

Visual Marking: Selective Attention to Asynchronous Temporal Groups

Yuhong Jiang^{1,2}

Marvin M. Chun³

Lawrence E. Marks^{1,2}

1. Yale University
2. The John B. Pierce Laboratory
3. Vanderbilt University

Send correspondence to:

Yuhong Jiang

Department of Brain and Cognitive Sciences

77 Massachusetts Avenue

MIT, Building NE20 Room 443

Cambridge, MA 02139

E-mail: yuhong@MIT.EDU

Phone: (617)-258-0670

Fax: (617)-258-8654 (note "NE20-443" on fax)

Abstract

In visual search tasks, when a subset of distractors is previewed 1 s before the target and the remaining (new) distractors, search speed is independent of the number of previewed items. The process of ignoring old visual items is called visual marking (D. G. Watson & G. W. Humphreys, 1997). This study explores the mechanism that allows the old items to be marked. Four experiments show that marking is disrupted if the onset of the new items is accompanied by changes to the old items, but is not disrupted by changes restricted to the background nor by changes to the old items that are not synchronized with the onset of the new items. Further, old items can be prioritized over new items when they are behaviorally relevant. Visual marking is based on temporal asynchrony between new and old items, allowing segregation of these items into two temporal groups, with attention then selectively applied to one group.

Human visual attention is limited (Chun & Wolfe, 2001; Pashler, 1998). Because we cannot efficiently attend to multiple objects and locations simultaneously (Duncan, 1980; Treisman & Gelade, 1980; Kahneman, 1973; Wolfe, 1994) or to rapidly succeeding information (Broadbent & Broadbent, 1987; Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992), only a subset of visual information can be selected, processed, and responded to.

As an intelligent system, the visual system has developed strategies to circumvent such limits in attention. One important strategy is to allocate attention selectively to a subset of perceptually segregated items. For example, attention can be effectively directed to a group of items defined by color (Egeth, Virzi, & Garbart, 1984; Kaptein, Theeuwes, & van der Heijden, 1995), depth (Nakayama & Silverman, 1986), common fate (Driver & Baylis, 1989), or orientation (Friedman-Hill & Wolfe, 1995). Other strategies include attentional capture by abrupt onset (Yantis & Jonides, 1984), location-based top-down attention (Paquet & Lortie, 1990), attentional guidance by familiar context (Chun & Jiang, 1998), and visual marking of old items (Watson & Humphreys, 1997).

In this study, we provide evidence suggesting that perceptual segregation through asynchronous grouping can be central to visual marking. This proposal contrasts with an existing account for visual marking (Watson & Humphreys, 1997) in some aspects but complements and extends that account in others. In the remaining introduction, we will first briefly review visual marking, and then explain how it may reflect selective attention by temporal segregation.

A brief review of visual marking

The paradigm of visual marking was introduced by Watson and Humphreys (1997) to study how attention is selectively deployed to new objects (Gibson & Jiang, 2001; Kahneman, Treisman, & Burkell, 1983; Olivers, Watson, & Humphreys, 1999; Theeuwes, Kramer, & Atchley, 1998; Watson & Humphreys, 1997, 1998, 2000). In studies of visual marking, a subset of distractors

appears at least 400 ms before other search items. As a set of new items is added to the display, the old items remain in their locations and maintain all their visual properties. The target appears among the new items. The previewed, old distractors can be readily ignored or “marked,” having limited impact on target search. As reviewed elsewhere (Jiang, 2000; Watson & Humphreys, 1997), the benefit of preview cannot be explained by attentional capture of new items (Yantis & Hillstrom, 1994; Yantis & Jonides, 1984), Inhibition of Return (IOR) of the previewed locations (Klein, 1988; Klein & MacInnes, 1999; Posner & Cohen, 1984), or feature-based inhibition (Treisman & Sato, 1990) and feature-based negative priming (Tipper, 1985).

Watson and Humphreys (1997) suggested that the mechanism underlying visual marking in static displays is inhibition of previewed locations^[1]. The old items are “marked” by temporary templates set up by the goal state and inhibition is applied to these marked items. This special inhibition mechanism is sufficient to allow the new items to be prioritized against the old ones. Supporting this proposal, detection of a dim probe-dot was impaired when it fell at the location of an old item, compared with the location of a new item (Watson & Humphreys, 2000). Detection of a probe at the location of an old item was not delayed, however, if participants were released from the search task and performed the probe task only. Such inhibition requires attention, hence the efficiency of visual marking relies on central processing resources. When a secondary task is introduced, the resources allocated to inhibition of old distractors are reduced, and so is marking. Watson and Humphreys proposed that the mechanism involved in marking is specific for prioritizing new objects and filtering out old ones. They also noted that the inhibition mechanism is somewhat flexible, so that it is reset when something new occurs at the location of the old items or when there is no advantage of inhibiting them. These authors contend that by prioritizing new objects, visual marking is of considerable importance for survival.

The basis of visual marking

In Watson and Humphreys's (1997) account, inhibition of old items itself underlies visual marking. The origin of such inhibition comes from voluntary resource allocation of the participants. Although this account can explain most of the extant data on visual marking, for the following reasons we believe it is incomplete.

The inhibition account seems underspecified. The critical question left open by this account is how visual marking may be disrupted. Data from Watson and Humphreys (1997) showed that when the old items changed in luminance at the moment the new items were added, visual marking was abolished. To incorporate such data, the inhibition account added an important caveat that "inhibition through visual marking can be removed or overridden by bottom-up factors such as rapid luminance changes" (p. 107). The inhibition account also postulates that the mechanism of visual marking is flexible: "A dynamic change at the location of an inhibited distractor would then reset or remove the template that marked that particular location." (p. 117). Further, inhibition is adaptive to the goal of the participants (Watson & Humphreys, 2000).

Although it is reasonable to posit that the inhibition process is sensitive to task demands, such top-down influences can be difficult to define and predict a priori. Consider the basic question of when visual marking occurs. What kind of perceptual events disrupt marking? Can the marking system ignore irrelevant changes in old items? Does the change have to occur at the location of the old items? When, in relation to the onset of new items, must a change occur for it to be disruptive? The inhibition account does not readily answer these questions because its flexibility permits an explanation for any possible outcome.

We argue that if the driving principle of visual marking is to prioritize new objects and deprioritize old objects, then irrelevant changes should be ignored. For example, a flag that changes

shape as it flutters in the wind is still the same old flag. A bush that is darkened by a cloud passing under the sun is still the same old bush. A mechanism that prioritizes new objects cannot be overly sensitive to surface features. Yet the inhibition account attempts to incorporate both ideas. It suggests that marking is disabled as irrelevant changes occur to old objects because it is adaptive to detect any change. However, as just noted, many kinds of change do not signal the presence of a new object. Further, the sensitivity to irrelevant changes contradicts other common visual operations, where object-oriented processing is typically token-driven and insensitive to feature changes. For example, apparent motion allows two or more tokens to be linked into one single perceptual object; apparent motion is perceived even when the tokens differ in color, shape, or size (Kolers & Pomerantz, 1972). Visual short-term memory of spatial locations is unaffected by the color or shape of placeholders (Jiang, Olson, & Chun, 2000). More generally, in the object file construct of Kahneman, Treisman, and Gibbs (1992), a new object is defined by its spatio-temporal characteristics and not by surface features. Change in color, luminance or shape is insufficient to upgrade the status of an old object into a new object, and thus should be efficiently ignored (see Watson & Humphreys, in press, for a related discussion) ^[2].

The fact that visual marking is abolished by a change in the shape or luminance of the old items indicates the limitations of an account that relies on a flexible inhibition mechanism alone (Watson & Humphreys, 1997). The sensitivity of visual marking to surface changes suggests that visual marking, instead of being a flexible mechanism that prioritizes new objects, appears to be enslaved to the nature of bottom-up perceptual changes and temporal transients.

Temporal Segregation Hypothesis

We therefore propose an alternative hypothesis with a stronger perceptual basis. This account divides visual marking into a two-step process. Visual marking first involves a temporal segregation

process that separates new and old items based on their transient temporal differences. Following segregation, attention is selectively deployed to the group that contains the target - typically, the new items.

This account is plausible given the importance of perceptual grouping processes in vision (Kanizsa, 1979). Attention can be efficiently allocated to a group of items over another group (Humphreys & Müeller, 1993; Grossberg, Mingolla, & Ross, 1994). For example, Egeth et al. (1984) asked participants to search for a red Q among black Qs and red Ns. This conjunction search task typically leads to inefficient search (Treisman & Gelade, 1980; Wolfe, 1998). However, Egeth et al. further instructed participants to search only the red items. Results showed that participants were able to restrict their search to the red items, rejecting the black items efficiently. In this example, the black items and the red items formed two perceptual groups, and attention was efficiently restricted to one group based on color grouping cues. Efficient selection is also possible through other grouping cues, such as depth (Nakayama & Silverman, 1986), common fate (Driver & Baylis, 1989), and orientation (Friedman-Hill & Wolfe, 1995). Similarly, visual marking may reflect the allocation of attention based on perceptual grouping, only in this case the perceptual segregation cue is temporal asynchrony.

In temporal grouping, items that change together are perceived as one event (Alais, Blake, & Lee, 1999; Blake & Yang, 1998; Lee & Blake, 1999; Leonards, Singer, & Fahle, 1996; Palmer & Levitin, 1998; Usher & Donnelly, 1998). Two events can be perceived if changes to two groups are out of synchrony. Leonards et al. (1996) found that a difference of 10 ms sufficed to produce segregation, showing that the visual system is highly sensitive to temporal disparity. As the temporal difference between sets of items increases, perceptual segregation can become stronger.

Visual marking, we propose, relies heavily on temporal segregation cues. Marking can occur because the old items are out of synchrony with the new items. So all the old items are perceived as a single event, while the new items are perceived as another. Segregation between new and old sets via temporal grouping allows visual attention to be prioritized to one set over another, consistent with other demonstrations of selective attention by perceptual segregation (Driver & Baylis, 1989; Treisman & Sato, 1990).

