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A Review of Capacity Limitation From Visual Perception to Short-Term Visual Memory of a Single Curved Contour

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This study reviewed the literature regarding capacity limitation in processing curvature from visual perception to short-term visual memory (STVM) for a single curved contour with multiple convex parts. Capacity limitation was defined in terms of both set-size effects and decay with a retention interval. The results of psychophysical experiments and simulations involving signal detection theory indicated that visual perception exhibited some capacity limitation, which was caused by attentional allocation rather than sensory activation. In contrast, both iconic memory and STVM showed entirely limited capacity. Decay in STVM lasted for up to a minute and was reduced via an increase in the duration of stimulus presentation. Variance in represented stimulus values was shown to cause STVM decay. Decisional confusion, rather than capacity limitation in perception and STVM, was a primary factor in the deterioration of recognition of complex curved contours. Only one contour could be retained in STVM with very high fidelity, but at least four objects could be retained in STVM with some degree of fidelity. STVM appeared to exhibit little decay for a simple curved contour with four convex parts.

Keywords: capacity limitation, short-term visual memory, visual perception, curved figure, curvature

Section 1: Introduction

Object recognition occurs when a representation in memory is matched to new physical information. Therefore, we perceive physical information regarding an object and maintain it in long-term memory as a cue for recognition. Of the five human senses, vision provides information that is a particularly important cue in object recognition. Various types of visual information, such as contour, color, shade, and texture, can be processed and maintained in memory, and contour is an important cue for object recognition. The importance of contour in object recognition is understandable considering that we recognize objects via cues such as their two-dimensional figures or shaded contours.

For many decades, research has shown that information perceived through sensory organs is processed via the following three memory systems: sensory, short term, and long term. Sensory memory possesses high capacity and is maintained for a very short period (approximately 200-500 ms); short-term memory possesses limited capacity and is maintained for up to a minute; and long-term memory possesses very high capacity and can be maintained for a lifetime. The processing of visual information involves the following perceptual and memory processes: visual perception (VP), iconic memory (IM), and short-term visual memory (STVM). In addition, Nee and Jonides (2013) found that perceptual memory system could be partitioned into three distinct states (attention, STVM, and long-term memory), and identified the neural areas involved in accessing these

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three states in the brain. In Figure 1, the study stimulus, S_1, is perceived visually, immediately stored in IM as M_{S1}, and retained with decay in STVM as M'_{S1}. Recognition of similarity or difference occurs via comparison of the subsequent test stimulus, S_2, and the representation of M'_{S1}.

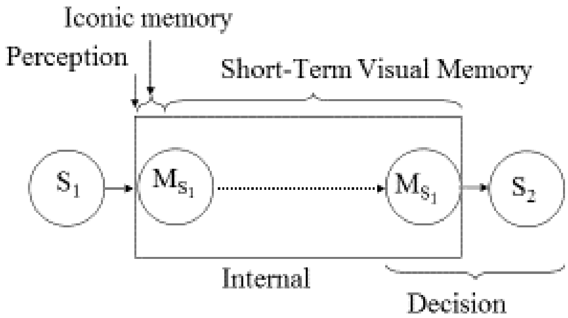

Figure 1. Flowchart of visual information processing from perception to short-term visual memory for recognition.

The present study reviewed the literature regarding capacity limitation in processing curvature from VP to STVM of a single curved contour with multiple convex parts, as shown in Figure 2. Capacity was interpreted in terms of two main classes of theory (discrete slots and continuous resources) suggested by Luck and Vogel (2013). Brady, Konkle, and Alvarez (2011) argued that the capacity of a memory system can be estimated by multiplying the maximum number of items stored by the fidelity with which each individual item is stored (capacity = quantity × fidelity). Furthermore, Alvarez and Cavanagh (2004) found that numbers of items and visual information load or complexity imposed capacity limits on STVM. Therefore, in the present study, *capacity* was defined as the amount of information, such as contour items or complexity, processed or retained with high fidelity. In memory processes, fidelity deteriorates over time; therefore, *decay* was defined as the deterioration of fidelity in the perceived representation with an increase in the retention interval in memory. As reported by Brady, Konkle, Gill, Oliva, and Alvarez (2013), fidelity in STVM remains the same as it is in long-term visual memory. *Capacity limitation* was defined spatiotemporally, as two data trends: (a) lower performance with increasing set size or complexity in the input stimulus, or the set-size effect and (b) decay with an increasing retention interval in STVM.

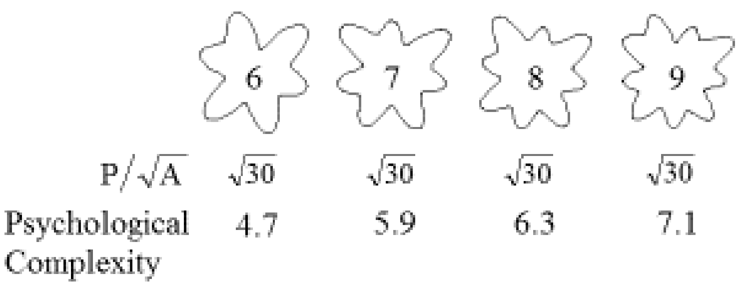

Figure 2. Curved closed contours used in the reviewed experiments. The numbers in the curved contours indicate numbers of convex parts, and $P/\sqrt{A}$ represents perimeter divided by root area. Psychological complexity increased with the number of convex parts, even with a constant $P/\sqrt{A}$ value.

In the remainder of this article, Section 2 presents a review of the properties of VP and STVM of figures; Section 3 presents a review of VP, IM, and STVM in processing contour curvature; Section 4 presents a review of experimental methods for STVM of curved contours (Figure 2); Section 5 presents a review of results regarding STVM in change-detection tasks; Section 6 presents a review a model of recognition in STVM based on signal detection theory (SDT); and Section 7 presents a summary of the findings.

Section 2: Properties of VP and STVM of Visual Patterns

The external world contains rich information, but our ability to process this information is limited. In fact, we neither perceive nor retain external information, such as a picture or video, precisely. One of the reasons for this is that we perceive the details of the external world in fovea vision, and our capacity is limited in perception and memory processes. The following four properties of VP and STVM are related to the above limitations in information processing for visual patterns.

Preattentive and Focal Attentive Processes

In visual information processes, global information is processed in parallel with the preattentive process. Local information is then processed serially via the focal attentive process. Global information possesses multidimensional properties, such as complexity, symmetry, and largeness, in visual patterns. In focal attentive processes, a piece of information is processed precisely and immediately, and this process is continued serially while the observer views the external world. Inui (1989) explained that characteristic points, such as high curvature, in visual patterns are detected via the preattentive process and constitute important physical information in object recognition. In addition, we are able to recognize a straight-line figure constructed by connecting points with high curvature (Attneave, 1954).

