A memory-based interference effect in midstream order deficit

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People do not accurately recognize the relative order of a letter sequence displayed in a rapid serial visual presentation when the letter sequence is presented repeatedly and the exposure of the letters is very brief in the first half of the presentation. This phenomenon is known as *midstream order deficit* (MOD), and is considered to reflect the limitation of temporal resolution in segmentation processes. However, the results from three experiments revealed that MOD occurred even when the stimuli induced exogenous segmentation. Furthermore, a MOD-like effect could be observed when an irrelevant letter sequence was presented before the target letter sequence. We propose a new explanation for MOD, based on interference between the representations of order in memory and current perception.

Participants' accuracy of recall for the relative order of a sequence of four sounds presented at a rapid rate is lower when the sequence is presented repeatedly rather than only once (Warren, Obusek, Farmer, & Warren, 1969). Holcombe, Kanwisher, and Treisman (2001) replicated this phenomenon using a rapid serial visual presentation (RSVP) procedure, in which stimuli appear sequentially and rapidly at the same spatial location. Holcombe et al. used two conditions: a cycling condition and a single-presentation condition. In the cycling condition, a four-letter sequence was presented five times. The exposure duration from the first to the ninth item (i.e., the first item of the third four-letter sequence) was gradually increased from approximately 16 msec to more than 100 msec (deceleration phase) by a constant amount, and the exposure duration of the ninth to the final item was constant (constant phase). In the single-presentation condition, items were presented in the same manner as in the cycling condition except that the four-letter sequence was embedded only once in a stream of line-pattern distractors, with the constraint that letters appeared only after the deceleration phase. Participants were asked to report the relative order of the sequence. For example, for the letter sequence BFGH, all of the following responses were counted as correct: BFGH, FGHB, GHBF, and HBFG. Holcombe et al. found that although letter identification accuracy was higher in the cycling condition than in the single-presentation condition, the accuracy of reporting relative order was lower in the cycling condition. They called this phenomenon the *midstream order deficit* (MOD).

In MOD, the multiple presentation of a four-letter sequence appears to impair the apprehension of the relative order of the letters, despite the fact that participants recall the identity of the letters more accurately in the cycling

condition than in the single-presentation condition. MOD is not predicted by any of the current models of the perception of or memory for serial order (e.g., Anderson & Matessa, 1997; Brown, Preece, & Hulme, 2000; Lewandowsky & Murdock, 1989; Page & Norris, 1998; for a review, see Neath & Surprenant, 2003). Holcombe et al. (2001) proposed that MOD reflects differences in temporal resolution between endogenous and exogenous segmentation processes. In the single-presentation condition, the perceptual or categorical discontinuity between the line pattern and the letter sequence allows automatic or exogenous segmentation. In contrast, in the cycling condition, endogenous segmentation is needed to designate an arbitrary item as the start of a sequence. Relative order accuracy is impaired in the cycling condition because of the lower temporal resolution of endogenous in comparison with exogenous segmentation. We refer to this explanation as the *temporal resolution hypothesis*.

In the RSVP procedure, when participants are asked to identify two targets (T1 and T2) successively, the accuracy of T2 identification is impaired when the interval between the two targets is less than approximately 500 msec; this is called the *attentional blink* (AB; Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992). One widely accepted explanation for the AB postulates that the first target temporarily occupies limited attentional resources that are essential for visual perception (Chun & Potter, 1995; Shapiro, Raymond, & Arnell, 1994; Ward, Duncan, & Shapiro, 1996; but see also Di Lollo, Kawahara, Ghorashi, & Enns, 2005). Similarities between the experimental procedures that elicit the AB and the MOD suggest the hypothesis that some form of AB contributes to MOD (see Tsubomi & Osaka, 2003). Indeed, some studies have reported MOD-like order deficits when participants are asked to report the

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relative order of a letter sequence presented as T2 (Raymond et al., 1992; Reeves & Sperling, 1986). Tsubomi and Osaka examined the effects of attention to T1 on accuracy of recall for the relative order of a four-letter sequence presented as T2. When their participants ignored T1, the relative order accuracy for T2 was high (over 80%). However, when they were asked to attend to (and report) T1, their accuracy for recalling the relative order of a four-letter sequence presented as T2 was significantly impaired, with an approximately 500-msec T1–T2 lag.