This hypothesis predicts that segregation of the two groups is disrupted when the old items change their shape, luminance, or color simultaneously with the onset of the new items. This prediction is supported by existing data (Jiang, Chun, & Marks, submitted; Watson & Humphreys, 1997). When changed simultaneously, the items are no longer perceived as separate events. Rather, through temporal synchrony of the transient changes, they form a single perceptual event. Because attention cannot easily be allocated to a subset of this unitized event, visual marking is eliminated.

Here, we provide further evidence to support the temporal segregation hypothesis. Our experiments test the following predictions. First, according to the temporal segregation hypothesis, any change in the old items that accompanies the onset of the new items will disrupt visual marking. Thus, a change in shape or luminance in the old items will destroy visual marking, even though such changes do not upgrade the status of old items into new ones. The effects of shape change and luminance change will be tested in Experiments 1 and 2, respectively.

Second, according to the temporal segregation hypothesis, a change in the background of the search array that accompanies the onset of the new items will not disrupt visual marking. As long as the old items do not change, a temporal transient on the display background does not destroy the temporal segregation cue. Thus, a dynamic change on the display per se is not sufficient to eliminate preview benefit. This prediction will be tested in Experiment 2.

Third, the temporal segregation hypothesis predicts that visual marking will not be disrupted by a change in the old items that is not synchronized with the onset of the new items. As long as there is a temporal interval between the change of the old items and the onset of the new items, and as long as this interval is long enough for attention to be deployed to one group and not the other (roughly, 200 ms, see Friedman-Hill & Wolfe, 1995), visual marking should persist. This prediction will be tested in Experiment 3. The inhibition hypothesis, in contrast, predicts a disruption of visual marking because changes occur at the locations of the old items. The inhibition hypothesis requires additional assumptions to account for the presence of marking under such asynchronous change conditions.

Fourth, because the temporal segregation hypothesis does not attribute any intrinsic advantage to the new over the old items, it predicts that old items can be prioritized over new items if (1) old items become behaviorally relevant and (2) new and old items can be segregated temporally. Experiment 4 requires participants to search for a target among the old items and to ignore the new items. The temporal segregation hypothesis predicts that temporal asynchrony of new and old items enhances performance. The inhibition hypothesis, in contrast, postulates visual marking as an ecological strategy developed specifically to prioritize new objects. Because prioritizing old objects conflicts with this system, participants should be unable to “mark” the new items.

Together the four experiments will delineate the temporal characteristics of visual marking, and to reveal an important strategy used by the visual system to cope with its limitations in attention. These experiments support the temporal segregation hypothesis and suggest substantial revisions of the inhibition hypothesis (Watson and Humphreys, 1997).

General Method

General Task

Participants searched for a rotated T among L-shaped objects. The target was present on every trial, rotated 90° clockwise or counter-clockwise. Participants were instructed to press one of two keys to report which target was present. Distractors were L-shaped objects presented in four possible orientations.

Each experiment had two basic conditions. In all trials, a certain number of old distractors were previewed for 1000 ms, after which a few new distractors and the target were added. In the valid preview condition, the previewed items maintained their locations as the new items were added. This condition corresponds to the “gap” condition used in previous studies of visual marking. In the invalid preview condition, the previewed items instantly moved at random to previously unoccupied locations. In a pilot study we found that performance in the invalid preview condition did not differ from that in the standard conjunction baseline, so it can provide a good baseline to assess visual marking (Jiang, 2000).

The valid and invalid preview conditions were tested in the same block, randomly intermixed. Before using this mixed design, we were concerned whether a mixed design would reduce or eliminate visual marking. Because the inhibition mechanism proposed by Watson and Humphreys (1997) may be flexible, affected by the goal of participants, intermixing valid and invalid preview trials may discourage participants from using the marking process. To find out, we tested 24 participants, half in a blocked design, the other half in a mixed design. Results showed that visual marking was identical in these two groups of participants, suggesting that a mixed design is not at all detrimental to visual marking (see Jiang, 2000, Experiment 3). The advantage of a mixed design is that it makes valid and invalid preview conditions maximally comparable. Conversely,

presenting these conditions separately opens up the possibility that the search of the unpreviewed items may not be the same in the two conditions because participants adopt different strategies in the different blocks.

Experiment 1 varied the size of new and old sets orthogonally. The new set size was 3 or 9; crossed with three levels of old set size (3, 6, 9). We then measured RT as a function of old set size, holding new set size constant. This reveals how RT depends on the number of previewed old items. The prediction is that the linear function relating RT to old set size should be steeper in the invalid preview than the valid preview condition. Finding that this pattern held up at all levels of new set size allowed us to simplify the design for later experiments by testing only one level of new set size. Experiments 2 and 3 used a fixed number of new items (6), and varied the size of the old set as 3, 6, or 9. Experiment 4 varied the size of new and old sets independently.

In this study, we will use the slope of the function relating RT to old set size (new set size in Experiment 4) as an index of the efficiency of the marking process. "Slope" is a term computed through linear regression; it is used only as a technical term to describe our data. It should not be confused with its associated meaning of "search rate" during visual search, because when marking is efficient, old items are not searched; hence the slope of RT as a function of old set size is not a real reflection of the speed of "search" through distractors. A significant reduction in slope in the valid compared with the invalid condition reveals a "preview benefit," an indicator of visual marking.

Participants

Participants were recruited from the Yale University and Vanderbilt University subject pools. They were 18 to 34 years old. All participants provided signed consent before the test and were fully debriefed afterwards. All had normal or corrected-to-normal visual acuity, and normal color vision.

Materials

Participants searched for a T rotated left or right among L distractors of four orientations presented in a gray background. Each item subtended 0.69 cm x 0.69 cm. The line segments forming the Ls had a 1 pixel offset (0.03 cm) at their junctions. The width of each line segment was 0.09 cm.

The locations of the items were randomly chosen from an invisible 8 x 8 matrix that subtended 20.00 cm x 20.00 cm. Each item was positioned at the center of a cell. A target was present on every trial, rotated 90° to the left or right, with the constraint that an equal number of left and right Ts were presented in each cell of the factorial design. Participants pressed one of two keys to identify the target orientation.

Procedure

In most experiments, each trial started with a blank screen for 1 s, followed by the preview display, which lasted 1000 ms. Then other items were added on the screen to form the search display, which was present until response. Each response was followed immediately by a high or low-pitched tone providing accuracy feedback. Half a second later, the next trial started automatically. Participants were instructed to respond as quickly as possible without sacrificing accuracy. Exceptions to this procedure will be noted.

Equipment

The experiment was conducted on a Macintosh computer (PowerPC) with a 17" monitor. The task was programmed with MacProbe software (Hunt, 1994). Participants were tested individually in a room with normal interior lighting. They sat at an unrestricted distance from the computer screen of about 57cm, at which distance, 1 cm corresponds to 1° visual angle.

General Treatment of the Data

In all the experiments reported here, mean error rate never exceeded 8% in any cell of the factorial design. ANOVAs were performed on the accuracy data in each experiment, revealing no significant main effects or interactions. Analysis of accuracy is therefore not reported any further. Appendix A shows the mean accuracy in each experiment. Incorrect trials were excluded from analyses of RT. For each individual, the median RT was calculated within each cell. The mean of the median RTs from different participants then underwent statistical analysis. Although not reported here, we performed the same analysis on mean RT, with a high cutoff of 4,000 ms. Analyses on mean and median RTs led to similar conclusions.

In addition to RT, we report slope and intercept computed from linearly regressing RT against the number of old items. Mean RTs are plotted in a figure in each experiment. Statistical significance is based mainly on an ANOVA using RT as the dependent measure. Marking efficiency, or slope, is based on the effects of old set size. An interaction between old set size and preview condition indicates a modulation of marking efficiency, revealing a preview benefit.

Experiment 1: Change in Shape of the Old Items

Experiment 1 tested the prediction that if the shapes of the old items change at the moment the new items are added, visual marking will be disrupted. This experiment serves two purposes. First, it tests the prediction of the temporal segregation hypothesis that marking should be impaired when changes in old and new items are synchronized. Second, this experiment tests whether prioritization is truly object-oriented, as postulated by the inhibition hypothesis (Watson and Humphreys, 1997). Studies of object files (Kahneman et al., 1992) and attentional capture (Jonides & Yantis, 1988; Yantis & Jonides, 1984) suggest that spatio-temporal parameters define an old object's continuity and the onset of new objects. In marking tasks, old objects do not undergo spatio-

temporal changes (old items remain old), so their shape changes should be ignored by an object-oriented system postulated by the inhibition hypothesis. However, Watson and Humphreys demonstrated that visual marking was disrupted by luminance change in the old items, suggesting that marking may not survive shape changes. Nevertheless, that finding was presented in a different theoretical context (i.e., attentional capture) than ours (i.e., marking as object-oriented). Thus we think it is necessary to replicate that result.

Three factors were manipulated in this experiment in a within-subject design. The number of old items was 3, 6, or 9; this provides a measure of slope. The number of new items was 3 or 9; this tests whether the preview benefit holds at different sizes of new set. Finally, the preview condition had three levels. In the valid preview condition, old items maintained their locations and shapes throughout presentation. In the invalid preview condition, old items moved to previously blank locations at the onset of the new items. In the shape change condition, old items were crosses (“+”) that maintained their previewed locations but changed instantly to Ls at the onset of the new items.

Method

Six participants were tested in 12 practice and 864 experimental trials. There were three main factors: old set size (3, 6, or 9), new set size (3 or 9), and preview condition (valid preview, invalid preview, or shape change). Each cell of the factorial design had 48 trials. Trials were randomly intermixed. Participants were permitted to take a break every 144 trials.

Results

Insert Figure 1 and Table 1 here

RTs are shown in Figure 1. Holding the number of new items constant, the slope in the valid preview condition was flat. The slope of RT against old set size was 3.6 ms/item when the new set size was three, and was 5.8 ms/item when it was nine. In both cases, RT was little affected by the number of old items, indicating that as many as nine old items could be efficiently ignored in the valid preview condition. These benefits cannot be easily attributed to attentional capture by the new items or to an object-oriented mechanism, because the slope of the shape change condition was steep. The slopes were 29.7 ms/item when the new set size was three and 24.5 ms/item when it was nine. These values were nearly identical to the slopes of the invalid preview condition: 27.7 ms/item when the new set size was 3 and 25.5 ms/item when the new set size was 9. Table 1 shows the slopes and intercepts of RT as a function of old set size.

