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Dividing attention between two different categories and locations in rapid serial visual presentations

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When two targets are embedded in a rapid serial visual presentation (RSVP) stream of distractors, perception of the second target is impaired if the intertarget lag is relatively short (less than 500 msec). This phenomenon, called *attentional blink*, has been attributed to a temporal inability of attentional resources. Nevertheless, a recent study found that observers could monitor two RSVP streams concurrently for up to four items presented in close succession, suggesting a much larger visual capacity limit. However, such high-capacity performance could be obtained by a rapid shift of attention, rather than concurrent monitoring of multiple locations. Therefore, the present study examined these alternatives. Results from six experiments indicate that observers can concurrently monitor two noncontiguous locations, even when targets and distractors are from different categories, such as digits, English alphabet letters, Japanese characters, and pseudocharacters. These results can be explained in terms of a modified input-filtering model in which a multidimensional attentional set can be flexibly configured at different spatial locations.

As shown by the fact that using a cell phone while driving can have serious consequences (Strayer, Drews, & Johnston, 2003), there is a cost to distributing attention to more than one task. Even in simplified tasks, when observers are engaging in a primary undertaking, they frequently fail to notice the occurrence of a salient but incidentally presented object (the inattentional blindness phenomenon; Mack & Rock, 1998; Most, Scholl, Clifford, & Simons, 2005). The same is true with experimentally controlled but natural environments (Simons & Chabris, 1999). These findings suggest that the ability of the human visual system is clearly limited. However, recent studies have also shown that our visual system has a strong capability to process natural scenes (e.g., Kirchner & Thorpe, 2006). Moreover, Li, VanRullen, Koch, and Perona (2002) found that observers can categorize briefly presented natural scenes even when they are simultaneously conducting a foveal task that is known to be attentionally demanding, suggesting that some types of objects can be recognized without attentional requirements.

Researchers have tackled the question of whether attention is required to perceive objects (Broadbent & Broadbent, 1987; Evans & Treisman, 2005; Joseph, Chun, & Nakayama, 1997; Sagi & Julesz, 1985) by asking how many objects we can process at a time. The attentional blink (AB; Shapiro, Arnell, & Raymond, 1997) procedure is a subtype of dual-task paradigm that is one major way to examine this issue. In this procedure, observers find two targets (e.g., letters) embedded in a rapid serial visual presentation (RSVP) of distractors (e.g., digits). When the intertarget interval is less than 500 msec, observers frequently miss the second target, although they correctly identify the first target. The AB deficit is not limited in the perception of RSVP stream; a similar pattern of results has been found when two targets and their masks are presented (Ward, Duncan, & Shapiro, 1996). Because varieties of stimuli and procedure can produce this dual target deficit (Pashler, 1997; Shapiro, 2001), the deficit has been ascribed to temporal unavailability of attention and has been used as a tool to control temporal aspects of attention and awareness (e.g., Kawahara, 2002; Kunar, Shapiro, & Humphreys, 2006).

It has been generally agreed that this AB deficit indicates that the visual system can process only one item at a time. For example, Shapiro et al. (1997) claimed that this deficit occurs because the attentional resource is depleted by processing the first target, resulting in resource scarcity for processing the second target when the temporal lag between the targets is short. The deficit recovers at longer lags because the resource is released after completion of first target processing. Although there are some detailed differences, most of the current AB models share this framework, agree-

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ing that the central processing limit is the source of the AB deficit (e.g., Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; Shapiro, Raymond, & Arnell, 1994).

An intuitive prediction from the resource-depletion model is that the second-target impairment should be most severe at the shortest lag (i.e., at lag 1), because the first target depletes the attentional resources and the scarcity of attention should be greater as the lag shortens. Thus, if the correct rate for the second-target identification is plotted as a function of the lag between the two targets, a gradually increasing trend along with lag increment would be expected with the lowest performance at the shortest lag. However, this is not always the case. Almost half of the published AB studies have reported a U-shaped function for the second-target performance (lag-1 sparing; for a review, see Visser, Bischof, & Di Lollo, 1999). That is, performance for the second target is unimpaired at lag 1 and as good as that at later lags (e.g., lag 7). In such cases, the deficit is most evident at lags 2–4.

Obviously, lag-1 sparing is inconsistent with the view of capacity limitation, because lag-1 sparing implies that the capacity of the visual system is not limited to one item, but rather two or more. Then how many items can be processed concurrently? Recently, Kawahara and Yamada (2006) focused on lag-1 sparing and challenged the conventional view that there is a severe capacity limit, that is, usually one item at a time, in the visual system. Kawahara and Yamada presented two RSVP streams side by side and embedded two first and two second targets. They predicted that if the capacity for concurrent processing is greater than one, observers would be able to monitor two RSVP streams containing two targets each. Specifically, lag-1 sparing should be evident concurrently in each stream. The results agreed with their prediction: there were two concurrent instances of lag-1 sparing. Clearly, this finding is inconsistent with a conventional view of capacity limitation. Rather, it suggests that the capacity for visual processing of RSVP targets is contingent on the attentional setting when viewing the display; if observers are attentionally set to monitor two streams, it is possible to process up to four items. This is consistent with the estimation of visual spatial short-term memory capacity (Luck & Vogel, 1997; Sperling, 1960; Xu & Chun, 2006).

Moreover, Kawahara and Yamada (2006) found that two instances of lag-1 sparing occurred at noncontiguous locations. Specifically, when two pairs of two targets were presented in the RSVP streams, there were two concurrent instances of lag-1 sparing. However, under a critical condition in which the second targets were presented at blank locations between the two RSVP streams, no lag-1 sparing was obtained; performance was worst at lag 1 and gradually improved as the lag was extended. Kawahara and Yamada interpreted this result as a manifestation of split foci of attention (e.g., Awh & Pashler, 2000; Kramer & Hahn, 1995) based on the following reasoning. In the AB literature, lag-1 sparing is said to occur only when there is no need to switch the attentional set for the first and second targets (Visser et al., 1999). For example, when two targets presented in a RSVP stream are drawn from the same target category (e.g., alphabet letters for both targets; Chun & Potter, 1995), lag-1 sparing occurs in most of the cases. However, when the two targets differ in more than two aspects, such as target defining dimensions, stimulus modality, location, and task/response requirements (e.g., identification of an auditorily presented letter as the first target and detection of visually presented letter "X" as the second target; Arnell & Jolicœur, 1999), lag-1 sparing does not occur. These meta-analyses by Visser et al. (1999) imply that the presence or absence of lag-1 sparing critically depends on whether observers adopt the same attentional set for the two targets. Therefore, it is conceivable that the presence of lag-1 sparing can be used as an index of the maintenance of the same attentional set to perceive two targets: if the observers can maintain the same attentional set, lag-1 sparing will occur. In Kawahara and Yamada's (2006) study, the concurrent occurrence of two lag-1 sparings at different locations can be considered as evidence that observers can maintain their attentional set at two noncontiguous locations.

