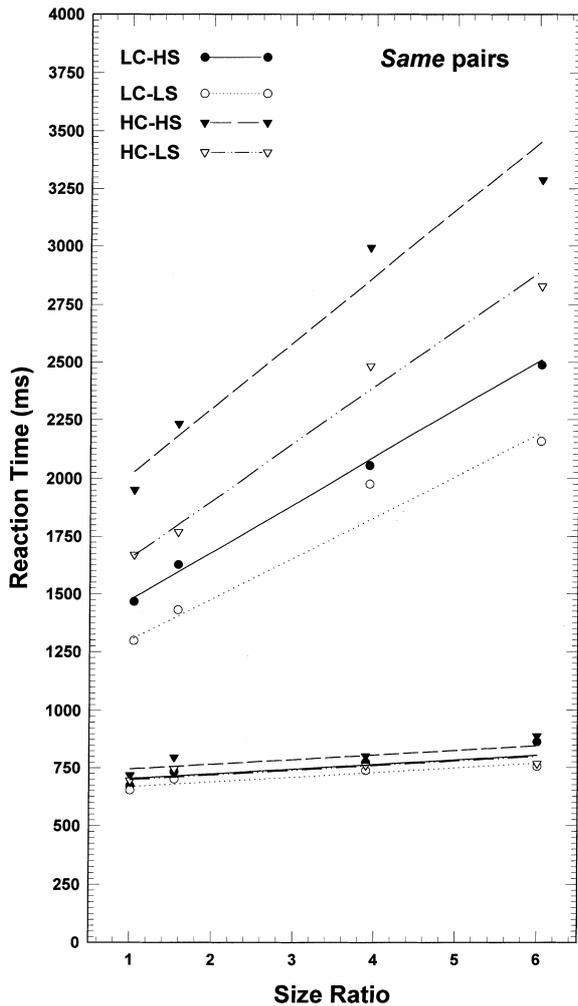


Fig. 2 Group means of median reaction times for correct responses to positive (*same*) stimulus pairs as functions of size ratio in eight conditions (types of blocks). *Upper curves* = simultaneous matching; *lower curves* = successive matching; HC = high complexity; LC = low complexity; HS = high similarity; LS = low similarity. The data for simultaneous matching are fitted by four straight lines with different slopes and intercepts. The data for successive matching in Figs. 2 and 3 are fitted by eight parallel lines

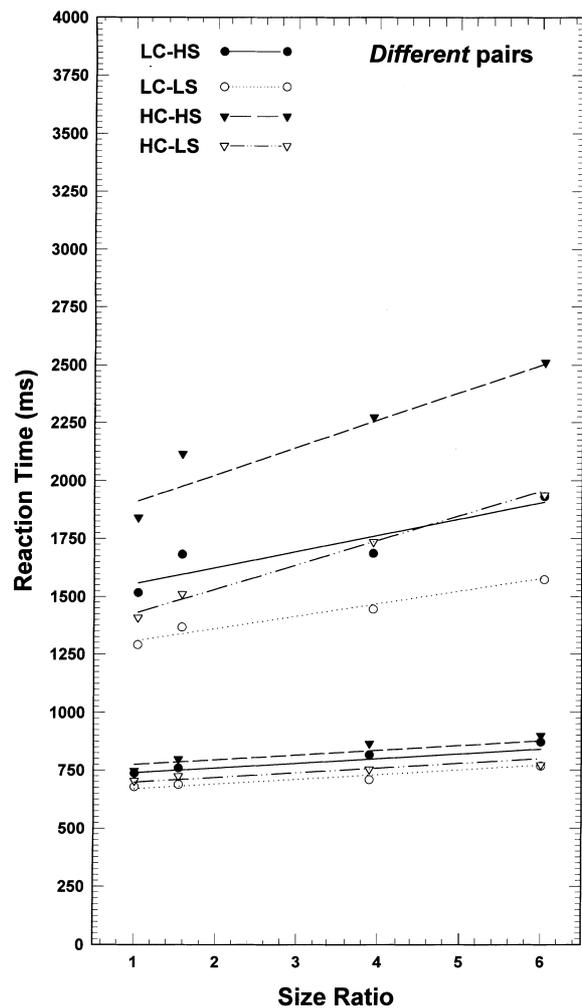


Fig. 3 Group means of median reaction times for correct responses to negative (*different*) stimulus pairs as functions of size ratio in eight conditions (types of blocks). *Upper curves* = simultaneous matching; *lower curves* = successive matching; HC = high complexity; LC = low complexity; HS = high similarity; LS = low similarity. The data for simultaneous matching are fitted by four straight lines with different slopes and intercepts. The data for successive matching in Figs. 2 and 3 are fitted by eight parallel lines