In contrast to the explanation that some form of AB results in MOD, Holcombe et al. (2001) pointed out that the time course of MOD was significantly different from AB. Namely, the exposure duration of each item in the constant phase was too long to induce either AB for identity or AB for relative order (Raymond et al., 1992). If AB occurred, processing of the first letter should interfere with perception of the successive letters, yielding lower identification accuracy. However, they demonstrated that there was no serial position effect of letter identity accuracy in the single-presentation condition (i.e., in the constant phase) of the MOD paradigm (all accuracy scores were over 96%).

Although AB does not seem to occur in the constant phase of the MOD paradigm, it remains possible that AB occurred in the deceleration phase and that this affected the perception of the letter sequence in the constant phase. For example, when the letter sequence BFGH is presented in a cycling manner, assume that participants attempt to identify one of the letters (e.g., F) as the first sequential letter in the deceleration phase. This identification task (i.e., T1) may impair the processing of the next letter (e.g., G) because the exposure duration in the deceleration phase is short enough to induce AB. In this case, participants could have an incorrect representation of order in the deceleration phase, such as saying that F was followed by H. Even if a target letter sequence is presented repeatedly in the constant phase, it is plausible that the incorrect representation of order generated in the deceleration phase interferes with that generated in the constant phase in memory. We refer to this explanation as the *interference hypothesis*. The critical difference between the interference hypothesis and the temporal resolution hypothesis is that the former assumes memory processes as the cause of MOD, whereas the latter assumes only perceptual/attentional processes. These two hypotheses also differ in their accounts of the role of the deceleration phase. The interference hypothesis assumes that the deceleration phase induces incorrectly represented order information, which interferes with subsequent order perception. The temporal resolution hypothesis assumes that the deceleration phase makes it difficult for participants to identify an initial letter in the stream, because the presentation rate decreases gradually such that the sequence seems to fade in without having a differentiated initial letter.

In this study, we examined the interference hypothesis of MOD. In Experiment 1, we replicated the results of Holcombe et al. (2001), using Japanese Hiragana characters. In Experiment 2, we embedded a distractor sequence (e.g., “\$&#@”) into the midstream of the cycling condition. In one typical set of conditions in Experiment 2,

the first, second, and fifth sets of the stream consisted of four-letter sequences, whereas the third and fourth sequences consisted of distractors. The temporal resolution hypothesis predicts that no MOD should be observed in this condition, because the contrast between the 16th item (i.e., the last item of the distractors) and the 17th item (i.e., the first item of the last letter sequence) would allow exogenous segmentation similar to the single-presentation condition. On the other hand, the interference hypothesis predicts the occurrence of MOD, because the incorrect order of the letter sequence could be represented in memory in the deceleration phase (i.e., the first and second sets of the stream), similar to the standard cycling condition. In Experiment 3, we directly tested the interference between the incorrectly represented order in memory and the current order in perception. The deceleration phase was eliminated: All of the items were presented for the long exposure duration (160 msec), and items in the second set (the 5th–8th items in the stream) were always distractors (distractor phase). We manipulated the compatibility of the relative order of the first sequence with that of the sequences presented after the distractor phase. Participants were asked to report the relative order of the sequence presented after the distractor phase. If the previously represented order interfered with the current order perception, as assumed in the interference hypothesis, a MOD-like effect should be observed in the incompatible condition.

EXPERIMENT 1

This experiment attempted to replicate the findings of Holcombe et al. (2001), using Japanese Hiragana characters as stimuli. Each participant performed the cycling and the single-presentation conditions with various final exposure durations. If MOD occurred as reported in Holcombe et al., the accuracy of relative order recognition should be lower in the cycling condition than in the single-presentation condition, whereas the accuracy of letter identification would be higher in the cycling condition.

Method

Participants. Nine undergraduate students at the University of Tsukuba participated in the experiment. All of the participants were naive to the purpose of the experiment and had normal or corrected-to-normal vision.

Apparatus. Stimuli were controlled by an AV tachistoscope (Iwatsu ISEL, IS-703) connected to an IBM-compatible PC. Images were displayed on a 22-in. color monitor (Mitsubishi Diamondtron Flat RDF22PII). The participants sat in a dark room; their heads were fixed in headrests, and they each had one hand placed on a response box (Iwatsu ISEL, IS-7211). The distance between the headrest and the computer monitor was approximately 114 cm.

