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The Maintenance of Apparent Luminance of an Object

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Results from luminance discriminations with objects defined by apparent motion suggest an object-specific temporal integration of luminance. Further experiments suggested that this integration is weighted to favor the initial display of an object and involves the percept of surface reflectance (lightness). These results are consistent with the object-file metaphor suggested by D. Kahneman, A. Treisman, and B. Gibbs (1992), in which an object's perceived initial surface reflectance is assigned and maintained in an object file. A strategy is proposed in which the intrinsic properties of an object are assumed not to change over time. As intrinsic properties are generally invariant and possibly difficult to compute, this strategy would have the advantage of relatively high accuracy at relatively low computational cost.

When considering the general evolutionary question of what matters to an animal in order to survive, three basic answers seem apparent. It must eat, it must avoid being eaten, and, finally, for the good of its species, it must reproduce. All these basic activities are done to or are done by other objects in the animal's environment, whether these objects are prey, predator, or a potential mate. To accomplish these basic activities, it is imperative that the correct object is chosen for the appropriate activity. Thus, from an adaptive view, a significant part of an animal's activity depends on the accurate identification and recognition of these objects.

Because objects have such practical importance, it would follow that objects should have equal functional and structural importance in humans' behavioral and mental processes, and it appears that this is the case. It is well known, for example, that one of the two major visual pathways in the brain is concerned primarily with object recognition (Farah, 1990; Goodale & Milner, 1992; Maunsell & Newsome, 1987; Ungerleider & Mishkin, 1982; Van Essen & Maunsell, 1983). Other examples are the object-specific effects on attention found more recently by several authors (e.g., Baylis & Driver, 1993; Behrmann & Moscovitch, 1994; Duncan, 1984; Egly, Driver, & Rafal, 1994; Tipper & Behrmann, 1996). Also, given the practical importance of objects, it would seem that understanding how the brain deals with objects would seem to be a necessary link in understanding how the brain works in general.

In the current experiments, we studied how the brain deals with objects through time, or how an object is represented after it has been found and identified. Specifically, these studies addressed how the property of luminance of an object is represented through time. The paradigm we used was based on a set of experiments by Kahneman, Treisman, and Gibbs (1992), who studied a long-range, apparent-motion stimulus similar to a Ternus (1938) display. Ternus showed that within two stimulus displays that give the appearance of coherent motion of a group of dots, the problem of identifying the corresponding dots across the two displays is determined by the relative position of each dot to the group, overriding otherwise effective cues such as proximity.

In Kahneman et al. (1992), two brief displays were shown in rapid succession (see Figure 1). Each display contained two letters, arranged to give the appearance of two objects moving either to the left or to the right. The direction of apparent motion was determined by the nontarget letter in the second display, and all other locations of the letters were identical. The task of the observer was to identify the target letter in the second display. Reaction times were faster if the letter in the first display that was linked to the target letter by apparent motion was the same as the target letter, compared with cases in which the linked letter in the first display differed from the target letter. These results suggest an object-specific integration process over time across the two displays for the identity of the letter.

To describe this integration process, Kahneman et al. (1992) have suggested the metaphor of an object file containing a list of attributes, such as its identity and shape (see also Kahneman & Treisman, 1984). An empty object

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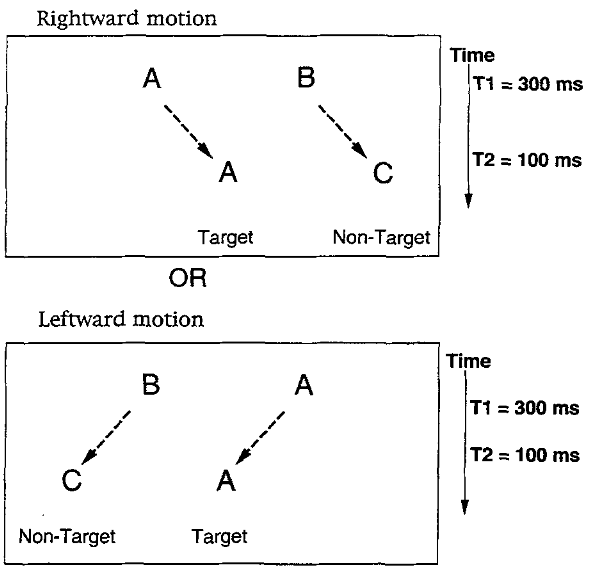