In enumeration tasks (Sakai & Fujii, 2007; Trick & Pylyshyn, 1993), the number of items in a stimulus with multiple items should be reported when it is presented. Results showed that the slope of reaction time for increasing items was very low for between one and four items but elevated monotonically for five or more items. They indicated that approximately four items could be perceived at once in the preattentive process. Trick and Pylyshyn (1993) proposed two different types of process. First, a stimulus with up to four items is processed via subitization, which is similar to the preattentive process. Second, a stimulus with five or more items is processed via counting, which is similar to the focal attentive process.

When the visual angle of a stimulus is wide within the field of peripheral vision, it is perceived via eye movement. However, when the visual angle of a stimulus is narrow within the field of foveal vision, it is processed via mental scanning (Inui, Kawato, & Suzuki, 1978). With respect to VP and STVM of a study stimulus in foveal vision, the amount of mental scanning performed increases during exposure, to ensure that it is perceived and retained precisely, and the perceived information is transferred from IM to STVM.

Segmented Representation

Hoffman and Richards (1984) found that the visual system deconstructs shapes into a hierarchy of parts in regions of concavity. In addition, in a model of object recognition developed by Biederman (1987), objects are represented in memory via the arrangement of the components of convex parts, which is cued for recognition via matching its internal representation with the external input.

According to these findings, visual patterns are perceived and retained in STVM via the arrangement of convex parts. Bartram (1978) reported that chunking heuristics operate to deconstruct the pattern into parts according to the following three possibilities: chunks are represented (a) connected to each other linearly, (b) connected to a network, or (c) independently. Chunking heuristics depend on the characteristics of visual patterns and tasks. Some chunks are grouped with a connected network for symmetry figures, while each chunk is represented independently for random patterns. For curved contours with no regularity, as shown in Figure 2, the parts divided at regions of concavity should be represented in STVM independently as sets of convex parts.

Decay With Memory Noise

Memory noise has been identified as a cause of decay in STVM in the delayed discrimination of visual information such as that concerning line orientation (Vogels & Orban, 1986) and dot position (Kinchla & Smyzer, 1967). Memory noise corresponds to the variance of the value of the represented stimulus, which accrues in STVM. In a model developed by Kinchla and Smyzer (1967), the stimulus value represented in STVM was a Gaussian random variable, with an expected value equal to the actual stimulus value, but the variance increased with the retention interval. This finding indicated that the cause of decay was not a decline in the represented value or convergence with a particular distorted value. Lee and Harris (1996) measured both the point of subjective equality (PSE) and the just-noticeable difference (JND) in contrast discrimination. Their results showed that the JNDs increased with retention intervals of 1-10 s, while the PSE was invariant. Similarly, Nilsson and Nelson (1981) found negative exponential growth in memory noise with retention intervals for monochromatic hue. These results indicate that memory noise is the cause of decay in STVM.

For curved contours with multiple convex parts, the stimulus value of each convex part divided at regions of concavity could be assumed to be represented independently as a Gaussian random variable (Figure 2). In addition, STVM decay with memory noise is assumed to occur at each convex part during retention intervals. Experiments examining the cause of decay in STVM for one convex part are reviewed in Section 3.

Limited Capacity

Capacity for VP and STVM is measured according to the set size or complexity of the study stimulus. Inui (1988) showed that a block pattern (BP) with a 3 × 3 matrix size could be recalled almost perfectly with presentation for 300 ms, while a BP with a 4 × 4 matrix size could not reach a 90% recall rate, even with presentation for 1 s. The interpretation of this result could be that BPs with matrix sizes of between 3 × 3 and 4 × 4 can be recalled almost perfectly after a single glance.

Memory capacity is uniquely difficult to measure, because STVM decay occurs with retention intervals. Phillips (1974) demonstrated that even a 4 × 4 BP could not be handled without loss and concluded that STVM has a limited capacity for block patterns with matrix sizes under 4 × 4. This interpretation is consistent with the definition of capacity limitation in the present study. Based on this definition, block patterns with a matrix size of 4 × 4 exceed the capacity of STVM. For curved contours with multiple convex parts (Figure 2), capacity is measured according to pattern complexity, with respect to the number of convex parts.

Section 3: Processing Curvature From VP to STVM

Based on the findings reported by Hoffman and Richard (1984), the convex parts in a curved contour divided at regions of concavity are perceived and retained in STVM. The physical value of a convex part is generally measured according to curvature. The findings regarding VP, IM, and STVM for contour curvature are reviewed in this section.

VP of Contour Curvature

In a visual search task, observers are asked to decide whether one or multiple targets are present among a large number of distractors. When an increase in set size reduces performance, such as that measured according to response time or percentage of correct responses, the interpretation is generally that stimuli are processed sequentially or perception is of limited capacity. Set size indicates the number of distractors, and this trend is referred to as the *set-size effect*. In contrast, when performance is independent of set size, it is assumed that stimuli are processed in parallel or perception is of unlimited capacity.

However, it could be possible that both perception and decision processes contribute to performance in visual search tasks. Therefore, the set-size effect does not always indicate limited capacity for perception, and it could be caused by decision noise. Figure 3 depicts the current schema of a visual search based on numerous previous models of perception and decision making (Baldassi & Verghese, 2002; Palmer, Ames, & Lindsey, 1993). Each item is processed as a possible perceptual limitation, but the perception of items for stimuli with larger set sizes could be less clear relative to that for stimuli consisting of a single item, because of limited perception capacity. Otherwise in decision, based on the max rule by SDT, the maximum output is chosen among all outputs and it is compared to observers' decision criterion. They should report "yes" when the maximum output exceeds the criterion and "no" when it does not. It is possible that observers' perception of higher maximum output mistakenly increases with increasing set size in decisional limitation. Therefore, performance could deteriorate with increasing set size, even without limitation of perceptual capacity.

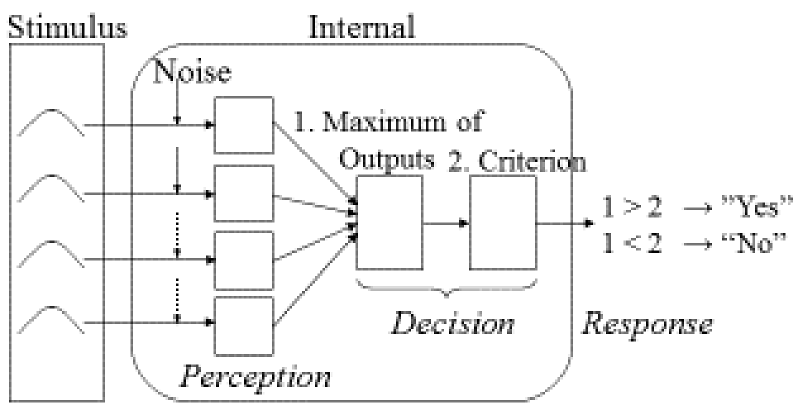

Figure 3. Flowchart of perception and decision processes in a visual search for a target contour with high curvature. In the model, observers would consider targets present when the maximum output value exceeded their criteria.