Stimuli. Four-letter sequences were generated by random selection of Japanese Hiragana letters, excluding “を (wo)” and “ん (nn),” with the constraints that the letters could only be presented once in a sequence and that the combination of letters did not make sense. The distractors were randomly chosen from 15 symbols (e.g., “#,” “&,” “@,” “¥”). A mask stimulus (“*”) was presented at the end of the stream to equalize perceptual saliency between the last and any other items. The Japanese hiragana letters, distractors, mask, and fixation cross subtended 1.5° of visual angle and were presented in black (0.07 cd/m²) at the center of a gray background (39.5 cd/m²).

Procedure. Each trial began with the appearance of a fixation cross for 500 msec. A 20-item stream was presented without an interstimulus interval (ISI). The mask stimulus appeared for 500 msec, immediately after the final item in the stream. The presentation duration of the 1st item was 40 msec; this duration increased by a constant amount for each subsequent item until the 8th item (deceleration phase). The rates of deceleration (approximately 12.5, 17.5, 22.5, and 27.5 msec/item) differed between trials because we used four conditions for the final duration (140, 180, 220, and 260 msec, respectively).

As in Holcombe et al. (2001), we used two presentation conditions. In the cycling conditions, a four-letter sequence was presented five times. In the single-presentation conditions, the four-letter sequence was embedded once within a stream of distractors beginning at the 9th, 13th, or 17th position of the 20-item stream. Thus, the four-letter sequence was never presented during the deceleration phase.

The participants were asked to fixate their eyes on the stimulus in the stream and to orally report the letters in order, beginning at any of the four letters. An experimenter sitting near the participants manually recorded their reports. The participants initiated the next trial by pressing a key on the response box.

We used a 2 (presentation) $\times$ 4 (final duration) within-subjects design in this experiment. Each condition involved 12 trials. We also added 3 catch trials, in which the four-letter sequence was presented twice during the deceleration phase in the stream of distractors. This was done to encourage participants to pay attention to items in that phase, because our pilot study showed that participants who voluntarily tried to ignore items presented during the deceleration phase could report relative order with extremely high accuracy. Thus, each participant passed through one block of 99 trials. Before the experimental trials began, all of the participants underwent 15 training trials that included at least 1 trial of each presentation condition and 3 catch trials.

Results and Discussion

All of the participants' responses were scored for accuracy of letter identity and relative order. As an example of the scoring, if a participant reported "yu" (ゆ), "ne" (ね), "ka" (か), "sa" (さ) in response to a presented letter sequence of さ ("sa"), き ("ki"), ゆ ("yu"), ね ("ne"), the participant was given a score of 3 (of 4; 75%) for correct letter identity (i.e., "yu," "ne," "sa") and 2 (of 4; 50%) for relative order (i.e., "yu" + "ne").

Table 1 gives the mean percentages of correct determinations for letter identity and relative order in this experiment. The participants reported letter identities with more than 85% accuracy, even when the shortest final duration was used. Analysis of the accuracy of letter identification by a two-way ANOVA (presentation $\times$ final duration) revealed significant main effects of both presentation [$F(1,8) = 6.09, p < .05$] and final duration [$F(3,24) = 15.44, p < .01$]. There was also a significant interaction between the two factors [$F(3,24) = 4.34, p < .05$]. The simple main effect of presentation was significant

Figure 1. The mean accuracy ratio of relative order to letter identity as a function of presentation type and final duration in Experiment 1. The error bars represent the standard error of the mean.

when using final durations of 140 msec [$F(1,8) = 9.09, p < .05$] and 180 msec [$F(1,8) = 12.45, p < .01$]. These results suggest that multiple presentations facilitated apprehension of letter identity within the stream.