However, there is a concern that such monitoring of two different locations (as shown by two concurrent instances of lag-1 sparing by Kawahara & Yamada, 2006) might be achieved by a rapid shift of attentional focus between the two streams, as several models have proposed that the metaphorical focus of the attentional spotlight can travel across space. For example, one of these models suggests that a spatial spotlight moves at a rate of 1º per 8–10 msec (Egly & Homa, 1991; Tsal, 1983). In Kawahara and Yamada's (2006) study, the two streams were separated by approximately 3º. Thus, it may be possible to perceive two targets at each stream with a single focus of attention by moving the focus from one stream to the other.

Therefore, we tested these alternatives by introducing two target categories. Using two categories for four targets should provide an optimal clue for distinguishing between the above two alternatives because, as reported in Visser et al.'s (1999) meta-analyses, when the target category switch is combined with other switches, such as spatial location or response tasks, lag-1 sparing never occurs. Therefore, if two concurrent lag-1 sparing found by Kawahara and Yamada (2006) is due to the quick shift of attentional focus between the RSVP streams, no lag-1 sparing would be observed when two different target categories are involved. Instead, performance for the second target would monotonically increase as the lag increases. In contrast, the two concurrent lag-1 sparing shown by Kawahara and Yamada represent a spatial split of the attentional set, two instances of lag-1 sparing would be observed because Visser et al. (1999) showed that mere category switch between the targets does not eliminate lag-1 sparing.

We conducted six experiments to test these alternatives using two RSVP streams each containing two targets. Answering this question would contribute toward understanding a critical mechanism—the attentional set—that determines the failure of attention to the second of two events occurring in close temporal proximity. Because lag-1 sparing and its interpretation is one of the critical issues in recent models of the AB (e.g., Bowman & Wyble, 2007; Kawahara, Kumada, & Di Lollo, 2006; Olivers, Van der Stigchel, & Hulleman, 2007), specifying the characteristics of the attentional set is important. Obtaining two instances of lag-1 sparing concurrently, even when there are two target categories, would suggest the flexible nature of attentional settings even in the nonspatial domain. Obviously, this aspect has not been examined in previous studies; Kawahara and Yamada's (2006) finding was limited to the spatial extent of attentional setting.

EXPERIMENT 1

We examined whether two concurrent instances of lag-1 sparing would be obtained with two RSVP streams when four targets were chosen from two target categories. A positive result would mean that observers can identify four targets in a brief moment and question the view that the AB deficit reflects a severe capacity limitation (i.e., the view that for sequentially presented items, only one or at most two items at a time can be processed). Two synchronized RSVP streams were presented to observers who searched for and identified four targets, two in each stream. The targets were two letters and two digits embedded in two streams of Japanese katakana-character distractors.

Method

Observers. Twelve Japanese students from Hiroshima University who were experimentally naive to the purpose of the experiment participated for extra course credit. All reported normal or corrected-to-normal visual acuity. They were tested individually in a darkroom.

Apparatus and Stimuli. The stimuli were displayed on a CRT monitor (GDM-19PS, Sony) controlled by a PC/AT-compatible computer equipped with a frame store (VSG 2/5, Cambridge Research Systems). A viewing distance of 72.5 cm was maintained using a headrest. The targets were two different uppercase letters randomly chosen in every trial from a set of English alphabet letters (A–H) and two different digits from 1 to 8. The distractors were Japanese katakana characters. The targets and distractors were presented in Windows system font and subtended 1.0º of visual angle in height. All stimuli were black on a white background. The stimulus display consisted of a fixation cross at the center of the screen and two synchronized RSVP streams, one to the left and the other to the right of the fixation cross (Figure 1). The letter targets appeared in one stream and the digit targets appeared in the other. The center-to-center distance between the two streams was 3.4º of visual angle.

Procedure and Design. Observers initiated each trial by pressing the space bar. After a delay of 500 msec, two synchronized RSVP streams were presented, each of which contained 5–10 leading distractors and two targets. The stream containing the letter or digital targets was determined randomly for every trial. Each item in the streams was displayed for 100 msec without an interstimulus interval. In any given trial, the distractors in each stream were randomly selected from a set of Japanese katakana characters, with the constraint that the selected character differed from the one immediately preceding the item. On any frame, the distractors in both streams differed from each other. The first targets in the left and right streams appeared simultaneously. The second targets appeared simultaneously in both streams, at one of five lags (100, 200, 300, 500, or 700 msec) after the first targets. The RSVP stream of distractors continued to be displayed during the lag. The second target was followed by two frames of distractors in each stream. Observers identified four targets by typing corresponding keys in any order. There were 12 practice trials prior to 300 experimental trials.

Results

In this and all subsequent experiments, performance of the second-target identification was based only on those trials in which both of the first targets had been identified correctly. Figure 2A shows the percentage of correct identification of the first and second targets. A two-way ANOVA with lag (100, 200, 300, 500, and 700 msec) and targets (first and second targets) as within-subjects factors revealed significant main effects of both lag [$F(4,44) = 3.75$, $MS_e = 61.51$, $p < .02$], and targets [$F(1,11) = 9.97$, $MS_e = 800.43$, $p < .01$]. The interaction between lag and targets was also significant [$F(4,44) = 17.45$, $MS_e = 107.52$, $p < .001$]. The tests of the simple main effects of the interaction indicate that the performance for the second target was higher than that for the first target at a lag of 100 msec [lag 1, $F(1,55) = 4.89$, $MS_e = 246.10$, $p < .04$], but the pattern was reversed for the other lags [lag 2, $F(1,55) = 14.40$, $MS_e = 246.10$, $p < .001$; lag 3, $F(1,55) = 24.23$, $MS_e = 246.10$, $p < .001$; lag 5, $F(1,55) = 9.62$, $MS_e = 246.10$, $p < .004$; lag 7, $F(1,55) = 9.75$, $MS_e = 246.10$, $p < .003$].

Figure 2B shows the percentage of correct identification of both second targets concurrently as a function of lag when both first targets were correctly reported. In other words, these are the means of trials when all four targets (i.e., two first and two second targets) were correctly identified. One-way ANOVA with one within-subjects factor (lag: 100, 200, 300, 500, and 700 msec) showed a significant effect of lag [$F(4,44) = 4.44$, $MS_e = 166.42$, $p < .005$]. Multiple comparisons using Ryan's method (Ryan, 1960) indicate that second-target performance at lag 1 was significantly higher than that at lag 3 [$t(44) = 3.87$, $p < .001$]. Based on Visser et al.'s (1999) study, lag-1 sparing was considered to have occurred when the performance at lag 1 was higher than the lowest level of performance by more than 5% in absolute terms. We found that the performance at lag 1 was higher than the lowest performance (at lag 3) by more than 5%, and the difference was statistically significant. Thus this result satisfies the Visser et al.'s (1999) criterion for lag-1 sparing.