Palmer (1994) examined the validity of both limited-capacity and decision noise models by comparing the slope between log set size and threshold. In the limited capacity model, both perception and decision making are limited, and in the decision noise model only decision making is limited. In this model, the decision noise and limited capacity models would predict slopes of 0.23 and 0.73, respectively, for Yes-No tasks with set sizes between two and eight. In the limited capacity model, the 0.5 slope of the perception factor and the 0.23 slope of the decision factor are combined to predict a slope of 0.73.

Sakai, Morishita, and Matsumoto (2007) examined whether perception or decision processes would contribute most to the set-size effects in a visual search for contour curvature, as shown in Figure 4. The results of four experiments and a simulation showed that the slopes of log thresholds versus log set sizes ranged from 0.24 to 0.32. These slopes were more similar to the prediction of 0.23 in the decision noise model relative to that of 0.73 in the limited capacity model. The interpretation of this finding could be that in simple visual searches for contour curvature, decision noise affects mainly set-size effects, and perceptual capacity is slightly limited.

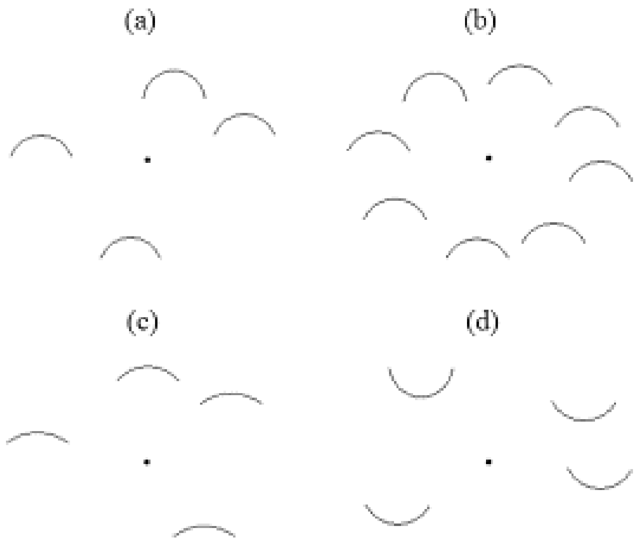

Figure 4. Curved multiple contours used for visual searches in the reviewed experiments. The curved contours in (a) to (d) have one target with high curvature; (a) setsize of four, (b) setsize of eight, (c) low curvature, and (d) downward convex parts.

IM of Contour Curvature

Phillips (1974) investigated change detection in the presentation of unfamiliar stimuli with various levels of complexity. In Phillips' experiments, the study stimulus was presented for 1,000 ms, and after a few hundred milliseconds, the test stimulus was presented until participants provided a response of "the same" or "different." The results showed that recognition performance for complex patterns deteriorated rapidly with increasing retention intervals of up to 100 ms but was asymptotic for intervals of 100-600 ms. Phillips posited that sensory storage possessed such high capacity that a matrix pattern of at least 8 × 8 could be retained; however, it decayed rapidly after 100 ms, even without stimulus masking. In addition, Bradley and Pearson (2012) showed that low-level visual features of 10 separate items could be retained for > 1 s, though at which process visual working memory (VWM) would be potentially involved with sensory IM.

Numerous studies examining STVM have used this paradigm (Phillips, 1974; Vogel, Woodman, & Luck, 2001). However, it could be unsuitable for use in examining IM because it is possible that IM capacity would be underestimated. Becker, Pashler, and Anstis (2000) tested two hypotheses as to why changes become difficult to detect in multiple character arrays when two arrays are presented successively. The first hypothesis was that IM of a study stimulus would decay when it was matched serially with a subsequent test stimulus. The second hypothesis was that IM of a study stimulus would be overwritten by the test stimulus, unless attention was sufficiently directed to the cued study items. Becker et al.'s (2000) results revealed that item-by-item matching between an icon and the test stimulus was rapid. However, change detection was somewhat difficult when the study item to be matched with the test did not receive full attention. These results provided evidence to support the second hypothesis. Therefore, single study stimuli should be used to examine IM.

Schulz (1980) examined the capacity of IM in cued discrimination tasks. Nine paired lines were presented for 50 ms, with delays of 0.00, 0.25, and 1.00 s, and a cue was presented. Participants judged whether the lengths of paired lines were the same or different. The results showed neither IM decay with cue delay times nor superiority of partial reports over entire reports. Therefore, the researchers concluded that IM did not possess high capacity and processed, rather than stored, visual information, such as pictures, reconstructively.

Sakai (2006) measured differences in thresholds for contour curvature in IM using the cued discrimination method (Figure 5). Study stimuli consisting of between two and six curved contours were presented to the fovea briefly, followed by two lines as cues. Observers discriminated between the two cued curves according to curvature. The condition on two items in a study stimulus is control condition for curvature discrimination without any effect of IM. Two items should be always discriminated at any number of items in a study stimulus, and therefore decision noise was constant, as described in Section 3.

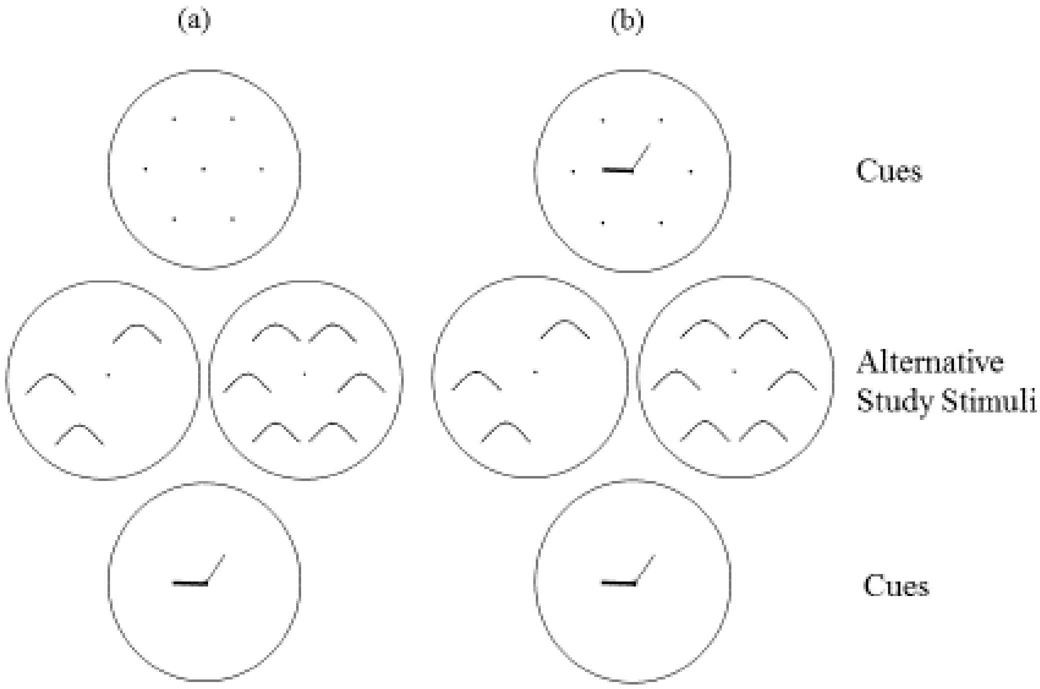

Figure 5. Experimental procedures for iconic memory in a cued discrimination task. The bold and thin lines, which were red and green, respectively, in the real experiments, were presented as cues (a) after presentation of the study stimulus and (b) before presentation of the study stimulus.