In contrast, multiple presentations impaired the apprehension of relative order. A two-way ANOVA examining the accuracy of relative order showed significant main effects of presentation [$F(1,8) = 14.62, p < .01$] and final duration [$F(3,24) = 49.07, p < .01$] and a significant interaction between the two factors [$F(3,24) = 3.63, p < .05$]. The simple main effect of presentation was significant at final durations of 140 msec [$F(1,8) = 27.58, p < .01$] and 180 msec [$F(1,8) = 10.25, p < .05$], but was only marginally significant at 220 msec [$F(1,8) = 3.82, p < .10$] and 260 msec [$F(1,8) = 3.81, p < .10$]. These results suggest that multiple presentations impaired the apprehension of relative order of the four-letter sequences.

To dissociate the determination of the accuracy of relative order from letter identity, we evaluated the ratio of accuracy of relative order to accuracy of letter identity as a function of presentation and final duration (Figure 1). Analysis of the accuracy ratio by a two-way ANOVA (presentation $\times$ final duration) revealed significant main effects of presentation [$F(1,8) = 47.21, p < .01$] and final duration [$F(3,24) = 43.62, p < .01$] and a significant interaction between these

Table 1
Mean Percent Correct in Experiment 1 As a Function of Presentation Type and Final Duration

		Final Duration (in Milliseconds)							
		140		180		220		260	
		<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
Letter identity	Cycling	93.36	1.16	95.29	1.28	96.99	1.13	98.84	1.42
	Single	86.42	2.07	89.12	2.35	93.86	2.50	96.99	1.13
Relative order	Cycling	57.25	2.26	70.68	3.97	85.26	2.15	87.27	3.18
	Single	72.45	2.36	81.60	3.11	90.21	3.71	94.91	1.77

factors [$F(3,24) = 8.31, p < .01$]. The simple main effect of presentation was significant at all final durations (F values of 68.08, 24.73, 34.63, and 7.01 at 140, 180, 220, and 260 msec, respectively) with p values smaller than .01, with the exception of the 260-msec condition ($p < .05$).

The results in this experiment are consistent with the findings of Holcombe et al. (2001). MOD could be observed in all final duration conditions, although the effect decreased with increasing final exposure duration. In Experiment 2, we tested the temporal resolution hypothesis, using the same stimuli and a duration of 180 msec.

EXPERIMENT 2

As we discussed in the introduction, one hypothesis is that MOD results from the lower temporal resolution of endogenous segmentation. In the cycling condition, participants have to make an endogenous segmentation to pick an initial letter of a sequence. In contrast, an initial letter can be automatically identified by the perceptual or categorical discontinuity between the distractors and the letter sequences in the single-presentation condition. This difference between conditions is hypothesized to result in MOD (Holcombe et al., 2001). On the basis of this temporal resolution hypothesis, the accuracy of relative order would significantly improve if an initial letter can be automatically identified in the constant phase. In contrast, the interference hypothesis predicts that MOD occurs irrespective of exogenous segmentation induced by stimuli.

Experiments 2A and 2B investigated whether MOD occurs when the discontinuity of items was embedded in the stream of stimuli. A single set of distractors (4 items) was embedded into the stream of the cycling condition in Experiment 2A, whereas two or three sets of distractors (8 or 12 items) were embedded into the stream of the cycling condition in Experiment 2B.

Experiment 2A

Method

Participants. Nine students at the University of Tsukuba participated in the experiment; none had participated in Experiment 1. All of the participants were naive to the purpose of the experiment and had normal or corrected-to-normal vision.

Apparatus, Stimuli, and Procedure. The apparatus, stimuli, and procedures were the same as in Experiment 1, with the following changes. The final duration remained constant at 180 msec/item. We added five new presentation conditions, which were similar to the cycling condition, except that one of the four-letter sequences was replaced with a sequence of four distractors (see Figure 2). For example, in the 2-3-4-5 set condition, the first set of the four-letter sequences in the stream was replaced with a distractor sequence. The same rules applied for the 1-3-4-5, 1-2-4-5, 1-2-3-5, and 1-2-3-4 set conditions, resulting in seven presentation conditions used in this experiment. Each participant passed through one block of 88 trials (12 trials of each condition plus 4 catch trials). Before beginning the experimental trials, all of the participants underwent 16 training trials, including at least 1 trial for each presentation condition.

Results and Discussion

The results of Experiment 2A are discussed with the results of Experiment 2B.

Experiment 2B

Method

Participants. Nine students at the University of Tsukuba participated in this experiment; none had participated in Experiment 1 or Experiment 2A. All of the participants were naive to the purpose of the experiment and had normal or corrected-to-normal vision.