Figure 1. Stimulus configurations for Kahneman, Treisman, and Gibbs (1992). Each trial consisted of two display intervals shown in rapid succession; both display intervals are shown in the figure. T1 = time for first display interval (300 ms); T2 = time for second display interval (100 ms). The dashed arrows indicate direction of apparent motion. The upper figure shows a trial in which letters appeared to move to the right; the lower figure shows a trial in which letters appeared to move to the left. All stimulus locations were identical except for the nontarget letter (Letter *C* in the figure) in the second display interval. The observers' task was to name the target letter in the second display interval (Letter *A* in the figure) as quickly as possible. The figure shows an example of the condition in which the identity of the target letter did not change from the first to the second interval.

file is created for each new object, which is filled as the different attributes are determined and assigned to the object file. The filled object file then is kept over time, maintaining the assigned values for each attribute.

In the current studies, we assessed the possibility of a similar object-specific integration process for the luminance of an object. As in Kahneman et al. (1992), two displays were shown in rapid succession so that observers perceived two objects moving by long-range apparent motion, either down and to the left or down and to the right (see Figure 2). Having a single object defined as two stimuli presented sequentially allows the luminance of the object to be manipulated from the first to the second display interval. The first display appeared for 300 ms, and the second display appeared for 100 ms. Observers judged the luminance of targets in the second display interval only. These targets could be either of high or low luminance and differed only slightly from each other, so that observers were required to perform a fine discrimination task. The luminance of the square in the first interval that was linked by apparent motion to the target square in the second interval could either change (i.e., low → high or high → low) or stay the same (i.e., low → low or high → high); these two conditions are called *change* and *no change,* respectively.

The suggestion is that the luminance of an object is integrated across the display intervals over time, predicting that the initial computation of luminance will be carried over to succeeding intervals. Thus, judgments of the luminance of the target in the second display should be biased by the luminance of the target in the first display. In conditions in which the luminance of an object changes from the first to the second display interval, this bias favors making an incorrect response. For conditions in which the luminance does not change from the first to the second interval, the bias favors making the correct response. Thus, performance in the no-change condition should be better than performance in the change condition.

Overview of Experiments

Experiment 1

The first experiment tested the basic hypothesis that judgments of the luminance of an object are biased toward the previous luminance of the same object. Observers viewed two displays that were made to appear as objects moving by apparent motion and judged the luminance of a target object in the second display only. Worse performance is predicted when the luminance of the target object changes, as opposed to the condition in which the luminance of the target object does not change.

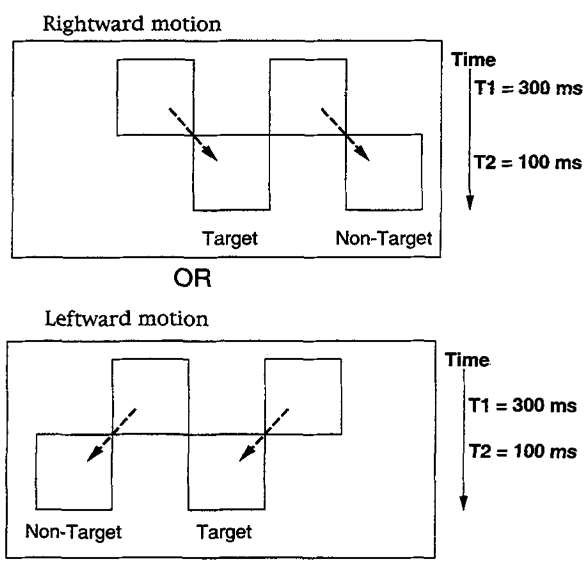

Figure 2. Stimulus configurations for Experiment 1. Each trial consisted of two display intervals shown in rapid succession; both display intervals are shown in the figure. T1 = time for first display interval (300 ms); T2 = time for second display interval (100 ms). The squares were 1° of visual angle. The dashed arrows indicate direction of apparent motion. The upper figure shows conditions in which squares appeared to move to the right; the lower figure shows conditions in which squares appeared to move to the left. All stimulus locations are identical except for the nontarget square in the second display interval. Observers judged the luminance of the target square in the second display interval.