Using RT as the dependent variable and new set size, old set size, and preview condition as the independent variables, an ANOVA showed significant main effects of new set size, $F(1, 5) = 201.87$, $p < .0001$, with longer RT as the number of new items increased; old set size, $F(2, 10) = 32.42$, $p < .0001$, with longer RT as the number of old items increased; and preview condition, $F(2, 10) = 37.97$, $p < .0001$, with faster RT in the valid preview condition than the other two conditions, which did not differ from each other, $F(1, 5) < 1$.

The interaction between new set size and preview condition was significant, $F(2, 10) = 6.02$, $p < .019$. The difference in RT between the valid preview condition and the other two conditions was greater when the new set size was 3 (186 ms) rather than 9 (95 ms). Note that the significant interaction did not mean that visual marking was less efficient when the new set size was 9. The efficiency of marking was high in the valid preview condition whether the new set size was large (slope = 5.8 ms/item) or small (slope = 3.6 ms/item). These two slopes were statistically indistinguishable, $t(5) = .45$, $p > .30$. Similar results were obtained in a separate study that covered a wider range of old (3-30) and new (3-15) set

sizes and that tested a larger number of participants ($N = 17$; Jiang, Chun, & Marks, in press). The significant interaction between new set size and condition showed that the difference in overall RT between the valid and the invalid preview conditions declined as the number of new items increased. This effect of new set size and its methodological implications were thoroughly examined elsewhere (Jiang et al., submitted-b). To summarize, Jiang et al. revealed that new set size affects the preview benefit in overall RT, potentially masking the presence of marking unless old set sizes are examined independent of new set size. Past studies that covaried new and old set sizes (typically new set size equaled old set size) did not exhibit an effect of new set size because they either tested small new set sizes (1-6; Watson & Humphreys, 1997) or gave observers extensive practice (Theeuwes et al., 1998). Here we just note that evidence of marking, as reflected by old set size slopes, was evident across the two levels of new set size. This outcome serves as a justification for testing only a single level of new set size (6) in Experiments 2 and 3.

The interaction between new set size and old set size was not significant, $F(2, 10) < 1$, showing additivity of these factors. The interaction between preview condition and old set size was significant, $F(4, 20) = 6.64$, $p < .001$, reflecting a shallower slope in the valid preview condition. The three-way interaction was not significant, $F(4, 20) = 1.72$, $p > .15$.

Additional ANOVAs were performed contrasting the three preview conditions in pairs. Comparing the invalid preview and the shape change conditions, none of the effects involving preview condition was significant, all $ps > .15$. Comparing the valid preview and the invalid preview conditions, the main effect of preview condition was significant, $F(1, 5) = 393.73$, $p < .0001$, as were the interactions between preview condition and new set size, $F(1, 5) = 9.84$, $p < .026$, and between preview condition and old set size, $F(2, 10) = 8.13$, $p < .008$. An identical pattern was found when comparing the valid preview and the shape change condition: preview condition: $F(1, 5) = 35.34$, $p < .002$; preview

condition X new set size: $F(1, 5) = 6.58, p < .05$; and preview condition X old set size: $F(2, 10) = 17.65, p < .001$. Thus, visual marking was present in the valid preview condition but absent in the shape change condition.

Discussion

Experiment 1 gave clear evidence of visual marking in conditions that used an invalid preview manipulation as the baseline, intermixed conditions within blocks, and varied new and old set sizes orthogonally. Slope of RT as a function of old set size was below 10 ms/item in the valid preview condition, significantly shallower than that in the invalid preview condition. By comparison, in the shape change condition, where “+”s were previewed but changed into Ls when new items were added, visual marking disappeared.

These results are consistent with the temporal segregation hypothesis. Because the changes in the old items occur at the same time as the onset of the new items, both sets are grouped into a single temporal event. Attention cannot be selectively allocated to a subset of this temporally unitized group, so previewing the locations of the old items is insufficient for visual marking to occur.

The results are diagnostic in testing other competing hypotheses. For example, elimination of visual marking in the shape change condition rules out the possibility that attentional capture is the sole source for the preview benefit. This is because a shape change is insufficient to create a new object file, so the old items are still old and the new items still have sudden onset, allowing new items the potential to capture attention. The elimination of the preview benefit in such conditions indicates that attentional capture is not a satisfactory explanation of visual marking (see also Watson & Humphreys, 1997).

Along the same line, this experiment suggests that visual marking may not reflect an inherent preference toward new objects or a bias to inhibit old objects. We argued earlier that it is not adaptive for an object-oriented system to be disrupted by superficial changes in form because old objects remain

old when their spatial-temporal continuity is preserved, as they always were in these experiments. A similar result – disruption of visual marking by changes in form – was initially observed by Watson and Humphreys (1997). This finding served not only to discount the attentional capture hypothesis, but also to call for a revision of the inhibition hypothesis. Watson and Humphreys postulate that inhibition is flexibly reset if something changes at the location of the old items.

Such flexibility allows the inhibition hypothesis to account for the elimination of visual marking in Experiment 1. However, making inhibition flexible appears to damage the spirit of the inhibition hypothesis – its function to prioritize new objects. The results of Experiment 1 imply that visual marking, whatever its function, is not object-oriented. One could argue that visual marking is object-oriented in the valid preview condition but not when old items change in shape. While possible, such a modification is not parsimonious as it calls for additional ad hoc constraints whenever a new case of disruption arises. As an alternative, we suggest a more general function for visual marking. Rather than serving to deprioritize old objects, visual marking may be the result of selective attention to temporally segregated groups of items. Experiments 2-4 provide further confirmatory tests of this hypothesis.

Experiment 2: Dynamic Change in the Old Items and in the Background

Experiment 1 replicated Watson and Humphreys's (1997) earlier finding that visual marking is sensitive to dynamic change in the old items. The results are consistent with the temporal segregation hypothesis. They are also consistent with a simpler hypothesis: that the visual marking mechanism is reset whenever a dynamic change occurs. Because the onset of the new items – a type of dynamic change on the display – does not reset visual marking, however, the dynamic change hypothesis requires additional constraint. One possible constraint is provided by the inhibition hypothesis. Instead of any dynamic change, the inhibition hypothesis postulates that a change is disruptive if it occurs at the location of old items because such a change indicates that something new is happening to them (Watson

& Humphreys, 1997). Although we have questioned the object-oriented approach of the inhibition hypothesis, we believe that by weakening its object-oriented bias, the inhibition hypothesis can account for a large amount of data, including the disruption of visual marking found in Experiment 1.

Consequently, it is worth testing the hypothesis that visual marking is reset by dynamic changes at the location of old items.

Experiment 2 sought to find out what type of change is critical for visual marking: a change specific to the old items (as predicted by the temporal segregation hypothesis), any change in general (as predicted by the dynamic change hypothesis), or a change that is restricted to the location of the old items (as predicted by the inhibition hypothesis). To accomplish this, Experiment 2 compared the effects of changes in the old items with effects of changes in the background. Instead of presenting the items in an invisible matrix, we made the matrix in the background visible. The grid was either white or black, and could either maintain or change its luminance from black to white or vice versa when the new items were added.

Insert Figure 2 here

The temporal segregation hypothesis predicts that visual marking should be disrupted by the luminance change in the old items, even though luminance does not affect the shape of the items and should be irrelevant to the task. In addition, we predict that the change in the background grid should not be disruptive. Although the luminance change in the background should trigger the dynamic change detection system, it should not synchronize the old and the new items. In contrast, the dynamic change hypothesis predicts disruption of visual marking both when the old items and when the background changes luminance. Prediction from the inhibition hypothesis depends on what counts as an old item

location. If it is highly specific to the region directly occupied by an item, then a background grid change may not disrupt marking. But if the old item location is tagged more loosely, then a change in the background grid that closely surrounds the location of old items will disrupt marking. The results of this experiment will clarify what counts as an old location. Finally, by using luminance change instead of shape change, this experiment serves to generalize the results from Experiment 1.

Method

Four factors were manipulated: validity of the previewed locations, old set size, consistency in luminance in the old items across the preview and the search images, and consistency in luminance in the background from preview to search. Items were presented in a visible grid, as shown in Figure 2. Both the items and the grid could (independently) be black or white. A number of old items (3, 6, or 9) were previewed, and a fixed number of new items (6) were added 1 second later. At the onset of the new items, the old items maintained or changed their locations (valid vs. invalid preview), and maintained or changed their luminance (luminance constant vs. luminance change). Orthogonal to these manipulations, the grid in the background maintained or changed its luminance at the onset of the new items. The new items always had the same luminance as the old items after their change. Eighteen participants were tested in 12 practice and 432 experimental trials.

Results

Insert Figure 3 and Table 2 here

Figure 3 shows RTs and Table 2 shows the slopes and intercepts. First, we carried out an ANOVA that included all four factors. The main effect of item luminance was not significant, $F(1, 17) = 2.62, p > .12$. But the other main effects were all significant. RT was slower when the luminance of the

background grid changed, $F(1, 17) = 14.39$, $p < .001$; when the number of old items increased, $F(2, 16) = 44.60$, $p < .0001$; and when the preview was invalid, $F(1, 17) = 43.40$, $p < .0001$. The detrimental effect of changing background luminance was greater when the luminance of the old items did not change, showing a significant interaction between item luminance and grid luminance, $F(1, 17) = 5.60$, $p < .030$. The under-additivity occurred equally at all three set sizes, shown by the non-significant interaction among item luminance change, background luminance change, and old set size, $F(2, 16) = 1.61$, $p > .20$.

Overall, the valid preview condition gave shallower slopes than the invalid preview condition, as shown by the significant interaction between preview condition and old set size, $F(2, 16) = 7.06$, $p < .006$. Changing the background grid did not interact with preview condition, $F(1, 17) < 1$, or with old set size, $F(2, 16) < 1$. Nor was the three-way interaction among background change, preview condition, and old set size significant, $F(2, 16) < 1$.