independent fits of least squares lines to each of the 16 median reaction time functions displayed in Figs. 2 and 3. For positive reaction times, the product-moment correlation coefficient between the intercepts for simultaneous and successive matching across the four combinations of complexity and similarity was .88. For negative reaction times, the corresponding correlation was .91. Across all eight combinations of complexity, similarity, and type of stimulus pair (positive vs. negative), the correlation between the intercepts for simultaneous and successive matching was .88.

By contrast, the independent fits of least squares lines to each of the 16 median reaction time functions in Figs. 2 and 3 showed no systematic correlation between the slopes of the reaction time functions for simultaneous and successive matching across the four different combinations of figural complexity and similarity. For

positive reaction times, the product-moment correlation between the slopes for simultaneous and successive matching across the four combinations of complexity and similarity was slightly negative: $r = -.03$. For negative reaction times, the corresponding correlation was .22. Across all eight combinations of complexity, similarity, and type of stimulus pair (positive vs. negative), the correlation between the slopes for simultaneous and successive matching was also negligible, $r = .13$.

For each subject, we tested the hypothesis that for every combination of response type (positive or negative), level of complexity, and level of similarity, the median successive matching reaction time was a linear function of size ratio with the same slope constant across the eight combinations. Thus, data for each subject were fitted by a linear model with one common slope and eight different intercepts. Goodness of fit was evaluated

by chi-square tests of the hypothesis that the probability that an observed reaction time exceeded the theoretical median was .5. Overall, the minimum chi-square fits were acceptable, $\chi^2(92) = 108.2$, $p = .12$. The median reaction times for simultaneous matching were subjected to similar analyses. In this case an acceptable fit by linear reaction time functions required a model with different slopes and intercepts for each subject, response type, level of complexity, and level of similarity; for this model, $\chi^2(64) = 80.7$, $p = .08$.

Error rates

Table 1 shows the group mean rates of erroneous negative responses (misses) and erroneous positive responses (false alarms) as functions of size ratio for each type of presentation (simultaneous vs. successive), level of figural complexity, and level of figural similarity. The data were analyzed by binomial tests. As can be seen in Table 1, the subjects made more errors in successive than simultaneous matching, $N = 128$, $x = 122$, $p < .001$. (Here N is the total number of comparisons and x is the number of comparisons in which the error rate was higher in the successive matching condition than in the corresponding simultaneous matching condition.) False alarms were more frequent than misses (a general positive response bias), $N = 128$, $x = 113$, $p < .001$. The error rates were higher in blocks in which the level of figural similarity (within the negative pairs) was high, $N = 128$, $x = 123$, $p < .001$. Finally, on the whole, error rates were higher in blocks in which the level of figural complexity was high, $N = 128$, $x = 84$, $p < .001$.

Subjective reports

During post-experimental debriefing, participants described their strategy in the successive matching task approximately as follows: At the onset of the first stimulus in a pair they often focused on one or more prominent parts of the stimulus pattern. During the ISI

they retained a global or schematic mental image, with more or less articulated parts. When the second stimulus appeared, the stimulus was compared against the image. Several participants reported that the task was difficult and that some of their responses were guesses.

Participants seemed to use a similar strategy in simultaneous matching. They claimed to attend to parts of one of the stimuli and attempt to match these with corresponding parts of the other stimulus. The process was frequently repeated (sometimes focusing on new parts) until a certain level of confidence was achieved that the patterns were the same or different. Again several participants reported that the task was difficult and that some of their responses were guesses.