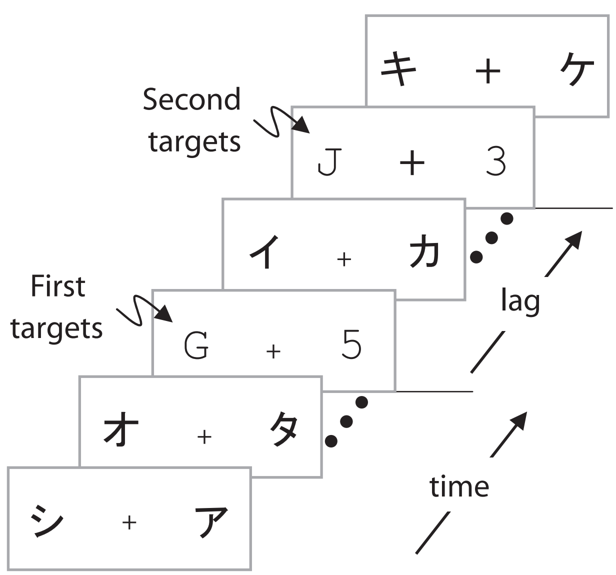

Figure 1. Schematic representation of stimuli used in Experiment 1. The alphabetical letters and the digits were targets, and the Japanese katakana letters were distractors. The first targets and the second targets, respectively, were presented simultaneously.

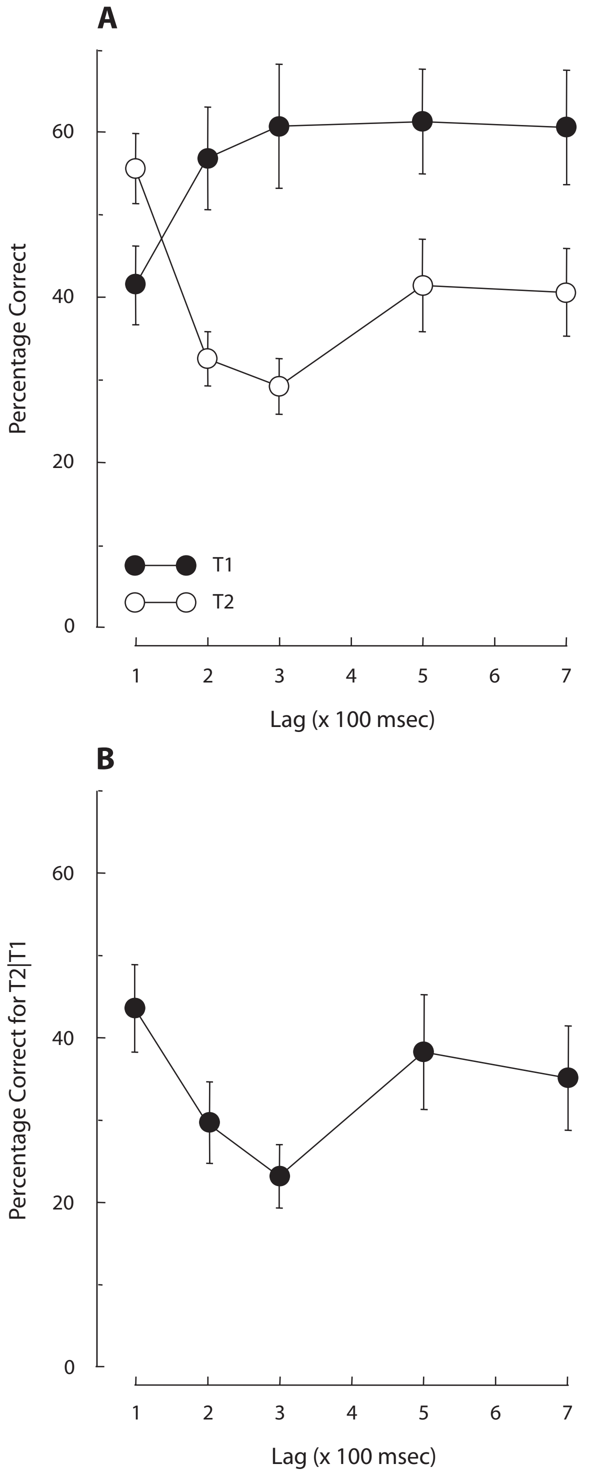

Figure 2. The results of Experiment 1. (A) Mean percentage of correct identification of the first and second targets. (B) Mean percentage of correct identification of the second targets, given correct identification of the first targets. T1, first target; T2, second target. Error bars indicate standard errors in both panels.

Discussion

The results of Experiment 1 indicate that lag-1 sparing occurred simultaneously in two noncontiguous RSVP streams. If the two instances of lag-1 sparing obtained by Kawahara and Yamada (2006) had been achieved by a rapid shift of spatial focus between the two streams, then there should have been no lag-1 sparing in the present experiment. This is because no lag-1 sparing has been reported when the categories of the two targets and their spatial location differ (Visser et al., 1999). In fact, we found two instances of lag-1 sparing at different locations. Therefore, our results exclude the possibility that a single focus of visual attention rapidly moved to report the four targets. Rather, the result suggests that observers can maintain their attentional set to monitor two noncontiguous locations for two different target categories, implying that up to four items can be processed during target identification in RSVP streams. This result is consistent with the finding that observers can relatively easily process up to four consecutive targets from a RSVP stream (Olivers et al., 2007). Similarly, Di Lollo, Kawahara, Ghorashi, and Enns (2005) reported that at least three targets can be reported correctly when they appear in succession at the same location. The results of these two recent studies argue against the view of severe capacity limitations in case of RSVP perception. The present results extend these findings in that it was possible to identify up to four targets in a rapid succession in the dual RSVP situation. Importantly, the present results suggest that this capability of visual processing is not limited to identification of a target category in a single RSVP stream. Instead, the visual system can monitor two streams for two categories. We will return to the spatial extent of this capability in Experiment 6.

It is worth noting that we found a crossover between the first- and second-target performance at shorter lags. Specifically, at lag 1 the second-target performance was better than the first, but at later lags the first-target performance was better than the second. This pattern is consistent with the findings by Potter, Staub, and O'Connor (2002), who found similar results using an ordinary two-target identification task with a RSVP stream. Our result leads us to question the explanation of such a crossover effect based on the resource limitation view. If the lower performance for the first target in an ordinary single RSVP stream condition represents the loss of competition for the attentional resource at shorter lags, then the residual amount of the attentional resource is not sufficient for the first target when the second target appears. In such occasions, there should be no extra attentional resource available for a *second* second target, as in our Experiment 1 in which there were two sets of first and second targets. Contrary to this reasoning, the present results indicate that both of the second targets could be reported at the shortest lag which should cause the most severe shortage of attention. In other words, if two second targets could be reported (i.e., there was sufficient attentional resource for the two targets at lag 1 in the four-target task), then the resource should have been available for the first target in an ordinary two-target task (i.e., there should have been no crossover effect). Instead, we suggest that the crossover effect that occurred here was not caused by resource competition, but rather a different factor, perhaps as visual masking. Regarding masking, the first target was masked by the second target at lag 1, but masked by a distractor digit at other lags. Therefore, it is possible that the masking effect on the first target was greatly enhanced because Dux and Coltheart (2005) have shown that AB is larger when masking items are chosen from the same category as the targets than when they are chosen from a different category.