The average difference in RT between the valid and the invalid preview conditions was smaller when the items changed their luminance, $F(1, 17) = 15.24$, $p < .001$. This was especially true when the background did not change luminance, reflected by a marginally significant three-way interaction among item luminance, grid luminance, and condition, $F(1, 17) = 3.20$, $p < .091$. The interaction between item luminance change and old set size was not significant, $F(2, 18) = 1.00$, $p > .30$. However, there was a significant three-way interaction among preview condition, old set size, and item luminance change, $F(2, 16) = 7.76$, $p < .004$. It appears that visual marking, as reflected by the reduction in slope of RT as a function of old set, was effective only when the items did not change luminance. The four-way interaction was not significant, $F(2, 16) < 1$.

To get a clearer view of visual marking, we carried out separate ANOVAs for the four different luminance change conditions. The factors entered into each ANOVA test were old set size and preview condition.

When neither the old items nor the background changed luminance, there were significant effects of preview condition, $F(1, 17) = 49.93$, $p < .0001$; old set size, $F(2, 16) = 9.30$, $p < .002$; and their interaction, $F(2, 16) = 7.87$, $p < .004$, showing visual marking.

When the luminance of the items changed but the luminance of the background grid did not, the main effect of preview condition was not significant, $F(1, 17) < 1$. The main effect of old set size was significant, $F(2, 16) = 19.92$, $p < .0001$. But the interaction between preview condition and old set size was not, $F(2, 16) = 1.02$, $p > .35$. Thus, when the luminance of the items changed but the background was constant, visual marking was abolished.

When the luminance of the items did not change but the luminance of the background grid did, the main effect of preview condition was significant, $F(1, 17) = 19.08$, $p < .0001$, as was the main effect of old set size, $F(2, 16) = 8.37$, $p < .003$, and their interaction, $F(2, 16) = 7.20$, $p < .006$. Thus, changing the luminance of the background grid did not eliminate visual marking.

Finally, when both the luminance of the items and the luminance of the background grid changed, the main effect of condition was marginally significant, $F(1, 17) = 3.99$, $p < .062$. The main effect of old set size was significant, $F(2, 16) = 7.17$, $p < .006$, but the interaction between preview condition and old set size was not, $F(2, 16) < 1$, ns. Visual marking was not observed when both the items and the background grid changed their luminance.

Discussion

Consistent with the temporal segregation hypothesis, visual marking was eliminated when a luminance change in the old items was synchronized with the onset of the new items. Together with

Experiment 1, where synchronous changes in shape disrupted marking, we interpret the results of Experiment 2 to indicate that visual marking is not object-oriented. Changes in a surface feature such as luminance are tangential to the "objecthood" of an item. The inability to ignore luminance change suggests that visual marking is unlikely to reflect a system that evolved solely to prioritize new objects.

The results also show what types of dynamic change disrupt marking. Changing the luminance of the background grid did not eliminate visual marking, consistent with the temporal synchrony hypothesis, which predicts that visual marking will be disrupted only when dynamic change within old and new items serves to group them together. The present results rule out the dynamic change hypothesis, which predicts that any type of dynamic change will disrupt marking. The data also help refine the inhibition account, which predicts that changes to the old locations will disrupt marking. Previously, the definition of "old item location" was ambiguous. It could be interpreted as a coarse region around an item's center of mass or tightly bound to an item's contours. Our background grid results suggest that marking is tightly restricted to the region directly occupied by the form contours of the old items.

Finally, disruption of visual marking by luminance change in the old items suggests that visual marking is not just sensitive to shape change. This finding conflicts with a recent finding that reported that visual marking was not affected by luminance or color change (Watson & Humphreys, in press). In addition to shape and luminance change, we have observed disruption of visual marking by color change (Jiang, 2000). Although we did not directly compare these three types of changes, which were not equated in saliency, our data do not warrant special treatment for shape changes over luminance changes or for luminance changes over color changes. Note that the temporal segregation hypothesis does not predict the three types of changes should be equally disruptive. Luminance processing and color processing may proceed at different speeds in the brain (see for example Dinse & Kruger, 1994; Gawne,

Kjaer, & Richmond, 1996). So even when a color change physically occurs at the same moment as a luminance change (onset of new items), these two types of changes may not be perceived as synchronized events by all stages of the visual system. So the data reported by Watson and Humphreys are not necessarily inconsistent with the temporal segregation account.

Additional studies should clarify why surface feature changes were not disruptive in Watson and Humphreys's (in press) study but were disruptive in ours. One factor may be the saliency of the changes between studies. Our luminance changes involved contrast reversals, while their luminance changes (e.g., dotted to solid lines) appear to have been more subtle (but clearly notable). We do not have a hypothesis for why color changes disrupted marking in Jiang (2000), but not in Watson and Humphreys's study (in press). The major difference was that they employed isoluminant colors, while we did not control for luminance. However, according to their luminance change experiment, luminance changes should not matter. We must note that we have replicated the disruptive effects of synchronous changes for form, luminance, and color across several experiments here and elsewhere (Jiang, 2000). To understand the discrepancy between these separate experiments, the relationship between the salience of perceptual change and visual marking should be examined parametrically. However, instead of conducting such a parametric study here, we will focus on more decisive empirical tests of the inhibition and temporal segregation hypotheses in the remaining two experiments.

Experiment 3. Desynchronized Change in Old Items Does Not Eliminate Visual Marking

A change in the old items is a useful but insufficient condition for synchronizing new and old items. The temporal segregation hypothesis predicts that, if the change in the old items is out of synchrony with the onset of the new items, old and new items should be perceptually segregated. Thus, visual marking should persist if the change in the old items is introduced prior to the onset of the new

items. In contrast, the inhibition account does not emphasize synchrony, so it predicts a disruption of visual marking by asynchronous as well as synchronous changes in the old items.

To test this prediction, we introduced a change in the old items a fraction of a second before the onset of the new items. To make the change obvious, we changed the luminance of the old items (\underline{L} s) and rotated the \underline{L} s by 90° . If change per se in the old items is sufficient to disrupt visual marking, as predicted by the inhibition hypothesis, we should not find a preview benefit. In contrast, visual marking should persist according to the temporal segregation hypothesis because asynchronous changes still preserve the segregation between old and new items.

Method

Twenty participants received 12 practice and 432 experimental trials. Three factors were manipulated: old set size (3, 6, or 9), preview condition (valid or invalid preview), and the inter-stimulus interval (ISI) between the change in the old items and the onset of the new items (107, 307, or 600 ms). The number of new items was always 6. We presented the old distractors for 1 s. Then they changed their shape (rotated by 90°) and luminance (from white to black or black to white). After the variable ISI, the new items, including the target, were added to the display.

Results

Insert Figure 4 and Table 3 here

Figure 4 shows RTs and Table 3 shows the slopes and intercepts. The main effect of ISI was not significant, $F(2, 18) < 1$. The main effect of preview condition was significant, showing faster RT in the valid preview condition, $F(1, 19) = 48.00$, $p < .0001$, as was the main effect of old set size, showing a

non-flat slope, $F(2, 18) = 29.73$, $p < .0001$. The interaction between preview condition and old set size was significant, $F(2, 18) = 4.03$, $p < .036$, showing efficient visual marking.

The interaction between ISI and condition was not significant, $F(2, 18) = 2.74$, $p > .092$. The trend toward a difference reflects the apparently smaller benefit when ISI was 307 ms (mean difference = 83 ms) than 107 ms (mean difference = 120 ms) or 600 ms (mean difference = 141 ms). The three-way interaction among ISI, condition, and old set size was not significant, $F(4, 16) = 1.08$, $p > .35$. This indicates that ISI did not significantly affect the size of preview benefit.

Follow-up tests showed that there was a significant reduction in overall RT at all ISIs, $F_s(1, 19) > 21.16$, $p_s < .0001$. Although the slopes tended to decline at all three ISIs, the interaction between old set size and condition was statistically significant only when ISI was 600 ms, $F(2, 18) = 4.23$, $p < .031$. The interaction was marginally significant when ISI was 107 [$F(2, 18) = 3.06$, $p < .072$], but not significant at 307 ms, $F(2, 18) = 1.52$, $p > .20$. Note, however, that individual tests may not have enough statistical power to reveal a change in slope. Overall, the valid preview condition gave a significantly shallower slope than the invalid preview condition. Because preview condition did not interact with old set size and ISI ($F < 1$), it is reasonable to conclude that visual marking, as indicated by slope reduction, was observed across all three ISIs. Thus, a change in the old items that is not synchronized with the onset of the new items does not eliminate visual marking.

Nevertheless, shape and luminance change in the old items was somewhat disruptive. The slope in the valid preview condition exceeded 10 ms/item at all ISIs. Visual marking is probably affected not only by temporal synchrony but also by visual transients in the old items, even though synchrony plays a much more critical role.

Discussion

When the change in the old items preceded the onset of the new items, the old items were no longer synchronized with the new items. Visual marking was observed under such conditions, and the strength of slope reduction was indistinguishable across the three ISIs (107, 307, and 600 ms). These findings, together with those of the earlier experiments, provide strong evidence for the temporal segregation hypothesis.

The inhibition hypothesis, in its current form, cannot easily account for the persistence of visual marking because it fails to specify the role of timing in the change signal. In a personal communication, D. Watson (2001) offered the following extension of the inhibition hypothesis to account for the results in Experiment 3. In this extension, visual marking is dissected into two steps: a set-up process and a maintenance process. A change affects only the maintenance of visual marking. During the interval between the change of the old items and the onset of the new items, visual marking does not need to be newly established from scratch. Recovery from a disruption in the maintenance process is more efficient, and Watson proposes that a temporal separation as small as 100 ms is sufficient for marking to reset itself. This extension of the inhibition hypothesis is plausible, but we think it does not jointly account for the complete disruption of visual marking in Experiments 1 and 2, and the persistence of marking in Experiment 3. Because the inhibition hypothesis does not ascribe any role for synchrony cues, it should predict that marking will quickly “reset” for both synchronous change conditions (Experiments 1 & 2) and for asynchronous change conditions (Experiment 3). Consider the case where the change in old items and the onset of new items are synchronous. According to the fast reset hypothesis, marking should be quickly reestablished even after the onset of the new items, leading to at least a partial preview benefit. There is no reason why resetting should not occur, unless synchrony plays a critical role.