Discussion

The results obtained for successive matching are consistent with the hypothesis that each decision to make a positive or negative response was based on a single execution of a process of encoding the first stimulus in a pair as a mental image, transforming the image to the size format of the second stimulus, and then testing for a match. Assuming that the mental transformation of size is done at the same speed (cf. Bundesen et al., 1981; Bundesen, Larsen, & Farrell, 1993) in all conditions of figural complexity and similarity, the hypothesis predicts that the increase in reaction time with increase in the linear size ratio between the patterns to be compared should be constant across variations in figural complexity, figural similarity, and response type (positive vs. negative). As predicted, the slope of the function relating the median latency of correct responses to the linear size ratio between the patterns to be compared showed no significant variation across the eight combinations of level of complexity, level of similarity, and response type. Systematic effects of figural complexity and similarity appeared only in error rates and in the intercepts at size ratio 1 of reaction time functions.

For simultaneous matching, we hypothesized that the process of encoding, transformation, and comparison

Table 1 Group error rates: HC = high complexity; LC = low complexity; HS = high similarity; LS = low similarity. Data are group means across all trials, including trials that immediately followed an error

Condition	Misses				False alarms			
	Size ratio				Size ratio			
	1.00	1.54	3.90	6.00	1.00	1.54	3.90	6.00
Successive matching								
LC-HS	.11	.16	.16	.23	.38	.36	.44	.44
LC-LS	.08	.09	.10	.12	.15	.16	.21	.27
HC-HS	.12	.21	.16	.26	.30	.30	.38	.43
HC-LS	.08	.13	.18	.16	.16	.13	.20	.25
Simultaneous matching								
LC-HS	.01	.03	.07	.09	.21	.30	.31	.26
LC-LS	.01	.01	.03	.10	.03	.09	.06	.11
HC-HS	.00	.02	.06	.12	.13	.22	.14	.20
HC-LS	.01	.01	.05	.08	.02	.03	.02	.04

would be executed several times for each pair of stimuli, until the participant felt that she or he had sufficient evidence to make a decision. Both slopes and intercepts of functions relating reaction time to the linear size ratio between the patterns to be compared should therefore to be higher for simultaneous than for successive matching. The results conformed to this prediction.

Random walk model

To understand the results for simultaneous matching in greater detail, we need a model of the way in which a subject's response is based on the evidence collected by repeated executions of the process of encoding, transformation, and comparison. Here we present a random walk model.

Let the duration of the encoding process be t_{encode} ; let the duration of the mental size transformation equal $\alpha(s-1)$, where α is a constant and s is the linear size ratio between the two patterns to be compared; and let the duration of the comparison process be t_{compare} . Thus, the time taken by a single execution of the process of encoding, transformation, and comparison equals $t_{\text{encode}} + \alpha(s-1) + t_{\text{compare}}$. If the process is executed n times for a given stimulus pair, then the total reaction time is given by

$$RT = \beta + n[t_{\text{encode}} + \alpha(s-1) + t_{\text{compare}}], \quad (1)$$

where β is a base reaction time that may depend on the type of response.

The way in which evidence is accumulated by repeated executions of the process of encoding, transformation, and comparison is modeled as a random walk (see, e.g., Townsend & Ashby, 1983, Chap. 10; see also Bundesen, 1982). Specifically, the development over time of the subject's internal state of evidence concerning the required type of response (positive vs. negative) is viewed as a movement in the state space $(\dots, -1, 0, 1, \dots)$. At the beginning of a trial, the subject is in initial state 0, a positive threshold is set at λ^+ and a negative threshold at λ^- , where λ^+ and λ^- are integers such that $\lambda^+ > 0 > \lambda^-$. Within trials the threshold states are regarded as absorbing.

During the analysis of a simultaneously presented pair of stimuli, the following cycle is run through. A subpattern of one of the stimuli is sampled and encoded as a mental image, which is transformed into the size format of the other stimulus and compared against that stimulus. The subjective state of evidence moves a unit step in the positive or negative direction according to whether a match or a mismatch is obtained. Another sample is taken and the process recurs. Each sample is assumed to be independent of the previous ones so that, for a given type of stimulus pair (positive vs. negative) in a given experimental condition (defined by figural complexity and similarity), there is a constant probability $p > 0$ that a step taken is a positive one. A positive response is initiated if and when the subjective state of

evidence reaches the positive threshold, and a negative response is initiated if and when the subjective state of evidence reaches the negative threshold.