Apparatus and Stimuli. The apparatus and stimuli were the same as in Experiment 2A.

Procedure. The procedures utilized were similar to those used in the cycling condition of Experiment 1, with the exception that two or three four-letter sequences were replaced by four-distractor sequences (see Figure 2). For example, in the 3-4-5 set condition, the first and second set, items presented in the first to the eighth positions of the stream, were replaced with a distractor sequence.

		Deceleration Phase		Constant Phase			Mask	Condition Name
		Fix	1st Set	2nd Set	3rd Set	4th Set	5th Set	
Both	+		B F G H	B F G H	B F G H	B F G H	B F G H	* Cycling
	+		%◇☆◎	∞&π.∴	B F G H	¥○※#	△@ \$□	* Single
Exp. 2A	+		%◇☆◎	B F G H	B F G H	B F G H	B F G H	* 2-3-4-5
	+		B F G H	∞&π.∴	B F G H	B F G H	B F G H	* 1-3-4-5
	+		B F G H	B F G H	¥○※#	B F G H	B F G H	* 1-2-4-5
	+		B F G H	B F G H	B F G H	△@ \$□	B F G H	* 1-2-3-5
	+		B F G H	B F G H	B F G H	B F G H	%◇☆◎	* 1-2-3-4
Exp. 2B	+		%◇☆◎	∞&π.∴	B F G H	B F G H	B F G H	* 3-4-5
	+		B F G H	B F G H	∞&π.∴	¥○※#	B F G H	* 1-2-5
	+		B F G H	B F G H	∞&π.∴	B F G H	¥○※#	* 1-2-4
	+		B F G H	B F G H	B F G H	¥○※#	△@ \$□	* 1-2-3
	+		B F G H	B F G H	∞&π.∴	¥○※#	△@ \$□	* 1-2
	+		%◇☆◎	∞&π.∴	¥○※#	△@ \$□		

Figure 2. Schematic diagrams of the stimuli for each condition in Experiments 2A and 2B. Japanese hiragana letters were used in place of the English alphabet.

Table 2
Mean Percent Correct in Experiment 2A as a Function of Presentation Type

	Presentation Condition													
	2-3-4-5		1-3-4-5		1-2-4-5		1-2-3-5		1-2-3-4		Cycling		Single	
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
Letter identity	97.92	0.69	96.30	1.02	90.97	0.69	95.37	0.90	91.44	1.40	94.28	1.66	88.43	2.33
Relative order	77.78	2.71	74.54	2.21	68.98	3.51	69.44	2.05	60.88	4.07	61.74	2.76	73.84	3.38

Similar rules applied for the 1-2-5, 1-2-4, 1-2-3, and 1-2 set conditions.

Results and Discussion

Table 2 and Table 3 show the mean percentages of correct determinations of letter identity and relative order, respectively. Figure 3 and Figure 4 indicate the accuracy ratios of relative order to letter identity in Experiments 2A and 2B, respectively. The participants reported letter identities with an accuracy of over 80%, even for the 1-2 set condition, in which the four-letter sequence was only presented during the deceleration phase.

We used a one-way ANOVA (presentation) to analyze the accuracy ratio of relative order to letter identity in Experiments 2A and 2B. In Experiment 2A, there was a significant main effect of the presentation condition on the accuracy ratio [$F(6,48) = 7.47, p < .01$]. Post hoc least significant difference (LSD) comparisons showed that the accuracy ratio of relative order to letter identity in the single-presentation condition was higher than in any other condition, with the exception of the 2-3-4-5 set and 1-3-4-5 set conditions ($MS_e = 0.0052, p < .05$). In Experiment 2B, we also observed a significant main effect of presentation on the accuracy ratio [$F(6,48) = 27.89, p < .01$]. Post hoc LSD comparisons showed that this ratio in the single-presentation condition was higher than in any other condition, with the exception of the 3-4-5 set condition ($MS_e = 0.0048, p < .05$). Thus, MOD was seen in all presentation conditions in Experiments 2A and 2B, with the exception of the 1-3-4-5 and 2-3-4-5 set conditions in Experiment 2A and the 3-4-5 set condition in Experiment 2B.