Cues were presented 1,500 ms before and 2,000 ms after presentation of a study stimulus to examine the following: (a) Presentation 1,500 ms before the stimulus (Figure 5b): observers were required to discriminate between two items that they knew about at the onset of presentation of the study stimulus; therefore, they would discriminate between them in VP. Whether sensory inputs not to be discriminated are inhibited to the fidelity of cued discrimination? (b) Presentation 0 and 300 ms after the stimulus (Figure 5a): observers were required to discriminate between two cued items after the presentation of the study stimulus; therefore, they would discriminate between them in IM. Does the set-size effect occur in IM? (c) Presentation 500 and 2,000 ms after the stimulus (Figure 5a): observers were required to discriminate between two items in STVM. Does decay occur between IM and STVM? The propositions described above were examined as follows. (a) No set-size effect indicated that attentional allocation, rather than sensory lateral inhibition, contributed to limited IM capacity. (b) Clear set-size effects indicated that IM was of limited capacity, and there was little IM decay at 300 ms. (c) Significant decay occurred at 500 ms, relative to that observed after stimulus presentation, and gradually continued in STVM during the 2,000 ms interval, and decay occurred in the shift from IM to STVM.

Factors Affecting Decay in STVM of a Single Contour Curvature

Curvature detection and discrimination have been examined extensively (Chen & Levi, 1996; Wilson & Richards, 1989). Chen and Levi (1996) demonstrated that angle discrimination depended on angle size as a global property rather than line orientation as a local property. Alternatively, Wilson and Richards (1989) proposed a two-process model for curvature extraction, in which high curvature is processed at the point of maximum curvature, and low curvature is processed by comparing orientation of points at a fixed distance along the curve. Watt (1987) showed that thresholds for curvature discrimination were low with presentation durations of ≤ 1,000 ms. However, while STVM of curvature is important in examining the representation of curved contours, it has not been examined.

Sakai (2003) measured the PSE and discrimination threshold for standard contour curvature (at 1.91 and 3.24 deg^{-1}) held in STVM in two-interval forced-choice of constant stimuli. The results showed that the PSE for remembered curvature was nearly constant for standard curvature with retention intervals of 2-16 s, while the discrimination threshold increased as a linear function of retention intervals. These results showed that the decay in STVM of contour curvature occurred because of noisy representation of curvature, rather than fading of the represented curvature or convergence with the constant curvature. For a curved contour with multiple convex parts (Figure 2), each convex part divided at regions of concavity was retained and decayed with retention intervals in STVM, because of the increase in the variance of the represented curvature value.

STVM of Contour Curvature

Palmer (1990) measured the difference in thresholds for a single feature (e.g., line length) of one of numerous items, using partial discrimination. In this procedure, a study stimulus consisting of one, two, or four items was presented, followed by a retention interval of 2 s and presentation of a single item as a test stimulus. The observer’s task was to judge whether the test item’s value was higher or lower relative to that of the corresponding study item. Increasing the number of cues when matching study and testing stimuli, generally increases the possibility of confusion in the decision process. However, setsize does not influence the decision process in partial discrimination tasks, because only one test item is matched to one of many study items. Palmer (1990) showed that the difference threshold increased with an increase in set size from one to four and concluded that only one item could be retained in fine detail, but at least four items could be retained with some fidelity.

In Palmer’s (1990) procedure, set size could be affected by both VP and STVM after VP. However, whether capacity limitation was caused by both VP and STVM, after VP, or another process remained unclear. When capacity limitation in STVM after VP was examined, certain factors, such as VP load and decisional confusion, should be constant at any set size.

Sakai (2005) measured the difference threshold for contour curvature in STVM using a two-interval, forced-choice partial discrimination task. As shown in Figure 6a, in Experiments 1 and 2, a study stimulus consisting of between one and four curved contours was presented briefly, followed by a retention interval and a single contour stimulus. The presentation durations in Experiments 1 and 2 were 500 and 1,500 ms, respectively. The participants determined whether the curvature of the test stimulus was higher or lower relative to that of the corresponding study contour. In the procedures of Experiments 1 and 2, the set-size effect was observed for both VP and STVM after VP. In Experiment 3 (Figure 6b), four contours were processed in VP in any set-size condition, but numbers of memorized items differed between conditions; therefore, performance was affected only by STVM after VP. In addition, the task involved discrimination between one of four items in study stimuli and the corresponding test stimulus, therefore, decisional confusion was constant in all set-size conditions.