These results are consistent with the idea that the processing capacity during target identification in RSVP streams is not limited to two but can be up to four items (Kawahara & Yamada, 2006), and suggest that observers can maintain their attentional set to monitor two noncontiguous locations for two different target categories (Awh & Pashler, 2000; Hahn & Kramer, 1998). Given that observers could maintain their attentional set at different locations, there are two possibilities regarding how they could monitor four targets distributed in two streams. One is that the observers were able to monitor only one category of targets at one location, but they could set two different unidimensional attentional sets at different locations. For example, they could prepare for digits in the left stream and for letters in the right stream. If the targets appeared as the observer expected, then the targets would be correctly identified. However, if letters appeared in the left stream and digits appeared in the right stream, the observers would have had to switch their attentional set for these categories in the left and right streams. The relatively lower performance for the first target (approximately 63%) might be attributed to the inefficiency of this strategy. The second possibility is that the observers were able to monitor two categories simultaneously at the same location. This possibility could have occurred if the observers prepared a multidimensional attentional set to identify the digit and letter categories. We examined these alternatives in Experiment 2.

EXPERIMENT 2

We tested the two alternatives of whether the observers prepared an attentional set for one category at one stream and switched the sets between the two streams if the target was in a different category, or whether the observers could prepare a multidimensional attentional set for the two streams. If the first option—that is, the unidimension hypothesis—is true, there would be no lag-1 sparing when each stream contained two targets drawn from two categories (e.g., the left stream contained a letter and a digit and the right contained a digit and a letter for the first and second target, respectively). If the second option, i.e., the multidimension hypothesis, is true, lag-1 sparing would be obtained concurrently in both streams.

Method

Observers. Thirteen Japanese students from Hiroshima University who were experimentally naive to the purpose of the experiment participated for extra course credit. All reported normal or corrected-to-normal visual acuity. The results from one participant were excluded from analysis because s/he failed to complete the task.

Procedure. The apparatus, stimuli, and procedure were identical to those of Experiment 1 except for the coupling of the targets. Experiment 2 was designed so that each stream contains two targets chosen from two categories. For example, one stream had letter and digit targets as the first and second targets, whereas the other stream had digit and letter targets as the first and second targets.

Results

Figure 3 shows the percentage of correct identification for the second targets as a function of lag, averaged across all observers in Experiment 2. Correct identification of the first targets, averaged across all lags, was 79.8%. One-way ANOVA with lag as a factor showed a significant main effect [$F(4,44) = 14.23$, $MS_e = 142.31$, $p < .001$]. Multiple comparison using Ryan's method indicates that second-target performance at lag 1 was significantly higher than that at lag 2 and lag 3 [$t(44) = 5.58$, $p < .001$; $t(44) = 5.39$, $p < .001$, respectively].

Discussion

The purpose of Experiment 2 was to examine whether the observers prepared different unidimensional attentional sets for each category at each stream or whether they could prepare a multidimensional attentional set for the two streams. The results clearly indicated that the latter was the case. Lag-1 sparing occurred concurrently in both streams, even when each stream contained different categories of targets. This result supports the multidimensional hypothesis that observers can monitor two different categories at two different locations simultaneously. The unidimension hypothesis, which stated that observers monitor a category for each stream, can be rejected because lag-1 sparing was obtained even though the second targets always belonged to a different category from the first targets.

Thus far, the results consistently show that observers can successfully report four targets when the targets appear in temporal proximity (<100 msec). This finding sharply contrasts the ordinary result of the AB deficit, in which the

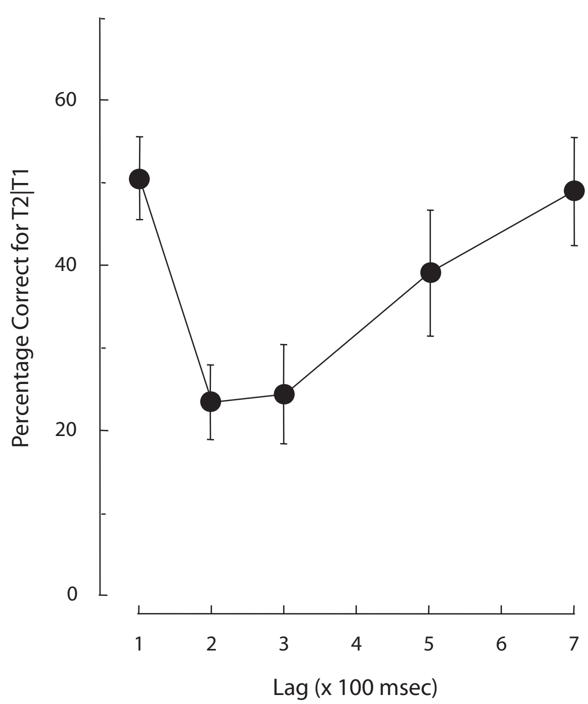

Figure 3. Mean percentage of correct identification of the second targets, given correct identification of the first targets in Experiment 2. Error bars indicate standard errors.

second-target deficit is most pronounced immediately after presentation of the first target. Such a conventional pattern of the results can be easily attributed to the idea that the AB deficit represents resource depletion by processing of the first target (see, e.g., Shapiro et al., 1997). In this sense, we question the premise that the AB deficit represents a scarcity of attentional resources. Instead, our results indicate that the visual system can concurrently monitor two RSVP streams for four items in a brief moment, even when those four items belong to two different target categories.

The present findings extend Visser et al.'s (1999) idea of input filtering. From an intensive review of AB studies, Visser et al. (1999) proposed that visual processing takes place through two sets of sequential stages. The first stage is a parallel processing stage and has no capacity limit. This stage detects target candidates among distractors and passes the candidates for further processing. The second stage is a resource limited stage, where elaborated processing and memory consolidation occur on the target candidates so that they can be reported.

Visser et al. (1999) argue that, in the first stage, the visual system prepares attentional sets, called input filters, which can be dynamically configured under endogenous control. This configuration determines whether a particular stimulus input can gain access to later domain-specific modules at higher processing levels. Processing at the later stage progresses under stimulus-driven control: once stimulus input matches the filter configuration, it passes through the filter and is processed at a later stage in an exogenous way. In this model, Visser et al. (1999) assumed that the filter could be configured flexibly, depending on the task demand. The present results are consistent with this idea and extend it by showing that observers can prepare two input filters to monitor two target categories at different locations.

Before taking the present results as supporting the idea of flexible input filtering that enables multicategorical monitoring, alternative explanations must be considered. For example, observers could switch their attentional set between stimulus categories once they encounter the first targets, because the category of the second targets was fully predictable from the category of the first targets. That is, observers might initially establish an attentional set, for example, expecting a letter in the left stream and a digit in the right stream, and switch the set immediately upon the arrival of the first targets. We believe that this is unlikely because the first targets consisted of different categories and their locations were unpredictable. Therefore, if they adopted this strategy, the first target performance should not exceed 50%. In fact, their first target performance was approximately 80% excludes this explanation. Moreover, there are several studies showing that it requires a much longer period to shift attentional set intentionally. For example, Yokosawa and Kumada (2003) reported that it took over 500 msec to use a preceding cue to shift attentional set to detect targets. Rogers and Monsell (1995) also showed that observers could not switch attentional set even when 1,200 msec of preparation time was allowed. Thus 100 msec of lag should be too short to use this strategy. Another concern is that observers did not set for two target categories, but simply rejected the distractor category and accepted the remaining category. We tested this possibility in Experiment 3.