In this experiment, the discontinuity between the end of the distractor set and the start of the letter set was the same in the distractor-embedded conditions and the single-presentation condition. We therefore consider that the same exogenous segmentation occurred in these conditions. MOD, however, was obtained in these conditions as much as in the cycling conditions. The accuracy ratio of relative order to letter identity was .66 for the cycling condition and .68 for the 1-2-5 set condition, which had the fifth set of four-letter sequences

preceded by eight distractors. These results are clearly inconsistent with the temporal resolution hypothesis.

However, the interference hypothesis can explain the results in this experiment. The interference hypothesis assumes that an incorrectly represented order in memory from the deceleration phase would interfere with the perception of order in the constant phase. Therefore, MOD would be affected by the experience of the letter sequence in the deceleration phase, but not the stimulus discontinuity. This account explains not only the small effect of stimulus discontinuity on MOD in the distractor-embedded conditions (e.g., the 1-2-5 set condition), but also the lack (or small effect) of MOD in the 1-3-4-5 and 2-3-4-5 set conditions in Experiment 2A and the 3-4-5 set condition in Experiment 2B. In these conditions, the experience of the letter sequence in the deceleration phase was less than in the other conditions, which may have decreased the effect of MOD. The results for the 1-2 set condition partially support the possibility that the experience of the letter sequence in the deceleration phase induced incorrectly represented order in memory. The accuracy of relative order in that condition (49%) was equivalent to the chance level (50%), whereas there was over 80% accurate letter identification. This indicates that although the participants could identify most of the four letters in a sequence during the deceleration phase, the relative order was not correctly represented.

It is important to note that we are not arguing for the absence of perceptual or categorical discontinuity effects on MOD. Indeed, the accuracy ratio of the relative order to letter identity in the 1-2-4 condition, which had two discontinuities between distractor set and letter set in the constant phase (i.e., before and after the fourth letter set), appeared to be higher than that seen in the 1-2-5 and 1-2-3 conditions, which had only one discontinuity (i.e., before the fifth letter set or after the third letter set). Individual *t* tests revealed that the accuracy ratio of relative order to letter identity in the 1-2-4 condition was significantly or marginally higher than in the 1-2-5 condition [$t(8) = 2.67, p < .01$, one-tailed] or in the 1-2-3 condition [$t(8) = 1.58, p < .10$, one-tailed].

Table 3
Mean Percent Correct in Experiment 2B as a Function of Presentation Type

	Presentation Condition													
	3-4-5		1-2-5		1-2-4		1-2-3		1-2		Cycling		Single	
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
Letter identity	97.45	1.33	90.74	2.53	89.58	2.11	87.96	2.66	80.32	3.91	94.91	1.63	89.81	3.21
Relative order	91.20	3.34	62.73	4.65	66.90	3.85	60.19	3.01	49.77	2.67	62.73	2.67	81.48	4.05

Figure 3. The mean accuracy ratio of relative order to letter identity as a function of presentation type in Experiment 2A. The error bars represent the standard error of the mean.

However, this effect is too small to explain all of the results of this experiment.

EXPERIMENT 3

The interference hypothesis is based on the assumption that the previously represented order would interfere with the perception of order in the subsequent stream. In this view, the deceleration phase is not necessary, because it is previously represented order that would distort the perception of order presented subsequently. In this experiment, we used an experimental procedure similar to that used in the previous two experiments, with two modifications. First, we eliminated the deceleration phase; all items were presented for the long exposure duration (160 msec). Since this duration is too long to induce AB (cf. Raymond et al., 1992), it was predicted that participants could correctly apprehend the identities and relative order of a four-letter sequence from the beginning of the stream. Second, we presented two sequences in a single stream, and manipulated the compatibility of relative order between these sequences. If the previously represented order interfered with the perception of order in the subsequent stream, we predicted that the accuracy of recognizing the relative order in the latter sequence would decrease in the incompatible condition in comparison with the compatible condition.

Method

Participants. A total of 15 students at the University of Tsukuba participated in the experiment; none had participated in the previous experiments. All of the participants were naive to the purpose of the experiment and had normal or corrected-to-normal vision.