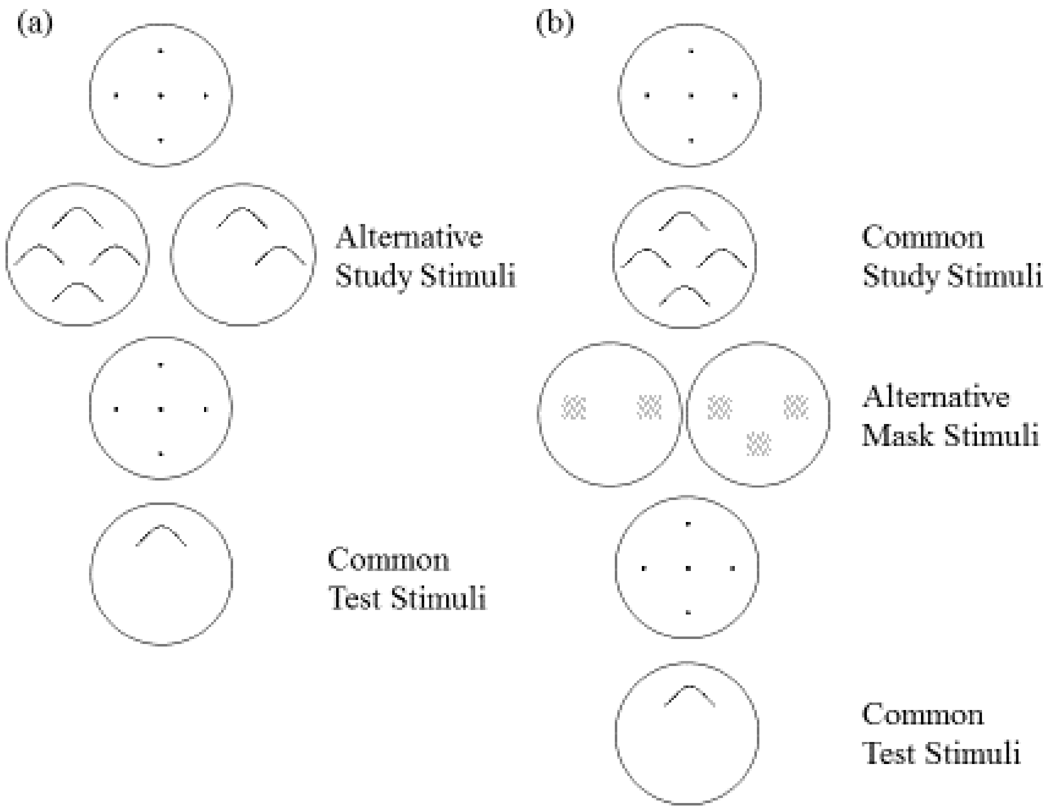

Figure 6. Experimental procedures for short-term visual memory in a partial discrimination task. The set sizes in the study stimuli were as follows: (a) One, two, or four contours with no masked pattern, and (b) four contours with no, two, or three masked patterns, presented in immediate succession.

Sakai’s (2005) results were as follows: (a) The set-size effect in Experiment 3 was lower relative to that in Experiment 1. This result indicates that the accuracy of VP was slightly lower in conditions with larger, relative to smaller, set sizes. (b) The difference threshold in Experiment 2 was substantially lower relative to that in Experiment 1, but the set-size effect occurred. This result indicates that increasing presentation duration reduced decay considerably but did not halt it entirely. (c) The set-size effect also occurred in Experiment 3. This indicates that capacity limitation occurred in STVM after VP. (d) In addition, the Weber fraction for a set size of four was only slightly higher relative to that for a set size of one (1.6 times in Figure 6a and 1.27 times in Figure 6b). The interpretation of this result could be that only one object could be retained in STVM with high fidelity, but at least four objects could be retained with some degree of fidelity.

Section 4: Experimental Methods for STVM of a Curved Contour

Previous findings regarding VP, IM, and STVM for curvature of one convex contour were reviewed in Section 3. Findings regarding STVM for curvature with many convex/concave contours (Figure 2) are reviewed in Sections 4 to 6. This section contains an experimental procedure for change-detection tasks in STVM. In addition, STVM for a visual pattern depends largely on its shape; therefore, recognition performance in STVM should be examined by determining physical characteristics and variables for the visual pattern. In view of this, shape-related characteristics and physical variables for the curved contours in Figure 2 are also reviewed. Moreover, the section contains a review of findings regarding the relationship between physical variables and psychological estimation of curved contours.

Experimental Procedure for Change-Detection Tasks

In experiments conducted by Sakai and Inui (1999; 2000; 2001a; 2001b; Figure 7), the first study stimulus was presented briefly on the left side of the screen, followed by a masked pattern. After a blank interval, the second test stimulus was presented on the right side of the screen until the observer responded. Observers were asked to indicate whether the first and second stimuli were the same or different. In trials in which the first and second stimuli, which were the named target (T) and distractor (D), respectively, differed in shape, the T and D stimuli had the same number of convex parts but different detailed contours (Figure 8), and observers were required to memorize the first study stimulus in STVM until the second test stimulus was presented.

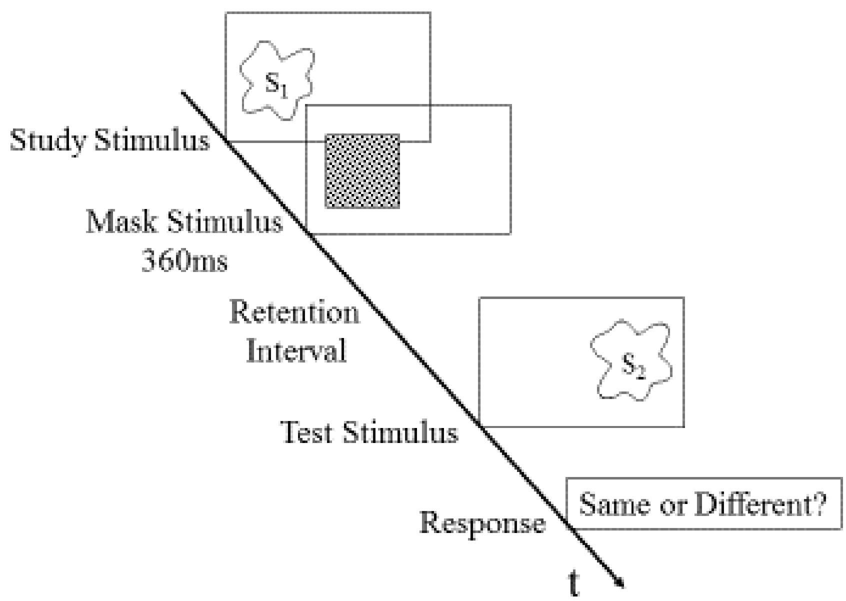

Figure 7. An experimental procedure for short-term visual memory in a change-detection task.