EXPERIMENT 3

In Experiment 3, we used two target categories (alphabets and numerals) and two distractor categories (Japanese katakana and hiragana characters). If the results of Experiments 1 and 2 indicate that observers cannot set to monitor two target categories, but simply reject a distractor category, then there would be no lag-1 sparing in Experiment 3 because such a strategy is not applicable when distractors are chosen from two categories. In contrast, if it is possible to actively monitor two target categories, lag-1 sparing will occur.

Method

Observers. Twelve Japanese students from Hiroshima University who were experimentally naive to the purpose of the experiment participated for extra course credit. All reported normal or corrected-to-normal visual acuity.

Procedure. The apparatus, stimuli and procedure were the same as those in Experiment 2, with the exception that half the distractors were presented in Japanese hiragana characters.

Results and Discussion

Figure 4 shows the percentage of correct identification for the second target as a function of lag, averaged across all observers. Correct identification of the first targets, averaged across all lags, was 65.0%. One-way ANOVA with lag as a within-subjects factor indicated a significant main effect [$F(4,44) = 23.58$, $MS_e = 108.41$, $p < .001$]. Multiple comparison by Ryan's method indicated that second-target performance at lag 1 was significantly higher than that at lag 2, lag 3, and lag 5 [$t(44) = 7.02$, $p < .001$; $t(44) = 7.54$, $p < .001$; $t(44) = 5.92$, $p < .001$, respectively].

Once again, the results revealed that there were two instances of concurrent lag-1 sparing in both streams. This suggests that observers could monitor two different target categories and rejects the possibility that they excluded a distractor category and accepted the remaining category in the previous experiments. General performance in the present experiment was somewhat lower than in the preceding two experiments. This decrement might have been caused by the inclusion of a fourth category (Japanese hiragana characters) that reduced the featural saliency of the targets, especially for numeral targets, because Japanese hiragana characters contain many curved strokes. Another possibility is that these new distractors were highly familiar to the observers of the present study. Because some Japanese hiragana letters can be nouns even when they are presented as a single letter, such words might produce semantic but irrelevant activation automatically thereby making it difficult to exclude them as distractors.

Although this experiment is consistent with the idea that observers can monitor two target categories, it is still possible that they excluded a distractor language (i.e., Japanese, in this case). Because the participants in Experiment 3 were Japanese, they may have ignored the katakana and hiragana distractors as a single category of "Japanese characters." Even if this occurred, this finding implies a flex-

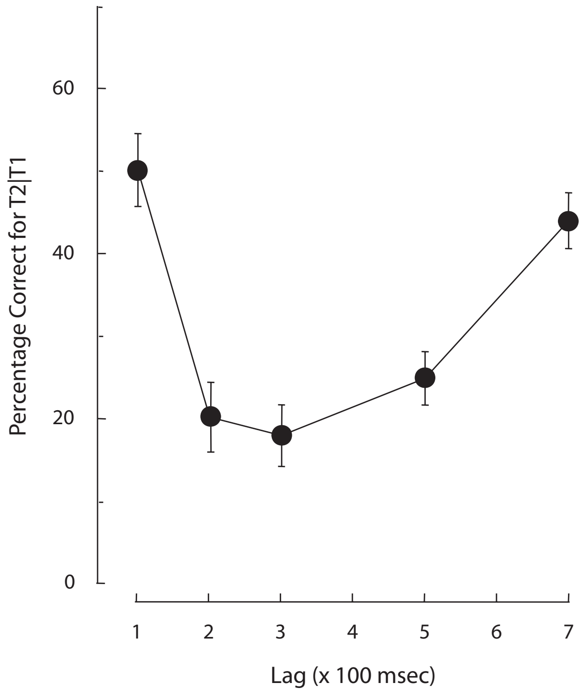

Figure 4. Mean percentage of correct identification of the second targets, given correct identification of the first targets in Experiment 3. Error bars indicate standard errors.

ible configuration of input filter in the sense that the criterion of exclusion is not a simple feature but a high-level concept such as a language (Rodriguez-Fornells, Rotte, Heinze, Nösselt, & Münte, 2002). However, this does not necessarily mean that observers can monitor two target categories. This possibility was tested in Experiment 4.

EXPERIMENT 4

In Experiment 4, we replaced the hiragana distractors with pseudocharacters used in Visser, Bischof, and Di Lollo's (2004) study. If observers adopted a strategy to exclude Japanese characters, no lag-1 sparing would be obtained in this experiment.

Method

Observers. Twelve Japanese undergraduate students from the National Institute of Advanced Industrial Science and Technology (AIST, Tsukuba, Japan) subject pool participated for pay. All reported normal or corrected-to-normal visual acuity and were naive with respect to the purpose of the experiment.

Procedure. The apparatus, stimuli and procedure were the same as those in Experiment 3, with the exception that hiragana distractors were replaced with pseudocharacters.

Results and Discussion

Correct identification of the first targets, averaged across all lags, was 49.3%. Figure 5 shows the percentage of correct identification for both second targets as a function of lag. One-way ANOVA with lag as a within-subjects factor revealed a significant main effect [$F(4,44) = 32.64$, $MS_e = 59.98$, $p < .001$]. Multiple comparison by Ryan's method indicated that second-target performance at lag 1 was significantly higher than that at lag 2 and lag 3 [$t(44) = 7.69$, $p < .001$; $t(44) = 6.61$, $p < .001$, respectively].

The results of Experiment 4 clearly indicate that lag-1 sparing occurred concurrently in both streams, even when distractors consisted of two categories (katakana and pseudocharacters). This result leads us to reject the idea that the two instances of lag-1 sparing found in the previous experiments were attributed to an efficient exclusion of a single distractor category. Specifically, it is unlikely that the results of Experiment 3 were due to filtering out of Japanese characters and accepting of remaining items because such a strategy could not be used in the circumstances in Experiment 4. Instead, our findings suggest that observers can prepare an attentional set to monitor two different categories at the same time at different locations.