Following Feller (1968, Chap. 14), let a be the distance between the positive and the negative threshold, let z be the distance of the negative threshold from zero, and consider the probability (u_n) of reaching the negative threshold after just n steps. Clearly, if $n < z$, then $u_n = 0$, and if $n = z$, then $u_n = (1-p)^n$. For $n > z$, a classical formula is that

$$u_n = a^{-1} 2^n p^{(n-z)/2} (1-p)^{(n+z)/2} \times \sum_{i=1}^{a-1} \cos^{n-1}(\pi i/a) \sin(\pi i/a) \sin(\pi iz/a) \quad (2)$$

(cf. Feller, 1968, p. 353).

Let U_n be the probability of reaching the negative threshold after at most n steps, that is,

$$U_n = \sum_{i=1}^n u_i. \quad (3)$$

The probability of a negative response equals the limit of U_n as n tends to infinity, which is given by

$$U_\infty = \begin{cases} 1 - \frac{z}{a} & \text{if } p = .5 \\ \frac{\left(\frac{1-p}{p}\right)^a - \left(\frac{1-p}{p}\right)^z}{\left(\frac{1-p}{p}\right)^a - 1} & \text{if } p \neq .5 \end{cases} \quad (4)$$

(cf. Feller, 1968, p. 345). The probability of a positive response equals $1 - U_\infty$.

The median number of steps taken to reach the negative threshold is readily obtained from Equations 2-4 by finding the smallest value of n for which $U_n \geq U_\infty/2$. The corresponding reaction time can then be obtained from Equation 1. By symmetry, formulas for determining the median number of steps taken to reach the positive threshold can be obtained from Equations 2-4 by substituting $1-p$ for p and $a-z$ for z (cf. Bundesen, 1982).

Fits

The random walk model was used to describe positive and negative simultaneous matching latencies and errors for each individual subject. The fitted version of the model contained 1 fixed and 22 free parameters (cf. Table 2). The fixed parameter was parameter α in Equation 1. For each subject, α was kept constant at the value found as the minimum chi-square estimate of the common slope of the functions relating median reaction times for *successive* matching to the linear size ratio between the patterns to be compared. The free parameters were the following: two base reaction times β (one for positive and one for negative responses), four encoding-and-comparison time parameters t (representing $t_{\text{encode}} + t_{\text{compare}}$ for each of the four combinations of levels of figural complexity and similarity), eight drift parameters p (one for each combination of level of complexity, level of similarity, and type of stimulus pair

Table 2 Estimates of parameters: α = rate of increase in transformation time with size ratio; β^+ and β^- are base reaction times for positive and negative responses; HC = high complexity; LC = low complexity; HS = high similarity; LS = low similarity; $t_{LC-HS} - t_{HC-LS}$ are encoding plus comparison times for each combination of complexity and similarity; $p_{LC-HS}^+ - p_{HC-LS}^+$ are drifts in the positive direction for *same* pairs in the indicated complexity and similarity conditions; $p_{LC-HS}^- - p_{HC-LS}^-$ are drifts in the positive direction for *different* pairs in the indicated conditions; $s_1 - s_4$ are size ratios of 1.00, 1.54, 3.90, and 6.00; $\lambda_{s_1}^+ - \lambda_{s_4}^+$ and $\lambda_{s_1}^- - \lambda_{s_4}^-$ are thresholds for positive and negative responses at the four size ratios

Parameter	Subject				Mean
	DB	JL	SE	TH	
α	24	18	14	25	20
β^+	796	1249	743	601	847
β^-	681	939	700	524	711
t_{LC-HS}	82	93	76	92	86
t_{LC-LS}	72	80	62	84	75
t_{HC-HS}	161	235	144	130	167
t_{HC-LS}	111	168	102	133	128
p_{LC-HS}^+	.62	.62	.60	.58	.61
p_{LC-LS}^+	.65	.68	.67	.68	.67
p_{HC-HS}^+	.63	.62	.62	.60	.62
p_{HC-LS}^+	.67	.68	.67	.69	.68
p_{LC-HS}^-	.46	.49	.49	.48	.48
p_{LC-LS}^-	.36	.42	.40	.37	.39
p_{HC-HS}^-	.42	.45	.46	.46	.45
p_{HC-LS}^-	.33	.36	.36	.31	.34
$\lambda_{s_1}^+$	4.1	5.0	4.7	4.7	4.6
$\lambda_{s_2}^+$	3.9	5.0	4.6	4.2	4.4
$\lambda_{s_3}^+$	4.5	6.1	5.0	5.0	5.1
$\lambda_{s_4}^+$	4.8	6.4	5.0	4.4	5.1
$\lambda_{s_1}^-$	-4.2	-3.5	-3.8	-4.0	-3.9
$\lambda_{s_2}^-$	-4.7	-3.9	-4.1	-4.8	-4.4
$\lambda_{s_3}^-$	-4.0	-3.4	-3.8	-3.8	-3.7
$\lambda_{s_4}^-$	-3.1	-3.1	-3.9	-3.4	-3.4

[positive vs. negative]), and eight threshold parameters λ (one positive and one negative threshold for each of the four levels of size ratio).