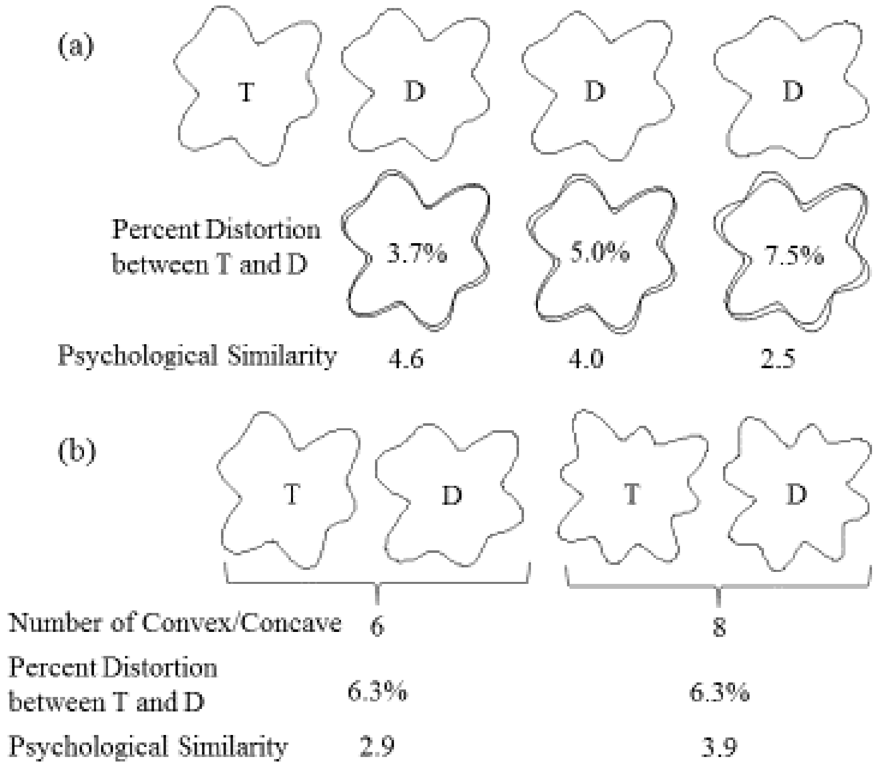

Figure 8. A pair of curved contours with the target (T) and distractor (D), which were used as stimuli in a change-detection task. (a) The numbers in curved contours indicate percentages of distortion between T and D as physical variables. (b) Percentages of distortion and psychological similarity between T and D with six and eight convex parts.

Characteristics of the Curved Contour

The curved contour in Figure 2 was constructed by describing a compound curve of three cosines in a coordinate system. To ensure that perceptual and memorized loads could be defined only by the number of convex parts, the figures possessed the following three properties: (a) No regular pattern: perceptual and memorized loads were lower for visual patterns with regular or symmetric structures, and the memorized pattern could be distorted toward a pattern with particular regularity; therefore, the stimulus was a curved contour with no regularity. (b) Circular pattern: elongated patterns with a high aspect ratio could be memorized based on the centered axis, to ensure that the memorized load was low; therefore, the stimulus was a circular pattern. (c) The equivalence of saliency for each convex part in a curved contour: curvature was almost constant at any convex part but differed slightly at each concave part. Therefore, convex parts possessed almost equal saliency, and perceptual and memorized loads and recognition cues could be considered almost constant at each convex part.

Physical Variables Regarding the Curved Contour

(1) Physical complexity of the curved contour

One of the ways in which the physical complexity of BPs can be measured involves perimeter^2/area (P^2/A; Attneave, 1957; Chipman, 1977). Parts with high curvature, such as turns in BPs, are important in patterns (Attneave, 1954), and convex/concave parts of curved contours correspond to turns in BPs. Physical complexity (Figure 2) could be measured according to numbers of convex parts and P^2/A. With respect to numbers of convex parts, a curved contour with *n* convex parts has *n* convex/concave parts. In addition, regarding $P/\sqrt{A}$, it has an invariant value at A. All of the curved contours in Figure 2 have constant areas; therefore, physical complexity was measured using only P.

(2) Physical similarity of two curved contours

As shown in Figure 8a, the positions of convex parts on polar coordinates were matched between T and D. In addition, physical similarity could be measured according to the percentage of distortion, which was calculated by dividing an approximate value for the distorted area superimposed on T and D by an approximate area of one curved contour.

Psychological Estimation of the Curved Contour

(1) Psychological complexity of the curved contour

Psychological complexity is measured mainly according to the number of turns in BPs (Attneave, 1957), and BPs with a high number of turns have a high $P/\sqrt{A}$ value. Real correlations between numbers of turns in BPs and P^2/A have been shown to be very strong (Chipman, 1977). To determine which of the two physical variables was more effective with psychological complexity, Chipman (1977) conducted an estimated experiment using a set of BPs that included different numbers of turns at a constant P^2/A value. The results showed that estimations of psychological complexity were higher for patterns with higher, relative to lower, numbers of turns, even though they all possessed constant P^2/A values.

Similar to the study conducted by Chipman (1977), Sakai and Inui (2000) conducted experiments involving psychological complexity estimation using a set of contours with different numbers of convex parts at a constant $P/\sqrt{A}$ value. The results showed that psychological complexity was predicted by the number of convex parts rather than $P/\sqrt{A}$. These results suggest that curved contours were perceived as convex/concave structures rather than overall perimeters.

(2) Psychological similarity between two figures

As shown in Figure 8, Sakai and Inui (1999) conducted experiments involving psychological similarity estimation using pairs of contours with the same number of convex parts but different details. The results showed that psychological similarity was reduced considerably with increases in the percentage of distortion, as described above. They also indicated that human beings are highly sensitive to dissimilarity in distorting subtle shapes. In addition, with a constant percentage of distortion, levels of psychological similarity were high for complex pairs of contours, as shown in Figure 8b. Moreover, psychological similarity was almost constant in any complex pair of contours when the percentage of distortion for one convex part was constant. This result indicates that psychological similarity was estimated by averaging the difference between two contours in each part.

Section 5: Results for STVM in Change-Detection Tasks

Previous Findings

Phillips (1974) examined STVM for BPs with $n \times n$ at various *n*s in change-detection tasks. The results showed that, in simple BPs with a 4×4 matrix, recognition performance was relatively high despite little STVM decay. However, in complex BPs with an 8×8 matrix, recognition performance was relatively low and STVM decayed rapidly. Phillips (1974) indicated that STVM possessed limited capacity below that of a BP with a 4×4 matrix.

Vogel et al. (2001) sought to determine whether VWM capacity could be established at a feature- or object-based level. In the same-different task, a study stimulus consisting of numerous items was presented, followed by a blank interval of 900 ms and presentation of a test stimulus. The test stimulus was either identical to the study stimulus or differed in one feature (e.g., color) of one item. Their results showed that performance was almost perfect for between one and three items but decreased systematically as setsize increased from four to 12 items. In addition, objects defined by a conjunction of four features could be retained just as well as single-feature objects. In light of these results, the researchers concluded that VWM capacity, which included three or four items, should be interpreted in terms of integrated objects rather than individual features.

Experimental Variables for Recognition Performance with a Curved Contour

In the experimental procedures performed by Sakai and Inui (1999; 2000; 2001a; 2001b), the experimental variables for recognition performance included pattern complexity factors, such as P/√A and number of convex parts; presentation duration for a study stimulus; retention interval; and physical difference between T and D. The effects of these variables on performance are partially reviewed in this section.

Effects of P/√A and Number of Convex Parts on Recognition Performance

In recognition experiments, pattern complexity is generally measured according to the number of matrices (Phillips, 1974; Inui, 1988) or number of dots in each matrix (Kikuchi, 1987). The P/√A and number of convex parts in curved contours are very strongly correlated; therefore, it is unclear which variable is more effective in reducing recognition performance for complex patterns. Sakai and Inui (2000) examined recognition performance using a set of curved contours with various numbers of convex parts and a constant P/√A. The results showed that recognition performance for patterns with higher numbers of convex parts tended to be lower relative to that for patterns with lower numbers of convex parts. Interpretation of this result with respect to those described in Section 4 indicated that the number of convex parts, rather than P/√A, was involved in perceptual and memory load.

