Journal of Experimental Psychology:
Human Perception and Performance
2002, Vol. 28, No. 3, 717–730

0096-1523/02/$5.00 DOI: 10.1037//0096-1523.28.3.717

Visual Marking: Selective Attention to Asynchronous Temporal Groups

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In visual search, when a subset of distractors is previewed 1 s before the target and the remaining distractors, search speed is independent of the number of previewed items. This is *visual marking*. What allows old items to be marked? Four experiments show that marking is disrupted if the onset of the new items is accompanied by synchronous changes to the old items, but it is not disrupted by changes restricted to the background or by asynchronous changes to the old items. Further, behaviorally relevant old items can be prioritized over new items. Visual marking is based on temporal asynchrony between new and old items, which allows segregation of these items into 2 temporal groups. Attention is then selectively applied to 1 group.

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

As an intelligent system, the visual system has developed strategies to circumvent such limits in attention. One important strategy allocates 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 briefly review visual marking and then explain how it may reflect selective attention by temporal segregation.

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 the 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 pre-

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This research formed part of a doctoral dissertation submitted by Yuhong Jiang to Yale University. The work was supported in part by National Institutes of Health Grant DC00271-15 to Lawrence E. Marks. We thank Carol Fowler, Bradley Gibson, Frank Keil, Jeansok Kim, Derrick Watson, and Karen Wynn for their insightful comments and suggestions.

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viewed 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. In support of 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; it is reset when something new occurs at the location of the old items or when there is no advantage in inhibiting them. These authors contend visual marking is of considerable importance for survival, because it prioritizes new objects.

Basis of Visual Marking

In Watson and Humphreys's (1997) account, inhibition of old items 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, we believe it is incomplete for the following reasons.

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 flag. A bush that is darkened by a cloud passing under the sun is still the same 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 of marking 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, 1971). 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 spatiotemporal 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, 2002, 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 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. After segregation, attention is selectively deployed to the group that contains the target, which is 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 *O* among black *O*s and red *N*s. This conjunction search task typically leads to an 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

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[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 is 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 article, Watson and Humphreys (2002) 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.

able to restrict their search to the red items, and they rejected 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; 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, 1998; Blake & Yang, 1997; 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; this showed that the visual system is highly sensitive to temporal disparity. As the temporal difference between sets of items increases, perceptual segregation can become stronger.

We propose that visual marking relies heavily on temporal segregation cues. Marking can occur because the old items are out of synchrony with the new items. 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, which is 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, 2001; Watson & Humphreys, 1997). When they are 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 (a) old items become behaviorally relevant and (b) 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 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 & Humphreys, 1997).

General Method

Task

Participants searched for a rotated *T* among *L*-shaped objects. The target was present on every trial and was rotated 90° clockwise or counterclockwise. 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 1,000 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 and were 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 and may be affected by the goal of participants, the intermixing of valid and invalid preview trials may discourage participants from using the marking process. To find out, we tested 12 participants in a blocked design and 12 in a mixed design. Results showed that visual marking was identical in these two groups of participants, which suggests that a mixed design is not 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, the presentation of 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 orthogonally the size of new and old sets. The new set size was 3 or 9 and was crossed with three levels of old set size (3, 6, 9). We measured response time (RT) as a function of old set size and held constant the new set size. 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. The 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 independently the size of new and old sets.

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,* which is an indicator of visual marking.

Participants

Participants were recruited from the Yale University and Vanderbilt University participant pools. All participants were 18 to 34 years old. They provided signed consent before the test and were fully debriefed afterward. All participants 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 that were presented in a gray background. Each item subtended 0.69 cm × 0.69 cm. The line segments forming the *L*s 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 × 8 matrix that subtended 20.00 cm × 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; an equal number of left and right *T*s 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 for 1,000 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 that provided 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 experiments were conducted on a Macintosh computer (PowerPC) with a 17-in. 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 57 cm, the distance at which 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. Analyses of variance (ANOVAs) were performed on the accuracy data in each experiment and revealed no significant main effects or interactions. Analysis of accuracy is not reported any further. The Appendix 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 and reveals 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. Experiment 1 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, it tests whether prioritization is truly object oriented, as postulated by the inhibition hypothesis (Watson & Humphreys, 1997). Studies of object files (Kahneman et al., 1992) and attentional capture (Jonides & Yantis, 1988; Yantis & Jonides, 1984) suggest that spatiotemporal parameters define an old object's continuity and the onset of new objects. In marking tasks, old objects do not undergo spatiotemporal changes (old items remain old), so their shape changes should be ignored by the object-oriented system that is postulated by the inhibition hypothesis. However, Watson and Humphreys demonstrated that visual marking was disrupted by luminance change in the old items, which suggests 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 Experiment 1 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 *L*s 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

RTs are shown in Figure 1. When the number of new items was held 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 3, and it was 5.8 ms/item when the new set size was 9. In both cases, RT was affected little by the number of old items, which indicates that as many as 9 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 3 and 24.5 ms/item when it was 9. 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.