Apparatus, Stimuli, and Procedure. The apparatus, stimuli, and procedures used were the same as in Experiment 1, with the exception of the following changes. The presentation rate remained constant at 160 msec/item. The second set in each stream, consisting of the items presented in the fifth to eighth positions of the stream, always consisted of distractors (distractor phase). The other sets con-

sisted of four-letter sequences, except for the single-presentation conditions outlined below. The participants were asked to report the relative order of the sequence presented after the distractor phase. We used three compatibility conditions in this experiment: compatible, order incompatible, and letter incompatible. In the compatible condition, the sequence of the first set was the same as that presented after the distractor phase. This condition was similar to that used in the 1-3-4-5 condition of Experiment 2A. In the order-incompatible condition, letter identities between the first set and the sets presented after the distractor phase were the same, but the relative order was not. In the letter-incompatible condition, the letter identities (thus the relative order) were different between the first set and the sets presented after the distractor phase. We also evaluated two single-presentation conditions. The single-presentation after-distractor-phase condition was the same as that described in the previous experiments. The second was a single-presentation before-distractor-phase condition, in which the four-letter sequence was always presented in the first set. This encouraged the participants to pay attention to the first set in the sequence. Thus, a total of five presentation conditions were used in this experiment. Each participant was subjected to one block of 75 trials (15 trials for each condition). Before beginning the experimental trials, all of the participants underwent 10 training trials, including 2 for each presentation condition. The participants were explicitly told that there was a condition in which the relative order of the first set was incompatible with that of the set to be reported, and that they should disregard the order information of the first set to cope with this task, unless the trial was a single-presentation condition.

Results and Discussion

Table 4 presents the mean percentages of correct determination of letter identity and relative order. Figure 5 shows the accuracy ratio of relative order to letter identity. As we predicted above, the relative order accuracy for the single-presentation condition was not significantly different from the single-after presentation condition. This indicates that the participants could recognize relative order accurately from the beginning of the stream in this experiment.

We used a one-way ANOVA (presentation) to analyze the accuracy ratio of relative order to letter identity in

Figure 4. The mean accuracy ratio of relative order to letter identity as a function of presentation type in Experiment 2B. The error bars represent the standard error of the mean.

Table 4
Mean Percent Correct in Experiment 3 As a Function of Presentation Type

	Presentation Condition									
	Compatible		Order Incompatible		Letter Incompatible		Single Before Distractor		Single After Distractor	
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
Letter identity	96.33	1.01	92.89	1.27	91.56	1.62	87.56	1.98	90.11	2.19
Relative order	84.67	3.39	53.67	4.74	66.00	2.39	76.44	3.83	75.44	3.76

Experiment 3. We found a significant main effect of presentation [$F(4,56) = 31.90, p < .01$]. Post hoc LSD comparisons showed that the accuracy ratio of relative order to letter identity in the order-incompatible condition was lower than in any of the other conditions; the accuracy ratio in the letter-incompatible condition was lower than in any other conditions with the exception of the order-incompatible condition ($MS_e = 0.0065, p < .05$). These results suggest that the previous perception of relative order information proactively interfered with the apprehension of subsequent relative order information.

However, other explanations may account for these findings. The participants had to switch the target from the relative order of the first set to the sequence after the distractor phase only in the incompatible conditions—both the order-incompatible and letter-incompatible conditions. This switch cost (for a review, see Johnson & Proctor, 2004) may have impaired relative order accuracy in these conditions. It is also possible that the number of items that were possible targets exceeded the capacity of working memory (cf. Cowan, 2001) in only the incompatible conditions. Thus, the perception of items presented after the distractor phase may be biased. Alternatively, participants might simply report the relative order of the first set.

None of these potential explanations, however, appear to be consistent with the findings of the experiment. Since the participants were told of the conditions in which the relative order was incompatible between the first and other sets, the participants were encouraged to disregard the relative order information of the first set if they saw letters after the distractor phase, regardless of the compatibility condition. Thus, the switch cost was equivalent in the two incompatible conditions. Even if memory load was the most important limitation, the relative order accuracy in the order-incompatible condition should have been higher than that in the letter-incompatible condition, because the number of letter identifications in the order-incompatible condition was equivalent to that in the compatible condition. Moreover, errors in reporting any letters in the first set were only 1.79% in the letter-incompatible condition. This indicates not only that the participants did not have a tendency to report the identities or the relative order of the first set in this experiment, but also that the perception of relative order is more sensitive to previously represented information than is letter identity.