Thus, Experiment 3 provides a critical confirmatory test for the temporal segregation hypothesis, and it suggests that the current form of inhibition hypothesis is under-specified in explaining when visual marking is disrupted^[3]. In our view, a “reset” account alone cannot explain why visual marking is abolished under synchronous change but not under asynchronous change conditions. The data favor the temporal segregation hypothesis, which does not require untested assumptions and succinctly describes the sensitivity of marking to synchrony.

Experiment 4 Prioritizing Old Items after Temporal Segregation

Aside from ascribing different bases to visual marking (inhibition or asynchrony), a central issue that differentiates the temporal segregation and inhibition hypotheses is whether visual marking reflects prioritization of new over old items. According to the inhibition hypothesis, visual marking evolved as a mechanism to suppress existing information (Watson & Humphreys, 1997). In contrast, the temporal asynchrony account does not attribute special status to the old items, beyond the fact that task demands dictate that these items should be ignored because they never contain the target.

In Experiment 4 we directly test whether visual marking is a specialized system dedicated to deprioritizing old information. The critical manipulation is to reverse the roles of old and new items, making the old items behaviorally important and new items irrelevant. If visual marking reflects deprioritization of old information, as suggested by the inhibition hypothesis, participants should not be able to prioritize old over new information. By contrast, the temporal segregation hypothesis proposes that selective attention can be allocated to any behaviorally relevant group following temporal segregation. Thus, if new and old information is desynchronized, participants should be able to selectively disregard irrelevant information, whether it happens to be new or old.

A few words are necessary to point out unique problems in conducting a marking experiment in which old items are behaviorally relevant. Behavioral relevance is established by presenting the target

among the old items. At the same time, it is important that the old information on the display be constant as new items are added. This is necessary because any change in the old items (such as the introduction of a target in an ongoing display) disrupts the temporal asynchrony between the new and old items. As a result, one cannot merely hide or camouflage the target among the old items, and reveal its identity as new items are added. Instead, the target has to be presented as one of the old items and be maintained throughout the trial. A natural consequence is that the duration of the old items cannot be too long; otherwise participants would detect the target before the new items are added.

Thus, we were obligated to present the target among the old items from their onset. In addition, we curtailed the duration of the old items so that it was too short for search to be completed but long enough to support temporal segregation. Given these constraints, we used the following trial sequence. First, a fixation cue was presented for 1 s. Then the old items, containing several Ls and one rotated T, were presented. The new items, all rotated Ts of random orientations, were added on the display 150 ms later. Presenting Ts in the new set made the task very difficult and further encouraged participants to attend to the old items. In the valid preview condition, the old items maintained their locations and other features. In the invalid preview condition, the old items moved instantly to previously unoccupied locations as the new items were added. The target is defined as the unique T in the *old* items. Thus, in both conditions participants had 150 ms to search for the unique T among the old items. In addition, if participants can temporally segregate the new and old items into two groups and selectively attend to the old items, they should be able to continue searching within the old set only in the valid preview condition. Therefore, A performance advantage in the valid compared with the invalid preview condition indicates that participants can prioritize old items.

Method

Eight participants completed 16 practice and 288 experimental trials. Three within-subject factors were varied: old set size (6 or 12), new set size (6 or 12), and preview condition (valid or invalid). Each trial started with a fixation dot of 1 second, followed by the addition of old items. New items were added 150 ms later. The old items contain several Ls and one T rotated to one of four orientations (up, down, left, or right). The new items contain all Ts rotated by 0°, 90°, 180°, or 270°. The target is the unique T among the old items. The task was impossible without the preview (150 ms).

Participants were instructed to report the direction of the unique T among the old items. They were encouraged to guess when not sure. To lower the level of chance performance, four possible orientations of Ts were used. Participants pressed one of the four arrow keys as responses. Visual feedback, in the form of “++” for correct response and “--” for incorrect response, was provided immediately after each response. Conditions were randomly intermixed and participants were allowed to take a break every 32 trials.

Results

Insert Figure 5 here

Figure 5 shows the average accuracy of the eight participants in reporting the orientation of the unique T among the old items. An ANOVA on new set size, old set size, and preview condition showed a significant main effect of preview condition, $F(1, 7) = 86.01$, $p < .0001$, in that participants were much more accurate in identifying the unique old T in the valid compared with the invalid preview condition. The main effect of new set size was significant, $F(1, 7) = 5.71$, $p < .048$, indicating that accuracy dropped as the number of new items increased. The main effect of old set size was also significant, $F(1,$

7) = 18.05, $p < .004$. The smaller the old set size, the higher the accuracy of identifying the unique old \underline{T} . This result is expected given that there was a larger probability for the participants to spot the old \underline{T} within the 150 ms time window when there were fewer old distractors.

The interaction between preview condition and new set size was significant, $F(1, 7) = 6.73$, $p < .036$. This suggests that the number of new items had a smaller effect when the preview was valid rather than invalid. That is, new items were better ignored when the preview was valid. Figure 5 shows that this pattern of results seemed more pronounced when old set size was 6 rather than 12, possibly because performance in the invalid preview condition approached floor when old set size was 12. Accuracy in the invalid preview condition with a new set size of 12 and an old set size of 12 was barely above chance, $p = .058$. The three-way interaction among preview condition, new set size, and old set size, however, was not significant, $F(1, 7) < 1$. The interaction between preview condition and old set size was not significant, $F(1, 7) < 1$, nor was the interaction between new set size and old set size, $F(1, 7) = 1.08$, $p > .33$.

Discussion

In traditional studies of visual marking, the to-be-ignored set of items is not only old but also behaviorally irrelevant. According to the inhibition hypothesis, old items are marked in order to prioritize new items. Is marking specific to old items? The inhibition hypothesis proposes that a specialized mechanism ignores irrelevant, old information. The temporal segregation hypothesis assumes that attention is allocated to whatever information is behaviorally relevant for the task.

To answer this question, Experiment 4 made the old items behaviorally relevant. The target was among the old items. So instead of deprioritizing the old items, as suggested by the inhibition hypothesis, participants must try to enhance old items, while deprioritizing new items. Participants were

clearly able to prioritize the old items and ignore new items when the new and old items were segregated into two temporal groups.

The results of this experiment provide strong evidence that visual marking reflects selective attention to a behaviorally relevant group of items. Visual marking as a unique mechanism to deprioritize old objects, in our view, loses its attractiveness given that the visual system is able to do the reverse. This finding strongly supports the explanatory power and generality of the temporal segregation hypothesis in comparison to the inhibition hypothesis.

Having provided evidence for the temporal segregation hypothesis, we do not wish to push it too far. In particular, we do not propose that the deprioritization of new items observed in Experiment 4 necessarily reflects the same process as the deprioritization of old items observed in Experiment 1. It is possible that deprioritizing old items is more efficient than deprioritizing new items. But this possibility awaits further, direct tests. We favor the temporal segregation hypothesis because it provides a single framework to account for deprioritizing either old or new items. The inhibition hypothesis, in contrast, has to propose that participants abandon marking in Experiment 4 for some other, as yet undefined process to deprioritize new items.

General Discussion

Visual marking is a mechanism for selective attention. In typical studies of visual marking, a subset of items is presented about 1 s before other items. Participants can efficiently ignore the old items and restrict their selection to the new ones (Watson & Humphreys, 1997). Watson and Humphreys proposed that visual marking reflects an inhibitory process that relies on central processing resources to deprioritize old items ^[4].

The temporal segregation hypothesis challenges the inhibition hypothesis in two main aspects. Most important is the claim that temporal segregation cues, based on asynchronous onset of old and new

items, allow observers to focus on new items. Temporal asynchrony provides the perceptual basis for the ability to perform visual marking. The inhibition account does not speak to this issue. The second difference concerns the role of inhibition. The inhibition account proposes a special mechanism to mark and suppress old items in order to prioritize new events. The temporal segregation account argues that there is nothing special about old items other than the fact that they are behaviorally irrelevant in the typical marking paradigm. Rather, temporal asynchrony permits the segregation of a visual array into two groups, and selective attention can be deployed to whatever group known to contain the target. Whether selection is accomplished via inhibition or some other process, our study demonstrates that this process is not restricted to old items.

This set of experiments was designed to support the temporal segregation hypothesis, which we believe has strong explanatory power with relatively few assumptions. Rejecting the inhibition hypothesis is difficult because it is under-specified in some ways, and overly flexible in others. Therefore, our goal is just to point out how the inhibition account needs to be revised to explain our data. The following provides a summary.

First, Experiments 1 and 2 demonstrate the importance of temporal segregation. Visual marking is destroyed when old items changed shape or luminance at the onset of the new items. This result supports the temporal segregation hypothesis because the changes in the old items and the onset of the new items are synchronized into a single event, unitizing the two groups, precluding selective attention to a subset of the group. In contrast, an object-oriented system should ignore such feature changes because they do not change the object file: old items should remain old because of their spatio-temporal continuity. The inhibition hypothesis must additionally postulate that marking is a flexible process reset by any type of dynamic change within the old items, but this limits the ecological utility of the claim that marking is specialized to deprioritize old objects.

Unlike changes in the objects themselves, Experiment 2 showed that a dynamic change of a background grid is not detrimental to visual marking. The temporal segregation hypothesis can naturally account for these data because the background grid is a different object from the old items. When the background changes, old and new items remain segregated into two temporal groups. This finding rules out the hypothesis that visual marking is reset by all kinds of dynamic change. The inhibition hypothesis states that only changes at “the location of old items” will affect visual marking, but it was not clear how specific the location must be. In Experiment 2, the background grid covered the entire display, and it surrounded the locations of the old items. Because there was no effect of background change, marking is only disrupted by changes within the objects themselves, rather than the general location of marked items. In other words, our data refine the inhibition hypothesis in showing that dynamic changes must occur specifically within the marked object locations.