When RT was used as the dependent variable and new set size, old set size, and preview condition were used as the independent variables, an ANOVA showed significant main effects of new set size, $F(1, 5) = 201.87$, $p < .01$, with longer RT as the number of new items increased; old set size, $F(2, 10) = 32.42$, $p < .01$, with longer RT as the number of old items increased; and preview condition, $F(2, 10) = 37.97$, $p < .01$, 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, $F(2, 10) = 6.02$, $p < .02$. 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, $t(5) = 0.45$, $p > .30$. 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, 2002). 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., 2001b). To summarize, Jiang et al. revealed that new set size affects the preview benefit in overall RT and potentially masks 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 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.

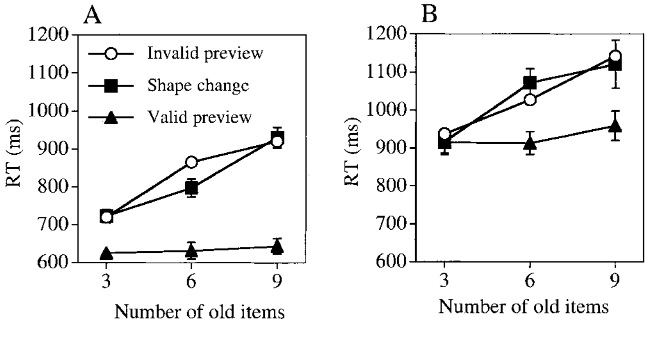

Figure 1. Results from Experiment 1. A: Number of new items was 3. B: Number of new items was 9. Error bars show standard errors of the condition effect. RT = response time.

Table 1

Slopes (Milliseconds per Item) and Intercepts (Milliseconds) of Response Time as a Function of Old Set in Experiment 1

New set	Preview condition	Slope	*SE*	Intercept	*SE*
3	Invalid	27.7	3	610	34
3	Valid	3.6	2	569	32
3	Shape change	29.7	3	572	30
9	Invalid	25.5	10	769	73
9	Valid	5.8	6	793	78
9	Shape change	24.5	4	774	43

The interaction between new set size and old set size was not significant, $F(2, 10) < 1$, and shows additivity of these factors. The interaction between preview condition and old set size was significant, $F(4, 20) = 6.64$, $p < .01$, and reflects 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 that contrasted the three preview conditions in pairs. When the invalid preview and the shape change conditions were compared, none of the effects involving preview condition was significant (all *p*s > .15). When the valid preview and the invalid preview conditions were compared, the main effect of preview condition was significant, $F(1, 5) = 393.73$, $p < .01$, as were the interactions between preview condition and new set size, $F(1, 5) = 9.84$, $p < .03$, and between preview condition and old set size, $F(2, 10) = 8.13$, $p < .01$. An identical pattern was found when the valid preview and the shape change conditions were compared: preview condition, $F(1, 5) = 35.34$, $p < .01$; Preview Condition × New Set Size, $F(1, 5) = 6.58$, $p < .05$; and Preview Condition × Old Set Size, $F(2, 10) = 17.65$, $p < .01$. Thus, visual marking was present in the valid preview condition but was 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; this was significantly shallower than the slope of RT in the invalid preview condition. By comparison, in the shape change condition, where crosses were previewed but changed into *L*s 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 a preview of 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, which allows new items 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, Experiment 1 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 spatio-temporal continuity is preserved (as it always was 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 in the inhibition hypothesis allows it to account for the elimination of visual marking in Experiment 1. However, when inhibition is made flexible, it appears to damage the spirit of the inhibition hypothesis, which is 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 in the shape change condition. Such a modification 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 Humphrey'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: 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, 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 when its object-oriented bias is weakened, 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.

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 change luminance and when the background changes luminance. Prediction from the inhibition hypothesis depends on what counts as an old item location. If the location is highly specific to the region directly occupied by an item, then a background grid change may not disrupt marking. 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 Experiment 2 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 s 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.