Therefore, the results in this experiment provide converging evidence for the interference hypothesis. The previously presented relative order information proactively interfered with the perception of subsequent relative order information.

GENERAL DISCUSSION

In this study, we conducted three experiments to examine the cause of MOD. Experiment 1 replicated the findings of Holcombe et al. (2001), using Japanese Hiragana characters as stimuli. Experiment 2 demonstrated that MOD could occur irrespective of the discontinuity of the stimulus stream, contrary to the prediction from the temporal resolution hypothesis. The findings in Experiment 2 supported the findings that MOD did not decrease even when a perceptual or categorical discontinuity between the four-letter sequences was salient. Tsubomi and Osaka (2003) manipulated the perceptual or categorical saliency of the first letter of a four-letter sequence by coloring the first letter red while the other letters were black or by replacing the first letter with a digit. Contrary to the prediction of the temporal resolution hypothesis, the degree of MOD in both conditions was not significantly different from that seen in the standard cycling condition. Experiment 3 demonstrated that previously perceived order information proactively interferes with perception of subsequent order information, even when the participants were aware that previously perceived order information could impair the perception of the relative order of the sequence to be reported. These results support the interference hypothesis, which assumes interference between the incor-

Figure 5. The mean accuracy ratio of relative order to letter identity as a function of presentation type in Experiment 3. The error bars represent the standard error of the mean.

rectly represented order in the deceleration phase and the perception of order in the constant phase.

On the basis of these findings, we conclude that at least some part of MOD was caused by memory-based interference. Although we did not directly examine whether the relative order deficit occurred in the deceleration phase in this study, several studies have reported that an order deficit could be observed in an AB paradigm using a short exposure duration (Raymond et al., 1992; Reeves & Sperling, 1986). It should be mentioned that AB is not the only candidate for inducing incorrectly represented order information during the deceleration phase. When a letter sequence of BFGH is presented in a cycling manner and one of the four letters (e.g., F) is missed by participants because of the too rapid presentation rate in that phase, they may misunderstand the relative order of the sequence (e.g., B was followed by G). Such incorrectly represented order in memory could induce misperception of the relative order in the constant phase. However, what we assert in the interference hypothesis is not the cause of misunderstanding the relative order during the deceleration phase, but the reason why participants could not correctly perceive the relative order of a sequence for a while. Note that the interference hypothesis and the temporal resolution hypothesis are not mutually exclusive. It is possible that there is both a perception-based MOD and a memory-based MOD that occur simultaneously in the standard MOD paradigm, and a memory-based MOD was mainly seen in Experiment 2 of this study.

Recently, Chiba and Yokosawa (2003) argued that MOD occurs only when relative order is phonologically encoded in working memory. They repeatedly presented to their participants a four-letter sequence with Japanese Kanji letters, demonstrating that MOD was eliminated when all of the Kanji letters had the same pronunciation. They argued that participants did not encode relative order phonologically in this situation, which decreased MOD. In light of these findings, we speculate that proactive interference of relative order is due to the limited capacity of working memory and the low accessibility of relative order representation. Additional evidence indicates that the capacity of working memory is approximately four, not seven, chunks (Cowan, 2001; Luck & Vogel, 1997). Therefore, if the relative order of the four-letter sequence was different before and after the deceleration phase, the participants could only retain one of these sequences. In addition to the inability of participants to retain more than four items, multiple presentations might also facilitate proactive interference. Given that the mental representation of order information is unidimensional (i.e., the magnitude of activation for each item; Farrell & Lewandowsky, 2002; Page & Norris, 1998), multiple presentations decrease the distinctiveness among activation levels of the four letters. If the initial activation levels of the four letters were distorted by an AB-like deficit at the beginning of the stream, the distinctiveness of activation levels would be confused.

This study has identified the conditions necessary for MOD, as well as shed light on the properties of the representation of relative order. Perception of relative order appears to be strikingly affected by previously perceived

order information. More studies are necessary to test recent models of memory for serial order (for a review, see Neath & Surprenant, 2003), using MOD as a method.

AUTHOR NOTE

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