Experiment 3 showed that visual marking is not abolished by a change in shape and luminance in the old items occurring a fraction of a second (e.g., 107 ms) before the onset of the new items. Because such changes are not synchronized with the onset of the new items, the two sets of items remain segregated. Thus, the temporal segregation hypothesis can easily explain the persistence of marking under such conditions. The inhibition hypothesis, in its current form, postulates that any change at the location of the old items is disruptive and should predict reduction or elimination of visual marking. The persistence of marking is thus inconsistent with this simple version of inhibition hypothesis. However, as Watson suggested in personal communication, visual marking may involve two separable processes: set-up and maintenance. A change in the old items disrupts only maintenance but not the set-up process. So reapplying inhibition to the old items during the interval between the change and the onset of new items suffices to produce marking. This amendment is plausible for this experiment, but we believe that such an explanation cannot jointly explain why marking is not reestablished under synchronous change

conditions (Experiments 1 and 2). The “reset” hypothesis also requires converging support for the newly added assumptions that changes in the old items selectively affect the maintenance and not the set-up of marking.

Finally, Experiment 4 presented the target among the old items and found that participants were able to deprioritize new items over old ones. Such results are consistent with the temporal segregation hypothesis, which allows attention to be allocated to either the new or the old items, whichever are behaviorally relevant, following temporal segregation. Because of its emphasis on the ecological validity of visual marking to deprioritize old information, the inhibition hypothesis does not apply to this finding. It is necessary to assume that some other process, unrelated to marking, allows the new items to be marked.

To summarize, the experiments presented here strongly suggest that visual marking reflects selective attention to temporally segregated perceptual groups. As a whole, the findings challenge the need to postulate a specialized marking mechanism that deprioritizes old objects. We acknowledge that the inhibition hypothesis can be refined to account for these data. Some revisions involve minor specifications, such as where a change needs to occur to be disruptive; others are substantial enough to call for a major modification of the theory, such as specifying its ability to re-mark items, and specifying why marking should be specialized for de-prioritizing old objects when they can be prioritized as well. In any case, the temporal segregation account provides, in our view, a more compact description of the data.

In other aspects, the temporal segregation and the inhibition hypotheses are complementary. In particular, it is possible that two processes act in concert to produce the preview benefit observed in most studies of visual marking. One is a process that inhibits old items during preview. It is relatively slow, and needs to be set-up and maintained throughout the preview. This mechanism has specifically

evolved to deprioritize old information. The other process is segregation by temporal asynchrony. New and old items are segregated to two perceptual groups due to their different time courses, and attention can selectively enhance one group over another depending on the behavioral relevance of each group. The two processes converge in a typical valid preview condition. The importance of temporal segregation takes precedence over inhibition when the asynchrony cue is disrupted. Sometimes the temporal segregation hypothesis works against the inhibition hypothesis, as when old items need to be prioritized. In the latter case, selective attention is applied to the old items segregated from the new items (which may or may not be inhibited) based on temporal asynchrony cues.

The temporal segregation hypothesis does not account for visual marking in dynamic displays. Watson and Humphreys (1998) showed that when old items moved linearly over the display, newly added items moving in the same direction could be prioritized. In addition, a new item that shared color with the old items was treated as old, as if the feature of the old items was inhibited. It appears that dynamic marking relies on a totally different mechanism from static marking. Dynamic marking is best characterized as perceptual grouping by color, as demonstrated by Egeth et al. (1984) and Kaptein et al. (1995). In fact, Olivers et al. (1999) showed that when the old and new items no longer differed in a single feature such as color, visual marking in dynamic displays was completely eliminated. The time difference between old and new items is neither necessary nor sufficient in this case, questioning the categorization of these tasks as revealing “marking” in a temporal dimension. Therefore, the presence of visual marking in dynamic displays is not evidence against the temporal segregation hypothesis, which applies only to static displays.

References

Alais, D., Blake, R., & Lee, S.-H. (1998). Visual features that vary together over time group together over space. Nature Neuroscience, 1, 160-164.

Blake, R., & Yang, Y. (1997). Spatial and temporal coherence in perceptual binding. Proceedings of the National Academy of Science: USA, 94, 7115-7119.

Broadbent, D. E., & Broadbent, M. H. (1987). From detection to identification : Response to multiple targets in rapid serial visual presentation. Perception & Psychophysics, 42(2), 105-113.

Chun, M. M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. Cognitive Psychology, 36, 28-71.

Chun, M. M., & Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. Journal of Experimental Psychology: Human Perception and Performance, 21(1), 109-127.

Chun, M. M., & Wolfe, J. M. (2001). Visual Attention. In B. Goldstein (Ed.), Blackwell Handbook of Perception (pp. 272-310). Oxford, UK: Blackwell Publishers Ltd.

Dinse, H. R., & Kruger, K. (1994). The timing of processing along the visual pathway in the cat. NeuroReport, 5, 893-897.

Driver, J., & Baylis, G. C. (1989). Movement and visual attention: The spotlight metaphor breaks down. Journal of Experimental Psychology: Human Perception & Performance, 15, 448-456.

Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. Psychological Review, 87(3), 272-300.

Egeth, H. E., Virzi, R. A., & Garbart, H. (1984). Searching for conjunctively defined targets. Journal of Experimental Psychology: Human Perception & Psychophysics, 10, 32-40.

Friedman-Hill, S., & Wolfe, J. M. (1995). Second-order parallel processing: Visual search for the odd item in a subset. Journal of Experimental Psychology: Human Perception & Performance, *21*, 531-551.

Gawne, T. J., Kjaer, T. W., & Richmond, B. J. (1996). Latency: Another potential code for feature binding in striate cortex. Journal of Neurophysiology, *76*, 1356-1360.

Gibson, B. S., & Jiang, Y. (2001). Visual marking and the perception of salience in visual search. Perception & Psychophysics, *63*, 59-73.

Grossberg, S., Mingolla, E., & Ross, W. D. (1994). A neural theory of attentive visual search: interactions of boundary, surface, spatial, and object representations. Psychological Review, *101*(3), 470-489.

Humphreys, G. W., & Müller, H. J. (1993). Search via Recursive Rejection (SERR): A connectionist model of visual search. Cognitive Psychology, *25*, 43-110.

Hunt, S. M. J. (1994). MacProbe: A macintosh-based experimenter's workstation for the cognitive sciences. Behavior Research Methods, Instruments, & Computers, *26*, 345-351.

Jiang, Y. (2000). Visual Marking. Dissertation submitted to Yale University.

Jiang, Y., Chun, M. M., & Marks, L. E. (in press). Visual marking: Dissociating effects of new and old set size. Journal of Experimental Psychology: Learning, Memory, & Cognition.

Jiang, Y., Chun, M. M., & Marks, L. E. (submitted). Visual marking does not rely on visual Short-term memory.

Jiang, Y., Olson, I. R., & Chun, M. M. (2000). Organization of visual short-term memory. Journal of Experimental Psychology: Learning, Memory, & Cognition, *26*, 683-702.

Jonides, J., & Yantis, S. (1988). Uniqueness of abrupt visual onset in capturing attention, Perception & Psychophysics, *43*, 346-354.

- Kahneman, D. (1973). Attention and Effort. Englewood Cliffs, NJ: Prentice-Hall.
- Kahneman, D., Treisman, A., & Burkell, J. (1983). The cost of visual filtering. Journal of Experimental Psychology: Human Perception & Performance, *9*, 510-522.
- Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object-specific integration of information. Cognitive Psychology, *24*, 175-219.
- Kanizsa, G. (1979). Organization in vision: Essays on Gestalt Perception. New York: Praeger.
- Kaptein, N. A., Theeuwes, J., & van der Heijden, A. H. C. (1995). Search for a conjunctively defined target can be selectively limited to a color-defined subset of elements, Journal of Experimental Psychology: Human Perception & Performance, *21*, 1053-1067.
- Klein, R. (1988). Inhibitory tagging system facilitates visual search. Nature, *334*, 430-431.
- Klein, R., & MacInnes, W. J. (1999). Inhibition of return is a foraging facilitator in visual search. Psychological Science, *10*, 346-352.
- Kolers, P. A., & Pomerantz, J. P. (1971). Figural change in apparent motion. Journal of Experimental Psychology, *87*, 99-108.
- Lee, S.-H., & Blake, R. (1999, May). Visual form created solely from temporal structure. Science, *284*, 1165-1168.
- Leonards, U., Singer, W., & Fahle, M. (1996). The influence of temporal phase differences in texture segmentation. Vision Research, *36*, 2689-2697.
- Nakayama, K., & Silverman, G. H. (1986). Serial and parallel processing of visual feature conjunctions. Nature, *320*, 264-265.
- Olivers, C. N. L., Watson, D. G., & Humphreys, G. W. (1999). Visual marking of locations and feature maps: Evidence from within-dimension defined conjunctions. Quarterly Journal of Experimental Psychology, *52A*, 679-715.

Palmer, S. E., & Levitin, D. (1998). Synchrony: A new principle of perceptual organization. Paper presented in 38th Annual Meeting of the Psychonomic Society, November, Philadelphia, PA.

Paquet, L., & Lortie, C. (1990). Evidence for early selection: Precuing target location reduces interference from same-category distractors. Perception & Psychophysics, *48*, 382-388.

Pashler, H. (1998). Attention. Hove, England UK: Psychology Press.

Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma & D. G. Bouwhuis (Eds.), Attention & Performance X, (pp. 531-556). Hillsdale, NJ: Erlbaum.

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? Journal of Experimental Psychology: Human Perception & Performance, *18*, 849-860.

Theeuwes, J., Kramer, A. F., & Atchley, P. (1998). Visual marking of old objects. Psychonomic Bulletin & Review, *5*, 130-134.

Tipper, S. P. (1985). The negative priming effect: Inhibitory priming by ignored objects. Quarterly Journal of Experimental Psychology, *37A*, 571-590.

Treisman, A., & Sato, S. (1990). Conjunction search revisited. Journal of Experimental Psychology: Human Perception & Performance, *16*, 459-478.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. Cognitive Psychology, *12*, 97-136.

Usher, M., & Donnelly, N. (1998). Visual synchrony affects binding and segmentation in perception. Nature, *394*, 179-182.

Watson, D. G., & Humphreys, G. W. (1997). Visual marking: Prioritizing selection for new objects by top-down attentional inhibition of old objects. Psychological Review, *104*, 90-122.