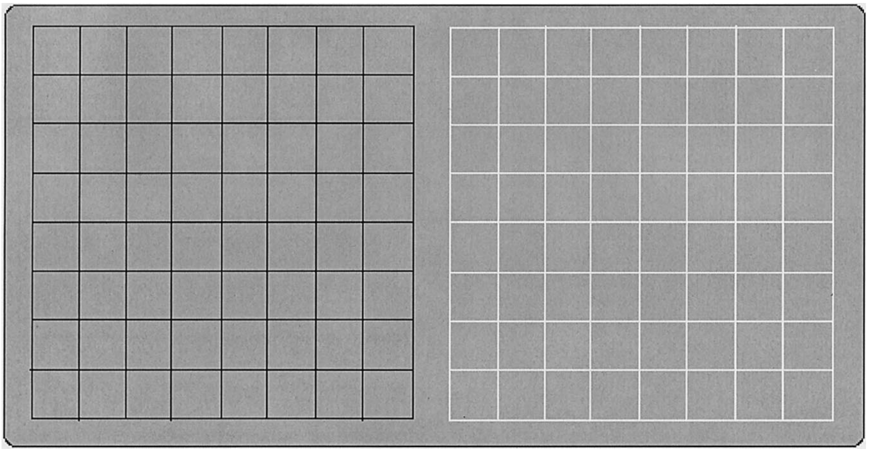

Figure 2. Two types of grid used in Experiment 2. The luminance of the grid may change from black to white or vice versa.

Results

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, $F(1, 17) = 14.39$, $p < .01$; when the number of old items increased, $F(2, 16) = 44.60$, $p < .01$; and when the preview was invalid, $F(1, 17) = 43.40$, $p < .01$. The detrimental effect of changing background luminance was greater when the luminance of the old items did not change; there was a significant interaction between item luminance and grid luminance, $F(1, 17) = 5.60$, $p < .03$. The underadditivity occurred equally at all three set sizes, which was shown by the nonsignificant 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, $F(2, 16) = 7.06$, $p < .01$. Change in the background grid did not interact with preview condition, $F(1, 17) < 1$, or with old set size, $F(2, 16) < 1$. The three-way interaction among background change, preview condition, and old set size was not 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, $F(1, 17) = 15.24$, $p < .01$. This was especially true when the background did not change luminance; this is reflected by a marginally significant three-way interaction among item luminance, grid luminance, and condition, $F(1, 17) = 3.20$, $p < .09$. 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,

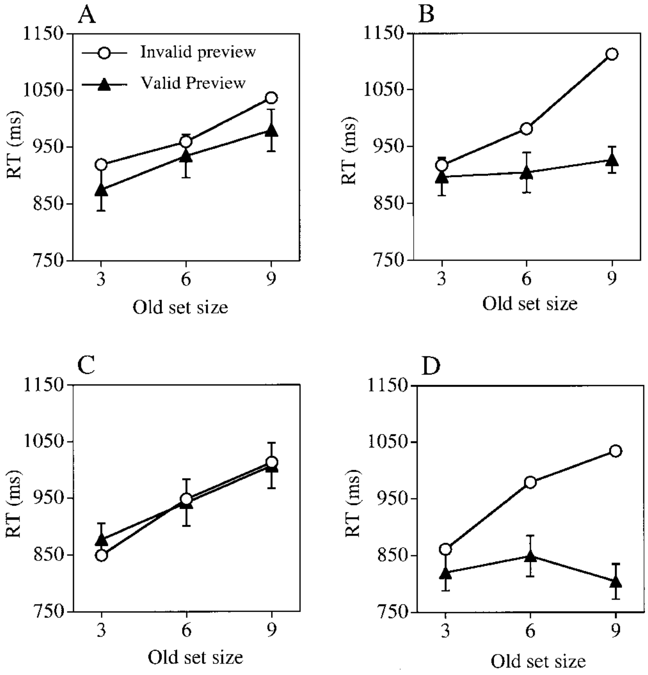

Figure 3. Results from Experiment 2. Luminance change in the old items and in the background grid. A: Both old items and background grid changed. B: Old items remained constant but background grid changed. C: Old items changed but background grid remained constant. D: Both old items and background grid remained constant. RT = response time.