Effects of Pattern Complexity on Decay Rates

Phillips (1974) demonstrated decay in STVM of BPs over a period of at least 9 s. Hole (1996) showed a linear increase in discrimination thresholds for two-dot separation during a retention interval of 30 s. These results indicated that STVM decayed for several seconds, but this decay was temporary. In experiments conducted by Cermak (1971), using curved figures as stimuli, recognition performance deteriorated during retention intervals of 1.5 to 12 s, but it was asymptotic during intervals of 12-20 s.

The STVM decay rate has been shown to be higher for complex patterns. Phillips (1974) examined decay in STVM of BPs and showed slow decay for simple pattern with a 4 × 4 matrix and rapid decay for complex patterns with an 8 × 8 matrix, even during retention intervals of 1 s. Kikuchi (1987) also reported rapid decay for complex dot patterns. Sakai and Inui (2001a) showed decay for curved contours, regardless of pattern complexity, with retention intervals of 8 s. STVM decayed, even for relatively simple curved contours with six convex parts, and decay rates tended to be slightly higher for complex curved contours with between six and nine convex parts.

Effects of the Duration of Study Stimulus Presentation on Decay Rates

Avons and Phillips (1980) demonstrated that recognition performance increased with presentation durations of 60-200 ms and were asymptotic with durations of 200-600 ms. In experiments examining BP recall, conducted by Inui (1988), performance improved with increases in presentation duration, and levels of improvement and asymptotic values were lower for complex relative to simple patterns.

STVM decay rates are expected to be low with longer presentation durations. Dale (1973) examined the accuracy of dot positions memorized in STVM by varying both presentation durations and retention intervals. The results showed rapid decay with short presentation durations of 500 ms and slow decay with longer presentation durations. Dale (1973) posited that 500 ms was sufficient time to allow accurate perception of dot positions, while longer presentation durations were required for accurate retention in STVM, with 10 retention intervals lasting several seconds. Sakai and Inui (2001b) demonstrated that decay decreased considerably with increases in presentation duration, regardless of pattern complexity, for curved contours with seven or nine convex parts. Decay continued during retention intervals of 16 s, even with presentation durations of 1 s.

Section 6: A Model of Recognition in STVM Based on SDT

SDT has been used to predict recognition performance in delayed discrimination for visual information such as dot position (Kinchla & Smyzer, 1967) and line orientation (Vogels & Orban, 1986). Sakai and Inui (2002) proposed a model of recognition in STVM of curved contours (Figure 2) and examined the validity of the model via simulation. The application of SDT to recognition performance in STVM, a model of recognition in STVM, and the findings obtained via simulation are reviewed in this section.

Application of SDT to Recognition Performance

Sorkin (1962) extended SDT for use in matching procedures for two-interval designs such as the same-different task, in which trials that are different and the same correspond with trials with and without signals, respectively, in single-interval designs. It was assumed that levels of encoding accuracy for the first stimulus were low with very brief presentation, and variance in the first stimulus value retained in STVM accumulated with increasing retention intervals between t_1 and t_2 ($t_1 < t_2$, Figure 9). Therefore, the psychological distance between the first and second stimuli varied in all trials and experimental conditions. It was also assumed that the value of psychological distance was distributed normally, with mean physical difference observed between T and D. Memory sensitivity for d' was higher with increases in Δs (equal to the physical difference between T and D) and reductions in $\sigma_m{}^2$ (equal to accumulated variance for the first memorized stimulus), as in the following Equation (1):

$$d' = \frac{\Delta s}{\sqrt{\sigma_m{}^2}} \tag{1}$$

Observers were required to fulfill a criterion for judgment as to whether the first and second stimuli were the same or different. The criterion constituted a threshold value for judgments of “different.” Observers provided responses of “different” if the psychological distance between memory for the first stimulus and presentation of the second stimulus exceeded their response criterion. When the value of the criterion was higher, relative to that observed at the horizontal point at which two normal distributions intersected, this indicated that the frequency with which observers provided a response of “the same” was higher relative to that observed for responses of “different.”

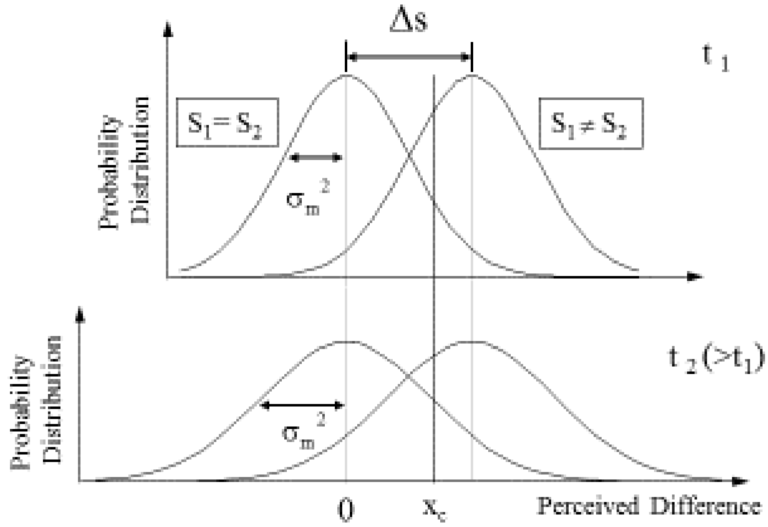

Figure 9. Probability distribution for an observer's response in recognition memory, based on signal detection theory. The left and right distributions represent conditions in which the study and test stimuli are the same and different, respectively. Retention intervals increased from t_1 to t_2 in short-term visual memory. The criterion corresponds to the vertical line.

Model of Recognition Memory of Curved Contours

By applying SDT to recognition memory of dot positions, Kinchla and Smyzer (1967) developed a model in which three processes (perception, memory, and decision) interacted to determine the relationship between stimulus and response. In accordance with the model developed by Kinchla and Smyzer (1967), Sakai and Inui (2002) produced a three-process model to predict recognition performance in STVM of curved contours (Figure 2). In the first VP process, the amount of visual information that was encoded precisely with brief presentation was limited; in the second STVM process, memory for encoded features decayed with time; and in the third decision process, the observer's response criterion was a Gaussian random variable rather than a constant. Therefore, it was possible to defined, or memory sensitivity in SDT, specifically as following Equation (2):

$$d' = \frac{\frac{\mathrm{k}_1}{c} \cdot \Delta s}{\sqrt{\frac{\mathrm{k}_2 \cdot c}{e} \cdot t + \sigma_\beta^2}} \tag{2}$$

where the four experimental variables, c, Δs, e, and t, denote the number of convex parts, physical differences between T and D, presentation for the first stimulus, and the retention interval between the first and second stimuli, respectively. The σ_β^2 value represents variance in the response criterion, and k_1 and k_2 are constant. The $k_1/c \times \Delta s$ value represents perceived difference between T and D, which is a function of Δs and c. The $k_2 \times c / e \times t$ value represents variance in the value of the first stimulus accruing in STVM. However, the k_2 value differs regardless of whether c exceeds limited capacity. The k_2 value is high when c exceeds limited capacity in STVM and very low or zero when c is below limited capacity in STVM. Sakai and Inui (2002) developed a model in which limited capacity in STVM involved the curved contour with four convex parts.