Watson, D. G., & Humphreys, G. W. (1998). Visual marking of moving objects: A role for top-down feature-based inhibition in selection. Journal of Experimental Psychology: Human Perception & Performance, 24, 946-962.

Watson, D. G., & Humphreys, G. W. (2000). Visual marking: Evidence for inhibition using a probe-dot detection paradigm, Perception & Psychophysics, 62, 472-480.

Watson, D. G., & Humphreys, G. W. (in press). Visual marking and visual changes. Journal of Experimental Psychology: Human Perception & Performance.

Wolfe, J. M. (1994). Guided Search 2.0 : A revised model of guided search. Psychonomic Bulletin & Review, 1, 202-238.

Wolfe, J. M. (1998). What can 1 million trials tell us about visual search? Psychological Science, 9, 33-39.

Yantis, S., & Hillstrom, A. P. (1994). Stimulus-driven attentional capture: Evidence from equiluminant visual objects. Journal of Experimental Psychology: Human Perception & Performance, 20, 95-107.

Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. Journal of Experimental Psychology: Human Perception & Performance, 10, 601-621.

Author Notes

This research formed part of a doctoral dissertation submitted by Yuhong Jiang to Yale University. The work was supported in part by NIH grant DC00271-15 to LEM. We thank Raymond Klein, Carol Fowler, Bradley Gibson, Frank Keil, Jeansok Kim, Derrick Watson, and Karen Wynn for their insightful comments and suggestions. Inquiries about this article should be sent to Yuhong Jiang, 77 Massachusetts Avenue, NE 20-443B, MIT, Cambridge, MA 02139. Electronic mail should be directed to yuhong@MIT.EDU.

Footnotes

[1] It is worth noting that the preview benefit was not location specific if the search elements moved linearly on the display. In moving displays, new distractors that are identical to previewed distractors are effectively discounted during search. Thus, the preview benefit is location-based in static search, but feature-based in dynamic search (Olivers et al., 1999; Watson & Humphreys, 1998). Although both are called “visual marking,” static and dynamic marking may not be produced by a common mechanism. This study is restricted to visual marking in static displays. Dynamic visual marking will be considered in the final discussion.

[2] In a recent paper, Watson and Humphreys (in press) also argued that marking should ignore irrelevant features. They showed that luminance and color changes did not disrupt visual marking. However, our Experiments 1 and 2 conflict with their new data. We will discuss the discrepancy in the experimental sections.

[3] One may find visual marking under the $ISI = 107ms$ condition surprising, given that past studies have shown that a preview of 300-400ms is needed for marking to reach asymptote. In two additional experiments, we tested the effect of preview duration on visual marking (Jiang, 2000). There, we presented observers with a preview display of 107, 307, or 600ms, followed by the addition of new items and the target. We failed to observe visual marking at a preview duration of 107ms, and confirmed that approximately 300ms is needed for visual marking to reach asymptote. These experiments may seem to be inconsistent with Experiment 3. However, note that Experiment 3 involved an additional 1000 ms preview of old items that subsequently changed their luminance and shape. Significant visual marking in Experiment 3 indicates that a representation of the old items persisted even after their shape and luminance changed.

[4] The load effect – reduced marking when a secondary task is carried out during preview – can also be accounted for by the temporal segregation account. It is likely that the secondary task (typically a working memory task) continues to demand attentional resources after the onset of new items. This competes with the deployment of selective attention to new items.

Table 1. Slopes (ms/item) and intercepts (ms) of RT as a function of old set in Experiment 1 (standard error in parenthesis).

New set		Slope (S.E.)	Intercept (S.E.)
3	Invalid preview	27.7 (3)	610 (34)
3	Valid preview	3.6 (2)	569 (32)
3	'+' preview	29.7 (3)	572 (30)
9	Invalid preview	25.5 (10)	769 (73)
9	Valid preview	5.8 (6)	793 (78)
9	'+' preview	24.5 (4)	774 (43)

Table 2. Slopes (ms/item) and intercepts (ms) of RT as a function of old set in Experiment 2 (standard error in parenthesis).

		Slope (S.E.)	Intercept (S.E.)
Both changed color	Invalid preview	19.4 (7)	855 (43)
	Valid preview	17.4 (5)	825 (37)
Grid changed color	Invalid preview	32.6 (7)	808 (48)
	Valid preview	4.8 (5)	880 (44)
Item changed color	Invalid preview	27.4 (5)	773 (29)
	Valid preview	21.8 (6)	811 (46)
Neither changed	Invalid preview	28.9 (6)	785 (35)
	Valid preview	-2.7 (4)	841 (40)

Table 3. Mean slopes (ms/item) and intercepts (ms) for RT as a function of old set in Experiment 3 (standard error in parenthesis).

ISI		Slope (S.E.)	Intercept (S.E.)
107	Invalid preview	28.6 (7)	840 (45)
	Valid preview	12.3 (4)	817 (37)
307	Invalid preview	27.3 (5)	816 (38)
	Valid preview	16.3 (4)	795 (36)
600	Invalid preview	32.2 (6)	811 (39)
	Valid preview	16.2 (5)	775 (35)

Figure Captions

Figure 1. Results from Experiment 1. A: The number of new items = 3; B: The number of new items = 9. Error bars show standard error of the condition effect.

Figure 2. Two types of grid used in Experiment 2. The luminance of the grid may change from black to white or vice versa.

Figure 3. Results from Experiment 2: Luminance change in the old items and in the background grid. A: Old items and background grid both changed; B: Old items constant but background grid changed; C: Old items changed but background grid constant; D: Old items and background grid both constant.

Figure 4. Results from Experiment 3: Asynchronous change does not eliminate visual marking. A: Inter-stimulus Interval (ISI) = 107 ms; B: ISI = 307 ms; C: ISI = 600 ms.

Figure 5. Results from Experiment 4: Prioritizing old over new items. A: Number of old items = 6; B: Number of old items = 12.

Appendix A. Mean Accuracy and F-tests

Experiment		Condition	Old set = 3	Old set = 6	Old set = 9	
1	New set size = 3	Invalid	99 (0.7)	99 (1.0)	98 (1.3)	
		“+” Preview	98 (1.0)	98 (0.5)	99 (0.7)	
		Valid	99 (1.0)	98 (0.7)	100(0.0)	
	New set size = 9	Invalid	98 (1.7)	99 (0.7)	99 (0.5)	
		“+” Preview	99 (0.7)	99 (0.7)	99 (0.7)	
		Valid	98 (1.1)	98 (1.4)	98 (1.7)	
2	Grid change	Old items change	Invalid	100 (0.3)	98 (0.9)	99 (0.7)
			Valid	98 (0.7)	99 (0.5)	100 (0.3)
		Old items same	Invalid	99 (0.6)	99 (0.5)	99 (0.4)
			Valid	99 (0.4)	99 (0.5)	99 (0.8)
	Grid same	Old items change	Invalid	100 (0.3)	100 (0.3)	99 (0.9)
			Valid	98 (0.6)	99 (0.5)	98 (0.7)
		Old items same	Invalid	99 (0.6)	99 (0.4)	98 (0.7)
			Valid	98 (0.8)	98 (0.7)	99 (0.8)
3	ISI = 107 ms	Invalid	100 (0.3)	99 (0.4)	98 (0.6)	
		Valid	99 (0.6)	99 (0.3)	100 (0.3)	
	ISI = 307 ms	Invalid	99 (0.4)	99 (0.9)	99 (0.7)	
		Valid	99 (0.4)	99 (0.3)	99 (0.4)	
	ISI = 607 ms	Invalid	100 (0.2)	99 (0.5)	99 (0.5)	
		Valid	100 (0.3)	99 (0.8)	99 (0.4)	

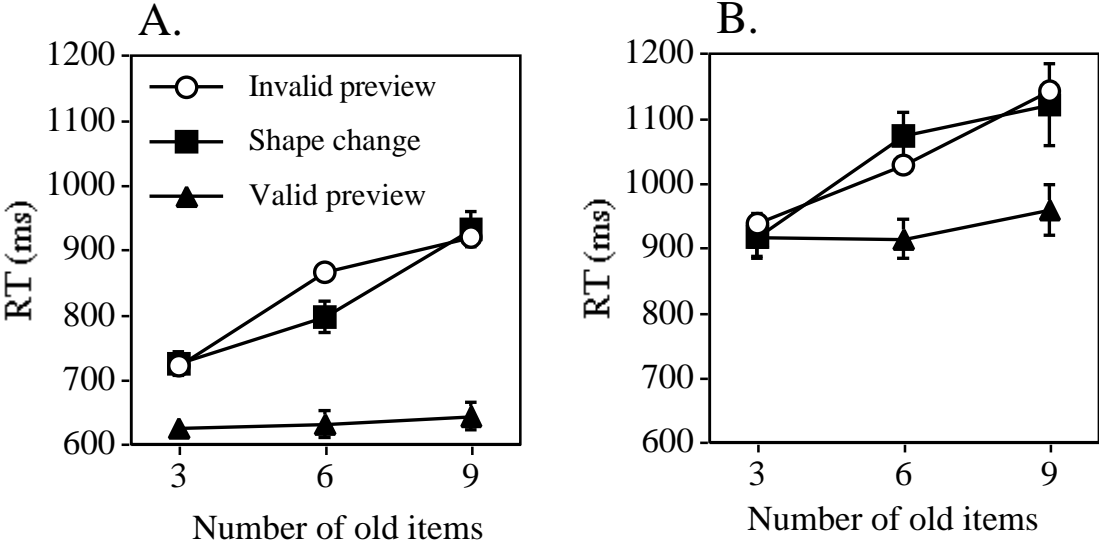


Figure 1.