Table 2

Slopes (Milliseconds per Item) and Intercepts (Milliseconds) of Response Time as a Function of Old Set in Experiment 2

Luminance	Preview condition	Slope	*SE*	Intercept	*SE*
Item and grid changed color	Invalid	19.4	7	855	43
Item and grid changed color	Valid	17.4	5	825	37
Grid changed color	Invalid	32.6	7	808	48
Grid changed color	Valid	4.8	5	880	44
Item changed color	Invalid	27.4	5	773	29
Item changed color	Valid	21.8	6	811	46
Neither changed color	Invalid	28.9	6	785	35
Neither changed color	Valid	−2.7	4	841	40

old set size, and item luminance change, $F(2, 16) = 7.76, p < .01$. 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, $F(1, 17) = 49.93, p < .01$; old set size, $F(2, 16) = 9.30$, $p < .01$; and their interaction, $F(2, 16) = 7.87, p < .01$, 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, $F(2, 16) = 19.92, p < .01$. The interaction between preview condition and old set size was not significant, $F(2, 16) = 1.02, p > .35$. 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 change, the main effect of preview condition was significant, $F(1, 17) = 19.08, p < .01$, as was the main effect of old set size, $F(2, 16) = 8.37, p < .01$; and their interaction, $F(2, 16) = 7.20, p < .01$. Thus, a change in 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, $F(1, 17) = 3.99, p < .06$. The main effect of old set size was significant, $F(2, 16) = 7.17, p < .01$, but the interaction between preview condition and old set size was not significant, $F(2, 16) < 1$. 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. A change in the luminance of the background grid did not eliminate visual marking; this is 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 as a region 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 visual marking was not affected by luminance or color change (Watson & Humphreys, 2002). 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 that 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). 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 (2002) study but were disruptive in ours. One factor may be the saliency of the changes between studies. Our luminance changes involved contrast reversals, whereas 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 (2002). The major difference was that Watson and Humphrey used isoluminant colors, whereas we did not control for luminance. However, according to their luminance change experiment, luminance changes should not matter. 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 Experiments 3 and 4.

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 (*L*s) and rotated the *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 interstimulus 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, and then we 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

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 and showed faster RT in the valid preview condition, $F(1, 19) = 48.00$, $p < .01$. The main effect of old set size was significant also and showed a nonflat slope, $F(2, 18) = 29.73$, $p < .01$. The interaction between preview condition and old set size was significant, $F(2, 18) = 4.03$, $p < .04$, and showed efficient visual marking.

The interaction between ISI and condition was not significant, $F(2, 18) = 2.74$, $p > .09$. 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, $Fs(1, 19) > 21.16$, $ps < .01$. 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, $F(2, 18) = 4.23$, $p < .03$. The interaction was marginally significant when ISI was 107, $F(2, 18) = 3.06$, $p < .07$, but was 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 an 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 do not think it jointly accounts 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

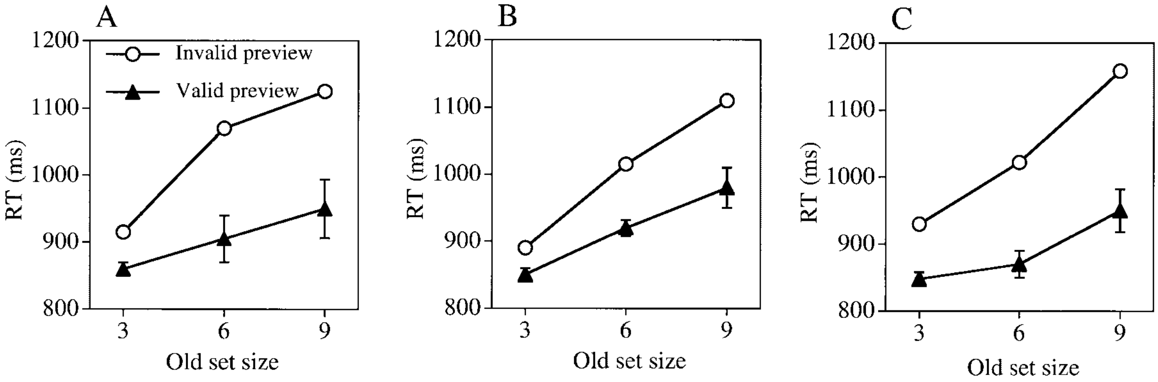

Figure 4. Results from Experiment 3. Asynchronous change does not eliminate visual marking. A: Interstimulus interval (ISI) was 107 ms. B: ISI was 307 ms. C: ISI was 600 ms. RT = response time.