Equation (2) differs from Kinchla and Smyzer's (1967) model with respect to the numerator k_1/c. Only physical difference (Δs) between T and D was used in Equation (1) in Kinchla and Smyzer's (1967) model. However, perceived stimulus difference ($k_1/c \times \Delta s$) is used in Equation (2). As described in Section 4, psychological similarity between complex pairs of curved contours was greater relative to that observed for simple pairs, even at a constant percentage of distortion between T and D. As a result, the level of decisional confusability was high for complex pairs of first and second stimuli in the same-different task. The complexity of first and second stimuli was constant in all trials in Kinchla and Smyzer's (1967) model; therefore, physical difference (Δs) was used. However, the complexity of the stimuli differed between trials in the model developed by Sakai and Inui (2002); therefore, perceived stimulus ($k_1/c \times \Delta s$), rather than physical difference (Δs), was used.

Simulation of Recognition Memory Performance for Curved Contours

Data for recognition memory in STVM were simulated in accordance with Equation (2) in Sakai and Inui's model (1999; 2000; 2001a; 2001b). The findings of their experiments and simulation were as follows.

(1) Availability of SDT for recognition memory in STVM: Recognition performance for dot positions (Kinchla & Smyzer, 1967) and line orientation (Vogels & Orban, 1986) increased linearly with increases in physical differences between T and D, which indicated that it was based on SDT. In these studies, one-dimensional visual information was used to provide stimuli. In addition, two-dimensional visual information, such as that concerning curved contours, could be available to provide stimuli for predicting recognition performance in SDT. It was assumed that recognition performance in the use of numerous types of visual information could be explained by SDT.

(2) Monotonic increase in memory noise with retention intervals: The hypothesis presented in the model was that the nature of STVM decay depended on memory noise. This was based on the finding that JNDs increased with increasing delays, but no change was observed in the PSE for contour curvature (Sakai, 2003). In cases involving line orientation discrimination (Vogels & Orban, 1986) and contrast discrimination (Lee & Harris, 1996), memory noise increased as a power-related function of retention intervals. In contrast, Nilsson and Nelson (1981) found negative exponential growth in memory noise with intervals for monochromatic hue. The model showed a linear function for retention intervals, which was similar to the diffusion model developed by Kinchla and Smyzer (1967). In addition, Wilken and Ma (2004) showed that performance in change-detection tasks was limited by internal noise, which is a function of set size. Considering these results, there is no doubt that memory noise increased monotonically over time for many types of visual information in STVM.

(3) Distinct decrease in memory noise with increasing presentation duration: A simulation revealed that the memory noise rate was inversely proportional to the presentation duration. The effect of presentation duration was strong, and prolonged presentation reduced the decay rate sharply. Furthermore, performance deteriorated progressively with retention intervals of ≤ 16 s and longer presentation durations of 1.2 s. This suggested that prolonged presentation exerted a strong effect on reductions in decay rates but did not prevent decay itself. Therefore, there appeared to be a limit to the benefits of prolonged presentation.

Nosofsky's (1983) explanation for the variance in stimulus values with memory reductions and increased presentation time was that a larger amount of information was acquired. In statistical theory, variance in detected stimulus values is divided by n when it is presented independently n times. Therefore, when stimuli are presented n times, detectability is $\sqrt{n}$ times higher relative to that observed when they are presented only once (Swets, Shipley, McKey, & Green, 1959). Sakai and Inui (2001b) examined the effects of presentation duration and hypothesized that mental scanning (Inui et al., 1978) was independent and would increase according to the duration of stimulus presentation. The results showed that the rate of increase in memory noise deteriorated $1/e$ times with increases in presentation duration of e.

(4) Effectiveness of visual rehearsal to reduce decay: Although decay occurred in STVM, performance did not deteriorate considerably over retention intervals of ≤ 8 s, even for complex contours. This result is consistent with findings indicating that visual information, such as that concerning two-dot separation (Hole, 1996) and vernier acuity (Fahle & Harris, 1992), could be retained in STVM with relatively high fidelity for prolonged periods of time, even though some loss of precision was inevitable. It appears that visual rehearsal occurs while memorizing even complex contours and levels of stability of representation in STVM are generally high.

(5) The model showed that STVM capacity, defined according to pattern complexity (the degree to which a pattern can be handled for several seconds with little loss), included approximately four convex parts. It was assumed that this number reflected approximately the same degree of complexity as BPs with matrix sizes between 3×3 and 4×4, which were recalled almost perfectly with a single glance (Inui, 1988).

(6) Levels of confusability in the decision process as a factor in reduced recognition of complex contours: the research demonstrated that it was more difficult to recognize complex, relative to simple, patterns. However, experimental data did not indicate which of the three processes was limited in its capacity for precision of visual information. Pattern complexity affected neither perception nor the STVM process in the model. In contrast, psychological similarity increased sharply when pattern complexity increased, as shown in Figure 8b in Section 4. Considering these findings, it is likely that decisional confusion is a primary factor in reductions in the recognition of complex figures, but pattern complexity operates within the limitations of these three processes.

Section 7: Summary

The present study reviewed experiments and model simulation involving capacity limitation in processing curvature from VP to STVM of a single curved contour with convex parts. A summary of the findings follows:

(1) In VP, the set-size effect appeared as experimental data in visual searches. However, SDT predicted that it occurred mainly because of decisional confusability rather than perceptual capacity limitation. VP exhibited some capacity limitation and lost some fidelity with increased set sizes. The set-size effect depended on attentional, rather than sensory limitation.

(2) Perceived visual information was stored in IM immediately, and set-size effects appeared in IM in cued discrimination tasks. These results indicated that IM was of limited capacity when the required visual information was retained with high fidelity. However, it hardly decayed at all during the 300 ms following VP.

(3) Visual information stored in IM was transferred into STVM. Decay began at approximately 500 ms in retention intervals and lasted for up to a minute. Decay rates tended to be high for complex patterns and deteriorated sharply with increasing presentation duration, but this was inevitable.

(4) Performance in recognition memory in STVM could be predicted by SDT. Perception, memory, and decision could affect performance; of these factors, decisional confusion was a primary factor in reductions in

the recognition of complex figures.

Declaration of Conflicting Interests

The author declares that there is no conflict of interest.

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