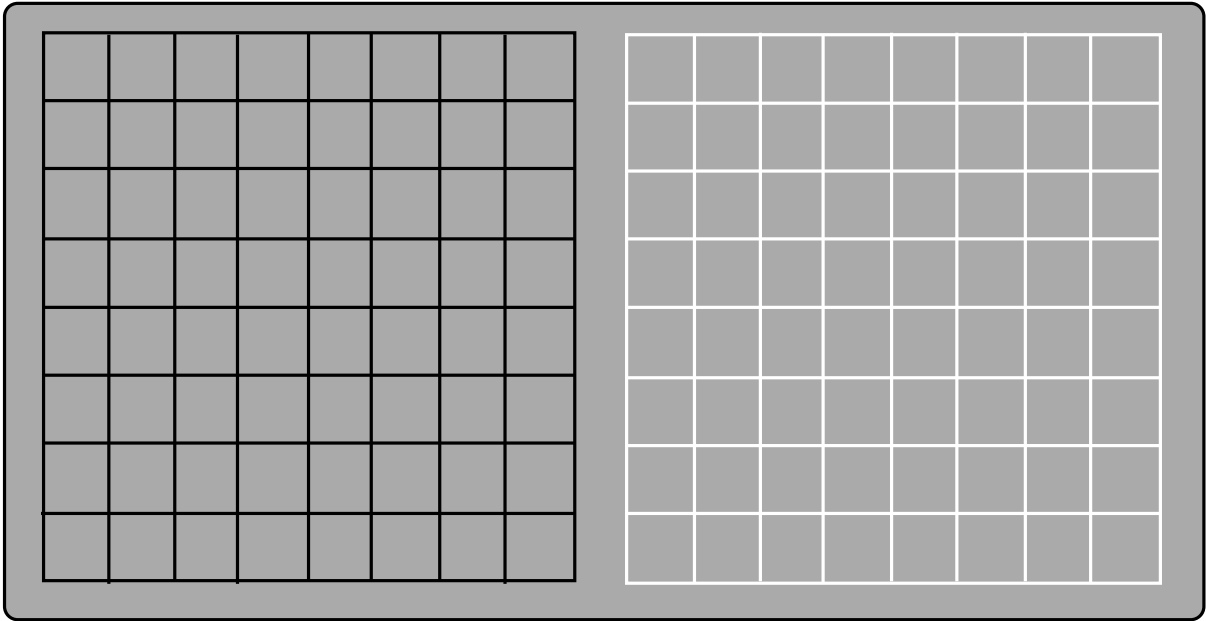


Figure 2. Jiang, Chun, & Marks

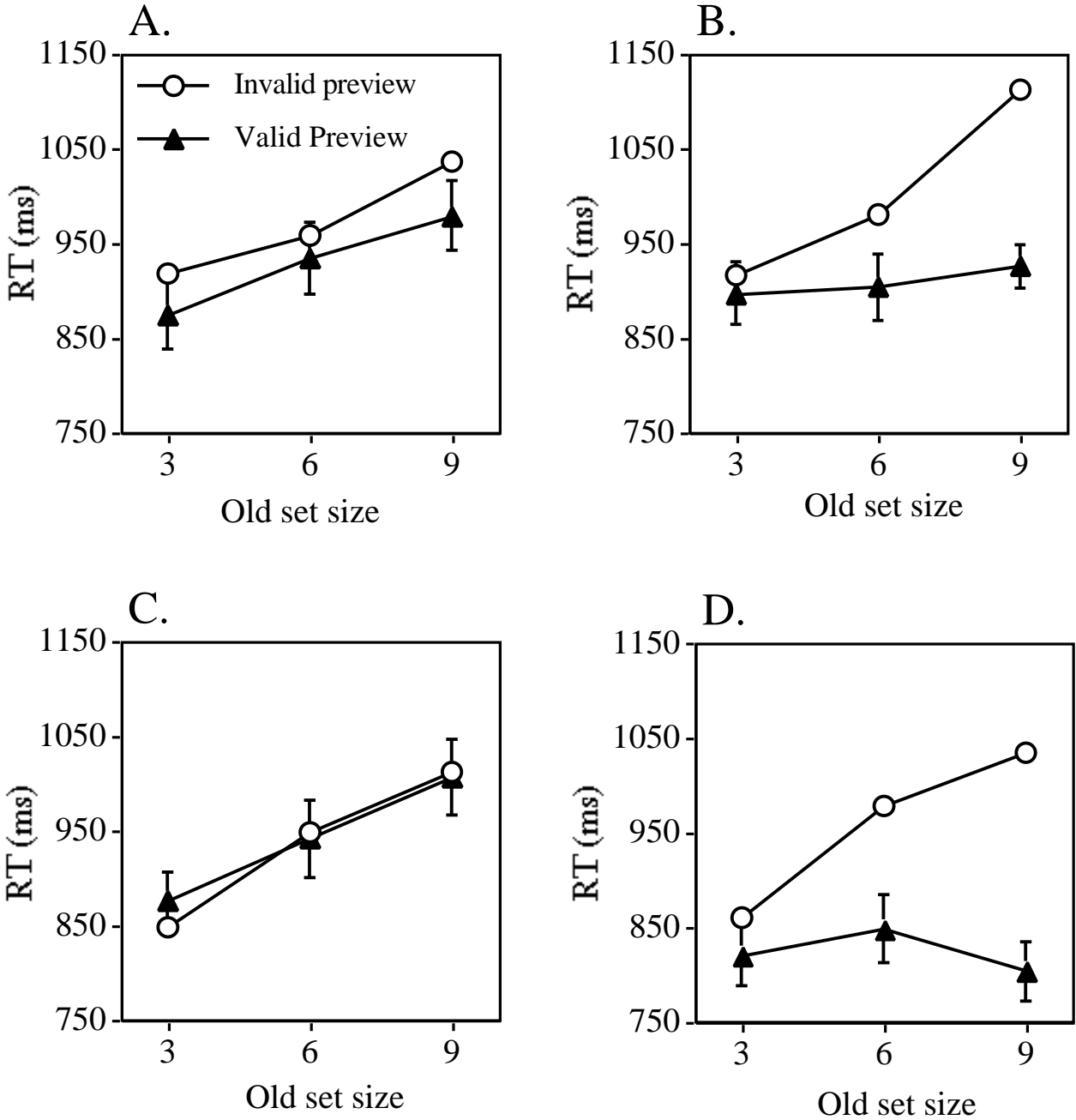


Figure 3.

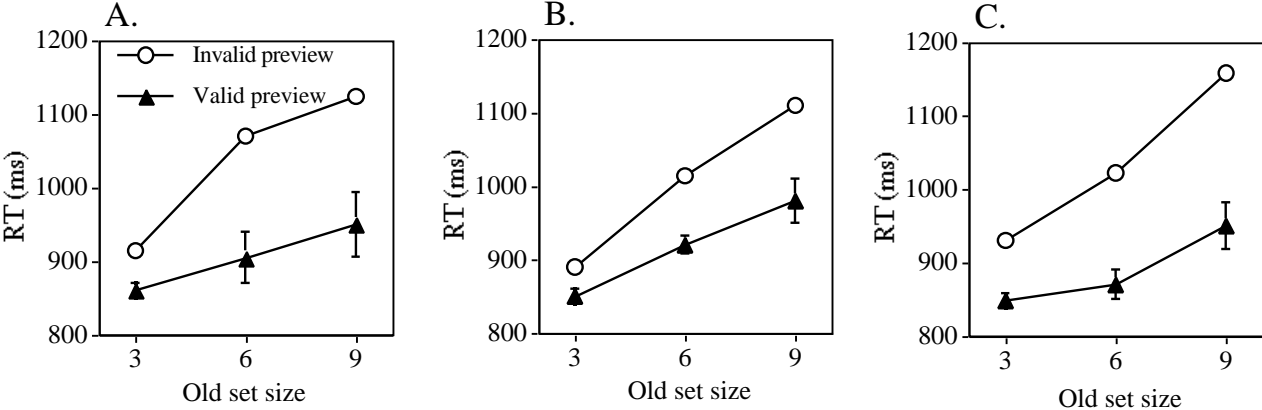


Figure 4.

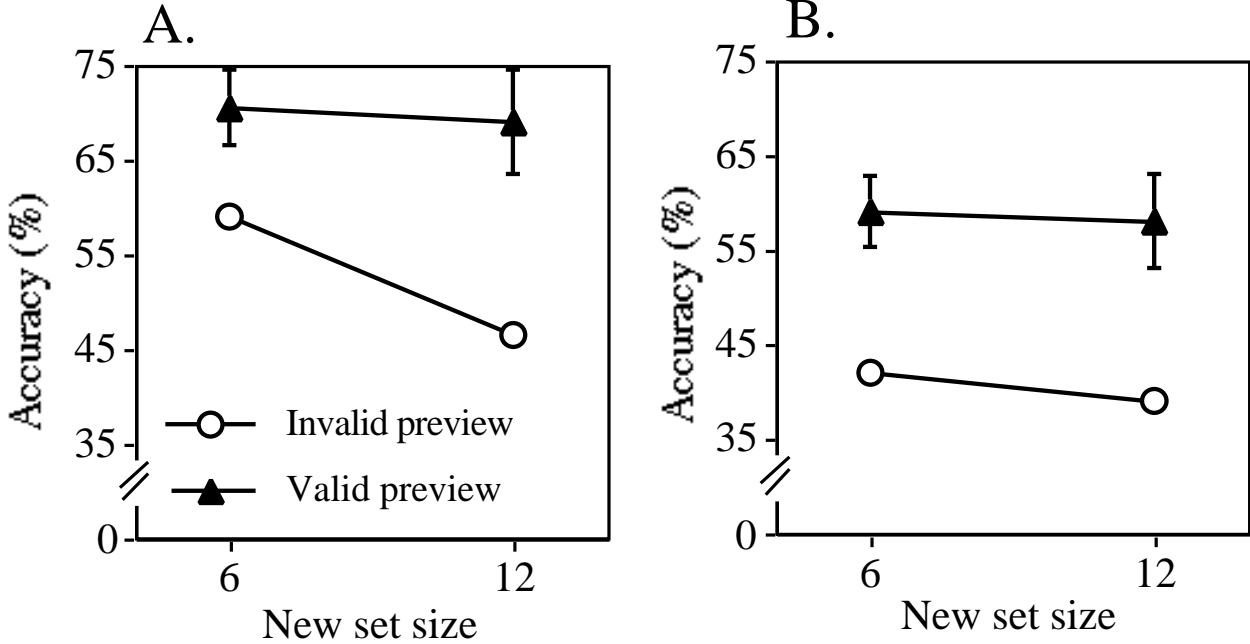


Figure 5.