The model was fitted to median latencies of correct responses and rates of errors on all trials except those that immediately followed an error. Minimum chi-square fits were computed by use of MATLAB sub-routines *constr* and *fmins* (see Math Works, 1996). All parameters were treated as continuous. Nonintegral-valued threshold settings represented probability mixtures; for example, a threshold setting at 2.9 represented a mixture of settings at 2 and 3 with probability 0.9 of having the threshold set at 3.

Figures 4 and 5 show observed and theoretical group means of both median latencies of correct responses and probabilities of correct responses to positive and negative stimulus pairs as functions of size ratio in each of the four simultaneous matching conditions formed by combining the two levels of figural complexity with the two levels of figural similarity. The underlying fits to individual data were obtained by the parameter values listed in Table 2. Although the deviations between observed and theoretical values were significant (overall,

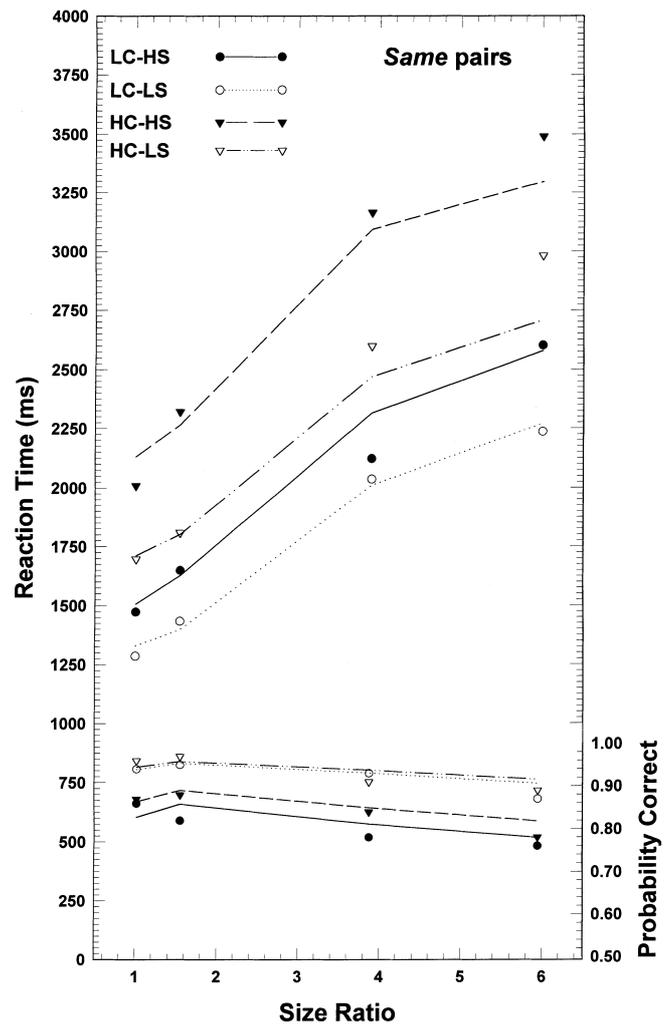


Fig. 4 Fit by random walk model to data for positive (*same*) stimulus pairs in simultaneous matching. The data are group means of both median reaction times for correct responses (*upper curves*) and probabilities of correct responses (*lower curves*) as functions of size ratio in four conditions defined by figural complexity and similarity. HC = high complexity; LC = low complexity; HS = high similarity; LS = low similarity. The theoretical fit is indicated by unmarked points connected with straight lines

$\chi^2(168) = 289, p < .001$), the fits were close. The product-moment correlation between all observed and theoretical median latencies was 0.98, and the correlation between observed and theoretical response probabilities was 0.94.