EXPERIMENT 5

The results of the previous experiments indicated that the number of items that observers could process in RSVP streams was larger than previously believed in extant AB studies; rather, we suggest that they can process up to four items in a brief moment. This is consistent with recent findings (Di Lollo et al., 2005; Olivers et al., 2007) that go against the limited capacity view of the AB. To test this idea directly, Experiment 5 examined how well observers can process four items as compared to the case in which only two targets were presented. If the processing limit is much larger than expected, the correct rate of trials in which there were four targets would be fairly high. As shown by Olivers

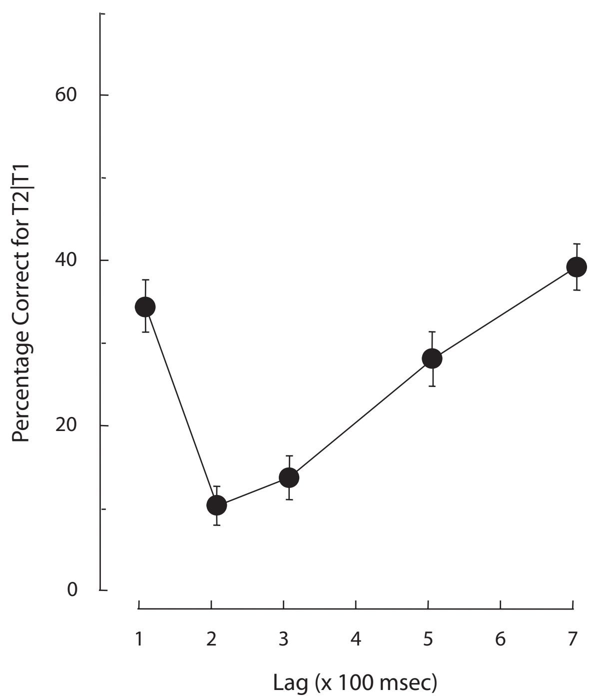

Figure 5. Mean percentage of correct identification of the second targets, given correct identification of the first targets in Experiment 4. Error bars indicate standard errors.

et al. (2007, Experiment 1), performance reporting four targets would be roughly the same as or slightly lower than that of reporting two targets (approximately 10% less). We predict a similar pattern of results.

In the present study, we presented two or four targets and asked the observers to report only two targets. At the end of the RSVP stream presentation, a marker was presented to prompt the observers to report one pair (right or left stream) of the targets. We predicted that the AB deficit and lag-1 sparing would be obtained under the two- and four-target conditions. We also expected a moderate decrement in performance in the four-target condition because our pilot experiment indicated that it took longer to enter responses under the four-target condition than under the two-target condition (see Discussion for details). More critically, this decrement would not be due to attentional resources but to short-term memory span (Peterson & Peterson, 1959; Sperling, 1960). Thus there would be no interaction between the number of targets and the AB deficit.

Method

Observers. Eighteen Japanese undergraduate students from the AIST subject pool participated for pay. All reported normal or corrected-to-normal visual acuity and were naive with respect to the purpose of the experiment.

Stimuli, Apparatus, and Procedure. The stimuli were the same as those used in Experiment 3 except the following changes. For technical reasons, we could not use the same equipment as in the previous experiments. The stimuli were displayed in MS-Gothic Japanese font on a CRT monitor (Multiscan G220, Sony) controlled by a computer operating Microsoft Windows and Psychophysics toolbox (Brainard, 1997). There were two conditions regarding the number of targets to be presented (2 vs. 4). When there were two targets, the first and second targets appeared in the same stream. The other stream consisted of distractors. The stream in which the targets appeared (left or right) was determined randomly. When there were four targets, both streams contained two targets, as in the previous experiments.

The procedure was the same as in Experiment 3, except for the following three points. First, the two target conditions (two vs. four targets) and the three lags (100, 300, and 700 msec) were combined factorially. Second, a prompt (a square 0.3º in width and height) was presented 1deg above the RSVP stream after all the RSVP items were presented, until the observers responded. The observers reported the targets presented in the prompted stream. When there were two targets, the prompt was presented above the stream where the targets were presented. When there were four targets, the prompt appeared above the right or left stream with equal frequency. There were 10 practice trials before the experimental session, which consisted of 360 trials. We also measured time required from the onset of the probe to the second response, although observers were instructed to respond at their leisure.

Results

Correct identification of the first targets, averaged across all lags, was 72.6% and 82.8% for the two- and four-target conditions, respectively. Figure 6 shows the percentage of correct identification for the second target as a function of lag for the two- and the four-target conditions. Two-way ANOVA with lag and the number of targets as within-subjects factors revealed significant main effects of lag [$Fs(2,34) = 25.94$, $MS_e s = 211.14$, $p < .001$], and the number of targets [$F(1,17) = 19.45$, $MS_e = 197.42$, $p < .001$]. The interaction between these two factors was not significant ($F < 1$).

The response time from the onset of the prompt to the second keypress was 2,715 msec ($SD = 636.69$) and 3,661 msec ($SD = 927.74$) under the two- and four-target conditions, respectively. A t test indicated that the response time under the four-target condition was significantly longer than that under the two-target condition [$t(17) = 7.13$, $p < .001$].

Discussion

As expected, performance under the four-target condition was fairly high: The difference between the two- and four-target conditions was only about 12%. Because there was no interaction between the number of targets and lag, the present results suggest that this difference is not due to the load related to the AB deficit itself. If we take performance at lag 7 as a baseline, performance at lag 1 was equally higher than the baseline under both the two- and four-target conditions. These results suggest that the visual system can handle four targets (at lag 1) almost equally with the same ease as two targets (at lag 1). In this sense, the present result is consistent with the results of Experiments 1–4 and with those from previous studies (e.g., Di Lollo et al., 2005; Olivers et al., 2007).

It is reasonable to assume that this difference occurred because it took extra time to make two responses under the four-target condition. Under the two-target condition, observers could simply enter two responses. However, under the four-target condition, observers needed to reorganize

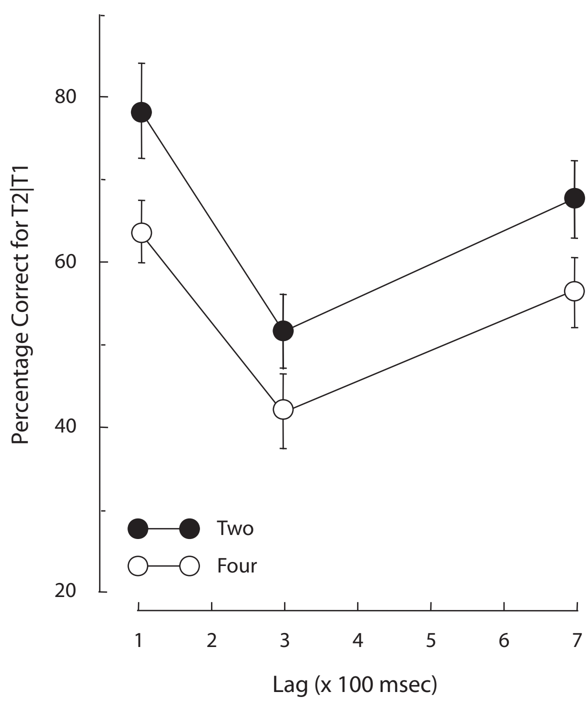

Figure 6. Mean percentage of correct identification of the second targets, given correct identification of the first targets in Experiment 5. "Two" and "four" represent the two- and four-targets conditions, respectively. Error bars indicate standard errors.

their responses, although a partial report equalized the number of responses. To be more specific, imagine a case in which there are four targets. The first targets would be "A" in the left and "1" in the right and the second targets would be "2" in the left and "B" in the right stream. Our observations showed that observers entered responses as "A–1–2–B" in most such cases, suggesting that they preserved the temporal order and spatial locations of the presented items. Therefore, if a location prompt is presented on the right side, to respond to it correctly (i.e., "1–B"), they need to reorganize the remembered sequence in terms of space. Observers' short-term memories may be lost during the delay caused by this mental operation. Although speculative, the reaction time data were consistent with this interpretation. However, detailed examinations of the cause(s) of this delay remain for future investigation.