Table 3
Mean Slopes (Milliseconds per Item) and Intercepts (Milliseconds) for Response Time as a Function of Old Set in Experiment 3

ISI (ms)	Preview condition	Slope	*SE*	Intercept	*SE*
107	Invalid	28.6	7	840	45
107	Valid	12.3	4	817	37
307	Invalid	27.3	5	816	38
307	Valid	16.3	4	795	36
600	Invalid	32.2	6	811	39
600	Valid	16.2	5	775	35

Note. ISI = interstimulus interval.

synchrony cues, it should predict that marking will quickly reset for both synchronous change conditions (Experiments 1 and 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 underspecified in explaining when visual marking is disrupted.[3] In our view, a reset account 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 the attribution of 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 the reversal in the roles of old and new items, making the old items behaviorally important and the 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 after temporal segregation. Thus, if new and old information is desynchronized, participants should be able to selectively disregard irrelevant information, whether it is 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 remains 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. 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 a 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, which contained several *L*s and one rotated *T*, were presented. The new items, all rotated *T*s of random orientations, were added to the display 150 ms later. The presentation of *T*s 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 s, followed by the addition of old items. New items were added 150 ms later. The old items contained several *L*s and one *T* rotated to one of four orientations (up, down, left, or right). The new items contained all *T*s rotated by 0°, 90°, 180°, or 270°. The target was the unique

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[3] One may find visual marking under the condition in which ISI was equal to 107 ms surprising, given that past studies have shown that a preview of 300–400 ms is needed for marking to reach asymptote. In two additional experiments, we tested the effect of preview duration on visual marking (Jiang, 2000). We presented observers with a preview display of 107, 307, or 600 ms, followed by the addition of new items and the target. We failed to observe visual marking at a preview duration of 107 ms and confirmed that approximately 300 ms 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 1,000 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.

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 they were not sure. To lower the level of chance performance, four possible orientations of *T*s 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

Figure 5 shows the average accuracy of the 8 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. $F(1, 7) = 86.01$, $p < .01$; 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, $F(1, 7) = 5.71$, $p < .05$, indicating that accuracy dropped as the number of new items increased. The main effect of old set size was also significant, $F(1, 7) = 18.05$, $p < .01$. The smaller the old set size, the higher the participants' accuracy of identifying the unique old *T*. This result is expected given that there was a larger probability for the participants to spot the old *T* within the 150-ms time window when there were fewer old distractors.

The interaction between preview condition and new set size was significant, $F(1, 7) = 6.73$, $p < .04$. 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 the old set size was 6 rather than 12, possibly because performance in the invalid preview condition approached floor when the 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, $F(1, 7) < 1$. Neither the interaction between preview condition and old set size, $F(1, 7) < 1$, nor the interaction between new set size and old set size, $F(1, 7) = 1.08$, $p > .33$, was significant.

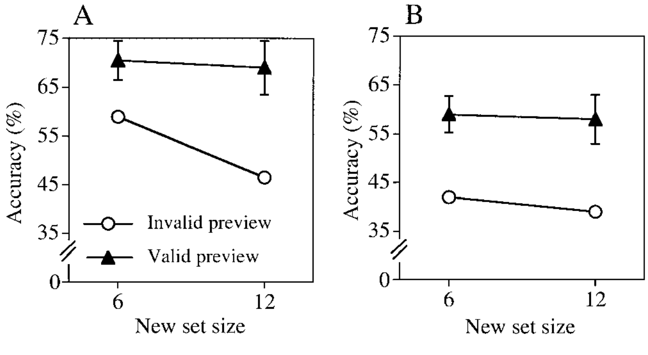

Figure 5. Results from Experiment 4. Old items prioritized over new items. A: Number of old items was 6. B: Number of old items was 12.

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 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 Experiment 4 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 the deprioritization of old items is more efficient than the deprioritization of new items. But this possibility awaits further, direct tests. We favor the temporal segregation hypothesis, because it provides a single framework to account for the deprioritization of 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.

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[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.

The second difference concerns the role of inhibition. The inhibition account proposes a special mechanism to mark and suppress old items 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 is 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. Rejection of the inhibition hypothesis is difficult, because it is underspecified in some ways and is overly flexible in others. Therefore, our goal is to point out how the inhibition account needs to be revised to explain our data. The following discussion provides a summary.

First, Experiments 1 and 2 demonstrate the importance of temporal segregation. Visual marking was 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 spatiotemporal 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 is 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 was only disrupted by changes within the objects themselves, rather than by the general location of marked items. In other words, our data refine the inhibition hypothesis by 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 that occurs 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, the reapplication of 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 Experiment 3, 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 assumption that changes in the old items selectively affect the maintenance and not the setup 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, after 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 deprioritization of 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 which calls into question 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.

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Appendix

Mean Accuracy

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

Note. Standard errors appear in parentheses. ISI = interstimulus interval.

Received December 6, 2000
Revision received September 18, 2001
Accepted September 24, 2001 ■