Consider the parameter estimates in Table 2. As one would expect, estimates for the encoding-and-comparison times t were greater for complex as compared with simple stimuli and greater in blocks with high as compared with low similarity between the members of a negative pair.

For all combinations of figural complexity and similarity, both p^- and $(1 - p^+)$ were high. Parameter p^- is the probability of a (spurious) match in the analysis of a negative stimulus pair, and $(1 - p^+)$ is the probability of a (spurious) mismatch in the analysis of a positive pair.

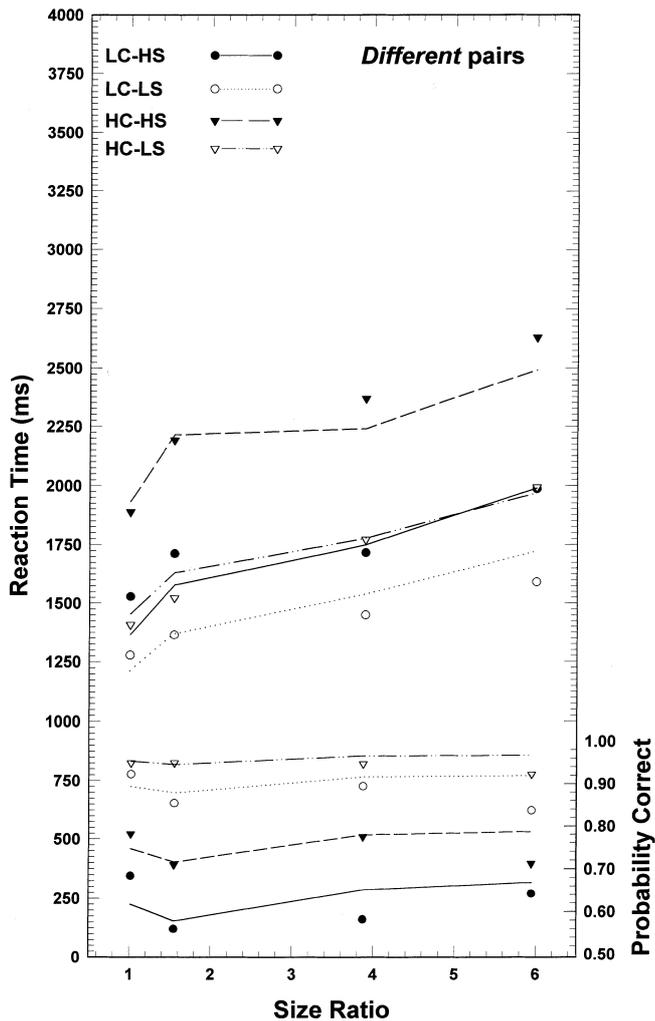


Fig. 5 Fit by random walk model to data for negative (*different*) stimulus pairs in simultaneous matching. The data are group means of both median reaction times for correct responses (*upper curves*) and probabilities of correct responses (*lower curves*) as functions of size ratio in four conditions defined by figural complexity and similarity. HC = high complexity; LC = low complexity; HS = high similarity; LS = low similarity. The theoretical fit is indicated by unmarked points connected with straight lines

Although estimates of p^- were high in all conditions, the estimates showed consistent variations depending on figural complexity and similarity. First, as strongly expected, estimates for p^- were considerably lower for pairs of stimuli at the lower level of similarity. Second, estimates for p^- were somewhat lower for complex than for simple stimuli.

Estimates of p^+ showed little effect of complexity, but the estimates were greater in blocks with low as compared with high similarity within negative pairs. Thus, in blocks with a low level of similarity within negative pairs, subjects appeared both to spend less time per encoding and comparison operation (measured by parameter t) and also to be less exacting in the requirements for a match (measured by p^+).

Estimates for the threshold parameters λ^+ and λ^- showed modest variations as functions of the size ratio between the patterns to be compared. As the size ratio was increased, the distance between λ^+ and λ^- remained nearly constant, but λ^- moved closer to zero, and λ^+ moved away from zero. The modest variations make sense: When the patterns to be compared were nearly the same in size, participants were biased in favor of *same* judgments. When the patterns to be compared were widely different in size, the bias was shifted in the direction of *different* judgments. Essentially the same effect was reported by Jolicoeur and Besner (1987). The effect can be described as a deficit in focusing attention on the relevant dimensions in the same-different matching task (cf. Larsen & Bundesen, 1998).