As noted in the introduction, our hypothesis in the present study was based on one of the models of spatial attention assuming that attentional spotlight can travel across space at a fixed rate. In fact, there are other possibilities in that one's spatial range of attention can change depending on the stimuli or task to be performed as if it were a zoom lens (Eriksen & Murphy, 1987) or a flexible spatial gradient (LaBerge, 1983; but see also Lavie, 1995). For example, it is possible that the observers simply adopted a large field of attentional spotlight encompassing both streams. Therefore, what is missing from our study is the exact evidence for attention being split between two "noncontiguous" locations. We examined this issue in Experiment 6.

EXPERIMENT 6

From our results thus far, it is unclear whether observers could split attentional sets to monitor two different categories embedded in two noncontiguous RSVP streams, or if they simply applied a large focus of attentional spotlight to encompass the two streams. Therefore, in Experiment 6, we tested these two possibilities by introducing two conditions: the *stream* and *inward* conditions as used by Kawahara and Yamada (2006). The second targets were presented either at the same locations as the first targets (in the same streams as the first targets; the stream condition) or between the two streams (the inward condition). The latter was the critical condition because if observers were able to split attentional sets at different locations, no lag-1 sparing would be expected. However, if they adopted a large spotlight encompassing the two streams, lag-1 sparing would be obtained.

Method

Observers. Twelve Japanese undergraduate students from the AIST subject pool participated for pay. All reported normal or corrected-to-normal visual acuity and were naive with respect to the purpose of the experiment.

Stimuli and Procedure. The stimuli and procedure were the same as those used in Experiment 3 except for the following changes. There were two conditions regarding the location of the second two targets and their masks. The apparatus was the same as that in Experiment 5. The second targets were presented in one of two locations: within the two streams (stream condition) or displaced toward fixation (inward condition). The intertarget distances in the stream and inward conditions were 3.4º and 1.2º, respectively (Figure 7). Under the inward condition, each first target was masked by a distractor and only the second targets and their trailing distractors were away from the streams; all items preceding the second targets were presented in the same locations as the first targets. Under the inward condition, two second targets and the two distractors to mask the first targets were presented in the same frame at lag 1. To compensate for the fact that there were four items in the lag-1 frame under the inward condition, two additional distractors were presented between the second targets under the stream condition at lag 1. The two location conditions (stream and inward) and the three lags (100, 300, and 700 msec) were combined factorially. There were 10 practice trials before the experimental session, which consisted of 360 trials.

Results

Correct identification of the first targets, averaged across all lags, was 71.2% and 69.4% for the stream and the inward conditions, respectively. Figure 8 shows the percentage of correct identification for both second targets as a function of lag for the stream and the inward conditions when the two first targets were correctly identified. Two-way ANOVA with lag and second-target location as within-subjects factors revealed a significant main effect of lag [Fs(2,22) = 71.28, MS_es = 187.66, $p < .001$]. The effect of second-target location was not significant. More

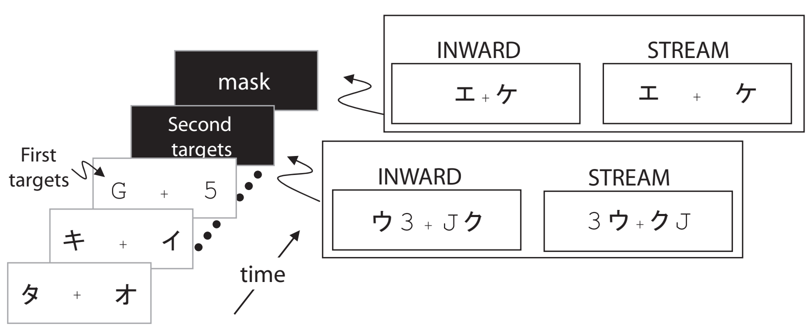

Figure 7. Schematic representation of stimuli used in Experiment 6. Each of the first targets was masked, in all instances, by a trailing distractor presented in the stream. Each of the second targets was masked by two trailing distractors that were presented at the same location as the second targets. Under the stream condition, two distractors were presented together with the second targets at the inward locations; under the inward condition, they were presented in the stream.

importantly, the interaction between these two factors was significant [$F(2,22) = 71.28$, $MS_e = 187.66$, $p < .001$]. Regarding this interaction, multiple comparison by Ryan's method on scores of the stream condition indicated that second-target performance at lag 1 was significantly higher than that at lag 2 [$t(44) = 4.82$, $p < .001$]. In contrast, the same comparison under the inward condition indicated that second-target performance at lag 1 was significantly lower than that at lag 2 [$t(44) = 2.88$, $p < .01$].

The results of Experiment 6 showed that lag-1 sparing occurred concurrently in both streams under the stream condition, but no lag-1 sparing was obtained under the inward condition. This pattern of results was consistent with the prediction from the hypothesis that attentional set could be split for two noncontiguous locations. However, the other hypothesis that a large attentional spotlight encompassed the two streams cannot explain the present results because if this were the case, lag-1 sparing should have been observed under both conditions. Therefore, the results of Experiment 6 suggest that observers can prepare an attentional set to monitor two different categories at the same time at different, noncontiguous locations.

There is a difference between the previous and present experiments in that performance at lag 1 was almost the same as that at the longest lag in the previous experiments, but the lag-1 performance in the stream condition was clearly lower than the performance at the longest lag. We assume that this difference was attributable to the following two reasons. First, the present experiment used a thicker font than that used in Experiments 1–4. This might have contributed to the elevation of the performance at lag 7, exaggerating the lag 1 − lag 7 difference. Second and more critically, in the present experiment, the second targets were accompanied with two additional distractors that served as masks for the first targets under the stream and inward conditions at lag 1. It is highly likely that these distractors impaired identification because of a crowding effect and/or lateral masking.

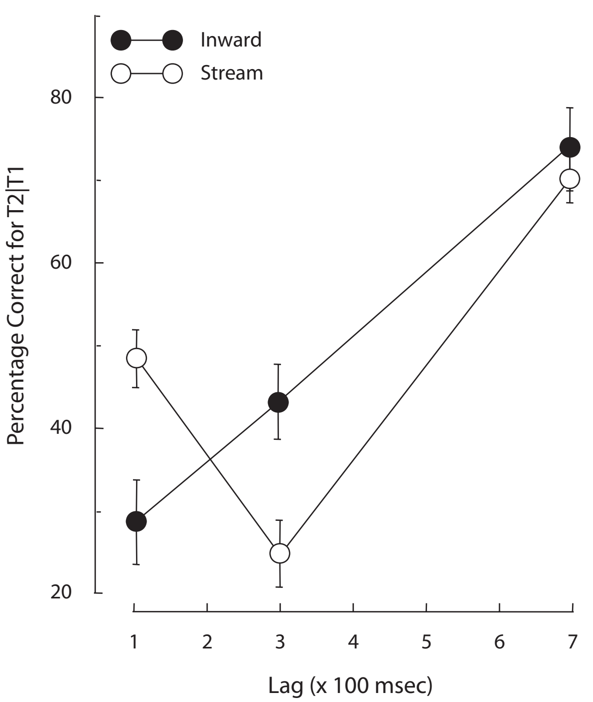

Figure 8. Mean percentage of correct identification of the second targets under the stream and inward conditions, given correct identification of the first targets in Experiments 6. Error bars indicate standard errors.

GENERAL DISCUSSION

The AB phenomenon has been interpreted widely as the inability of the visual system to process more than one item at one time. Contrary to this conventional view, Kawahara and Yamada (2006) reported two concurrent instances of lag-1 sparing at different locations and suggested that observers can monitor two streams concurrently for up to four items presented in temporal proximity. Such an estimation of visual capacity is consistent with the finding that visual short-term memory is capable of holding four items at one time (Luck & Vogel, 1997; Sperling, 1960). Given that lag-1 sparing is taken as an index of attentional set maintenance, the finding of two concurrent instances of lag-1 sparing provides converging evidence for split foci of attention (Awh & Pashler, 2000; Hahn & Kramer, 1998; Kramer & Hahn, 1995). However, Kawahara and Yamada's finding is inconclusive because it is possible to obtain the same pattern of results by deploying a single attentional focus if the focus shifts rapidly. We tested this possibility by introducing two target categories. Based on the fact that lag-1 sparing has never been found when there are spatial and categorical switches between two targets (Visser et al., 1999), we predicted that there would be no lag-1 sparing, if the two concurrent instances of lag-1 sparing in two RSVP streams were mediated by the rapid shift of a single attentional focus.

The results of the present experiments consistently indicate that two instances of lag-1 sparing occurred concurrently in both streams. In Experiments 1 and 2, strong AB was obtained, but the second-target performance at lag 1 was virtually identical to that of later lags, such as lag 7, even when four targets were chosen from two categories (letters and digits). Experiment 5 replicated this finding and indicated that observers could identify four items with a fairly high correct rate. In terms of the attentional set to monitor targets, Experiments 3 and 4 rejected the alternative that observers did not monitor two target categories but selectively inhibited a single distractor category (katakana letters). Therefore, we can exclude the rapid-shift hypothesis. Experiment 6 also excluded the possibility that observers adopted a broad attentional focus to encompass two streams. Rather, the results were consistent with the idea of split attentional foci. Thus based on these results, we can safely conclude that observers can maintain attentional set concurrently at different locations to monitor two RSVP streams and that the two concurrent instances of lag-1 sparing can be taken as evidence suggesting that the capacity of target identification in RSVP streams is not limited to one, but can be up to four. Regarding the capacity limit in the spatial domain, it has been suggested that the human visual system can maintain approximately four spatially distributed items by using various types of procedures (e.g., Luck & Vogel, 1997; Pylyshyn, 1989; Sperling, 1960; Xu & Chun, 2006). In the temporal domain, the conventional view of the available capacity as indexed by the AB procedure was substantially limited (i.e., one or two items). However, based on the present results, we can assume that capacity limit does not differ across spatial and temporal domains.

The present findings are inconsistent with traditional resource-depletion models, in which the AB deficit is attributed to the temporal scarcity of the attentional resource for second-target processing. Such models generally postulate a processing stage with limited capacity. The visual system relies on this processing stage to identify and consolidate a target for later reporting. Because of the capacity limit, the system cannot process any further item when the stage is occupied by the processing of a leading target. If a second target appears when the stage is busy with the first target, the second-target processing is delayed. During this delay, the representation of the second target is vulnerable to masking by trailing items (Giesbrecht & Di Lollo, 1998) or to decay (Kawahara, Zuvic, Enns & Di Lollo, 2003). Obviously, the present findings are not in agreement with this view, because if the processing capacity were limited to one item, it would be impossible to obtain two concurrent instances of lag-1 sparing.

Rather, the present results are consistent with recent findings showing that multiple targets are reportable in rapid visual streams. For example, Di Lollo et al. (2005) showed that observers can correctly report three successively presented targets. Moreover, Olivers et al. (2007) found that observers can relatively easily process up to four consecutive targets. It should be noted that these results arguing against the limited capacity view were obtained by using a single RSVP stream consisting of a single target and another different category of distractors. The present study extended the argument by showing that observers were capable of reporting up to four items even when they were monitoring two target categories at different locations.

These findings can be explained by recent models, such as the temporary loss of control (TLC; Di Lollo et al., 2005; Kawahara et al., 2006) account with minor modifications. Specifically, Di Lollo et al. found that the AB deficit occurs when a critical sequence contains two targets and an intervening distractor (i.e., target–distractor–target), but no deficit occurs when the sequence consists of sequential presentation of three targets (i.e., target–target–target). The TLC account suggests that the AB deficit is not due to scarcity of attentional resources that must be allocated to the second target; instead, the AB occurs because the visual system can execute only a single task at a higher level of cognitive operation, such as target identification, input control, or maintenance of task set, at a time. The model explains why the AB deficit occurs with a target–distractor–target sequence but not with a target–target–target sequence as follows. When observers are monitoring the leading RSVP stream, the visual system can apply an input filter that is tuned optimally to exclude distractors (e.g., Japanese katakana letters) and to accept targets (e.g., alphabet letters). The first target is correctly identified because this input filter is maintained by continuous signals from the central executive system to obtain the best performance. Upon the arrival of the first target, the executive function is now devoted to target identification and the maintenance signal is discontinued, resulting in loss of control over the input filter. When a distractor is presented during this period, as in the target–distractor–target sequence, the setting of the input filter is altered by the distractor in its own image (i.e., Japanese katakana letters). The second target cannot be identified because the target cannot pass the filter that is now set to pass distractor features. However, in the target–target–target sequence, the setting of the input filter does not change even when the maintenance signal is discontinued and the appropriate setting (to pass alphabet letters) is intact because the second item was itself a target.

Similarly, input filtering plays an important role in Olivers et al.'s (2007) explanation. In their model, the input filter accepts target properties and automatically enhances target representation, while rejecting distractor properties. To explain the AB deficit in a target–distractor–target sequence, this account assumes that the input filter passes the first target, allowing the distractor immediately after the first target to enter the identification process. The system corrects the erroneous behavior of allowing the entry of the distractor by closing the filter temporarily, so as not to process any more incoming items. This temporary disabling of the input filter causes the AB deficit. When multiple targets appear successively, the following targets can be identified easily because the leading target has already opened the filter. Although the difference between these two accounts is whether the leading target elicits a temporary loss of control or shuts down the input, they share the idea that the input filter is flexibly changed. These accounts can explain the present results by extending the view of input filter: it is not a simple feature detector but a multicategorical filter that also monitors two different locations simultaneously. It should be noted that a recent computational model (Bowman & Wyble, 2007) also hypothesizes a filter mechanism (the task filtered layer) that is flexibly and dynamically configured. Although the model focuses only on the case in which there are two targets drawn from the same category embedded in a single RSVP stream, extension of such models to the case of multidimensional target identification would be an important future direction for the AB studies.

AUTHOR NOTE

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