If threshold parameters λ^+ and λ^- had been entirely independent of the size ratio between the patterns to be compared, the predicted reaction times for the eight combinations of figural complexity, figural similarity, and response type would have been strictly linear functions of size ratio, and the predicted response probabilities would have been strictly constant across values of size ratio. The modest variations in λ^+ and λ^- as functions of size ratio account for the modest deviations from linearity in the observed reaction time functions and the modest effects of size ratio in the observed response probabilities.

Summary and conclusion

We investigated mental transformation of size in visual comparison of pairwise presented figures with respect to shape. The factorial combinations of two types of presentation (simultaneous vs. successive), two levels of figural complexity (6-sided vs. 10-sided polygons), and two levels of similarity within pairs of different-shaped figures (generated by small vs. large random perturbations) defined eight types of blocks of trials. For each type of block, both positive (*same*) and negative (*different*) median reaction times were approximately linear functions of the linear size ratio between the two patterns to be compared. For successive matching, systematic effects of figural complexity and similarity appeared in error rates and in the intercepts of the positive and negative reaction time functions at size ratio 1, but not in the slopes of the reaction time functions. For simultaneous matching, reaction times were much longer than for successive matching, and both slopes and intercepts of the reaction time functions showed strong effects of figural complexity and similarity. The results suggest that (a) in successive matching, each response was based on a single execution of a process of encoding a subpattern of the first stimulus in a pair as a mental image, transforming the image to the size format of the other stimulus, and then testing for a match; but (b) in simultaneous matching, the process of encoding, trans-

formation, and comparison was executed several times for each pair of stimuli. The interpretation was illustrated by a random walk model, which provided a good fit to the results.

References

- Besner, D., & Coltheart, M. (1976). Mental size scaling examined. *Memory & Cognition*, 4, 525–531.
- Bundesen, C. (1982). Item recognition with automatized performance. *Scandinavian Journal of Psychology*, 23, 173–192.
- Bundesen, C., & Larsen, A. (1975). Visual transformation of size. *Journal of Experimental Psychology: Human Perception and Performance*, 1, 214–220.
- Bundesen, C., Larsen, A., & Farrell, J. E. (1981). Mental transformations of size and orientation. In J. Long & A. Baddeley (Eds.), *Attention and performance IX* (pp. 279–294). Hillsdale, NJ: Erlbaum.
- Bundesen, C., Larsen, A., & Farrell, J. E. (1983). Visual apparent movement: Transformations of size and orientation. *Perception*, 12, 549–558.
- Feller, W. (1968). *An introduction to probability theory and its applications* (3rd ed., Vol. 1). New York: Wiley.
- Jolicoeur, P., & Besner, D. (1987). Additivity and interaction between size ratio and response category in the comparison of size-discrepant shapes. *Journal of Experimental Psychology: Human Perception and Performance*, 13, 478–487.
- Just, M. A., & Carpenter, P. A. (1976). Eye fixations and cognitive processes. *Cognitive Psychology*, 8, 441–480.
- Larsen, A. (1985). Pattern matching: Effects of size ratio, angular difference in orientation, and familiarity. *Perception & Psychophysics*, 38, 63–68.
- Larsen, A., & Bundesen, C. (1978). Size scaling in visual pattern recognition. *Journal of Experimental Psychology: Human Perception and Performance*, 4, 1–20.
- Larsen, A., & Bundesen, C. (1998). Effects of spatial separation in visual pattern matching: Evidence on the role of mental translation. *Journal of Experimental Psychology: Human Perception and Performance*, 24, 719–731.
- Math Works (1996). *Optimization toolbox user's guide* (2nd. ed.). Sherborn, MA: The Math Works.
- Shepard, R. N. (1984). Ecological constraints on internal representation: Resonant kinematics of perceiving, imagining, thinking, and dreaming. *Psychological Review*, 91, 417–447.
- Shepard, R. N., & Cooper, L. A. (1982). *Mental images and their transformations*. Cambridge, MA: MIT Press.
- Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, 171, 701–703.
- Townsend, J. T., & Ashby, F. G. (1983). *The stochastic modeling of elementary psychological processes*. Cambridge, UK: Cambridge University Press.
- Ullman, S. (1989). Aligning pictorial descriptions: An approach to object recognition. *Cognition*, 32, 193–254.