Experiment 2: Object Specificity

In Kahneman et al. (1992) and in Experiment 1 of the current study, the linkage by apparent motion between the stimuli in the two display intervals was unambiguous; thus, the objects defined across the two displays were also unambiguous. In Experiment 2, the object specificity of the luminance effect was studied further. A condition was added in which the linkage by apparent motion between the squares in the first and second displays was made ambiguous, and observers could not clearly define objects by apparent motion (*unlinked*). Thus, any object-specific component of the effect from the luminance in the first display on the judged luminance of the second display found in Experiment 1 should be removed in the unlinked condition. This should lead to performance in the unlinked condition that is intermediate between the change and no-change conditions.

Experiment 3: Equal Versus Weighted Temporal Integration of Luminance of an Object

Several examples of temporal integration processes for luminance have been described. One such example is known as Bloch's law (Barlow, 1958), which occurs primarily in the retina and affects detection thresholds of relatively brief dim targets in complete darkness. A longer temporal integration process with integration times up to 1 s also has been found for detecting targets in visual noise for both static and moving stimuli (Eckstein, Whiting, & Thomas, 1996). For both of these integration processes, each time interval is weighted either equally or symmetrically with respect to the temporal bounds of the integration. The object-file metaphor, however, suggests an integration process that is weighted unequally with respect to time, in which the initial intervals are weighted more heavily than the succeeding intervals.

Experiment 3 assessed the possibility that any object-specific integration of luminance found in the previous experiments was weighted equally with respect to time. Such a finding would argue against a description of the integration process in terms of an object-file metaphor.

An integration process weighted equally through time predicts a bi-directional effect, with both the initial and succeeding intervals having an equal effect upon the other. Experiment 3 tested these predictions by having observers make judgments with the target appearing in either the first or the second interval. The target displays appeared for 100 ms, and the nontarget display appeared for 300 ms. In this case, an integration process weighted equally with respect to time predicts equal effects of the nontarget interval on targets judged in either the first or the second interval.

Experiments 4a and 4b: Relative Contrast (Reflectance Simulation)

For the first 3 experiments, the initial absolute luminance and the initial relative contrast of the target object were perfectly confounded, and thus any effects could be due to either attribute. For very simple viewing conditions such as those in Experiments 1 to 3, the perception of light intensity is primarily based on luminance, and the perception of surface reflectance is primarily based on relative contrast. Thus, any effect found in the first 3 experiments probably can be attributed to the observers' perception of either light intensity or surface reflectance. Typically, these two percepts are labeled *brightness* and *lightness,* respectively, when discussing achromatic (white–gray–black) stimuli.

A consideration of the nature of surface reflectance and light intensity suggests that it would be advantageous to maintain the perceived surface reflectance of an object, as this is an intrinsic property of an object that is usually invariant through time, whereas light intensity is a combination of surface reflectance and the extrinsic property of illumination. In Experiment 4, we attempted to distinguish between the effects of perceived surface reflectance and perceived light intensity by simulating reflectance changes to the target. We assumed a simple viewing environment for the displays of the experiment, in which the targets and background were achromatic, coplanar, perpendicular to the viewer, and illuminated equally by a single illuminant. The surface reflectance of the target was simulated by changing the luminance of the background and the luminances of the objects concurrently between intervals so that the relative contrast of the target luminance with respect to the background luminance was fixed. Although in a natural viewing environment, there are many cues to perceived surface reflectance, such as orientation, shading, and specularity, for a simple viewing environment, relative contrast effectively simulates the surface reflectance of an object.

The design of Experiment 4a was similar to Experiment 2, except that the change and no-change conditions referred to changes of relative contrast. In all cases, the luminance of the background and the target changed from the first to the second interval so that absolute luminance could not be used as a cue for discrimination. The luminances were changed so that the relative contrast between the background and the target remained consistent and so that relative contrast was the relevant discrimination cue. Also, the target's relative contrast across the two intervals was manipulated so that the relative contrast either changed across the two intervals (change) or was constant across the two intervals (no change). Again, we predicted that the no-change condition would show better performance than the change condition, with an unlinked condition intermediate between these two conditions. If the relative contrast in the first interval biased the judgments in the second interval, then the results would suggest that any effects in the previous experiments were related to relative contrast.

In Experiment 4b, a subset of the conditions in Experiment 4a were reanalyzed, in which the effects of the initial absolute luminance of the target were compared directly against effects of the initial relative contrast of the target. In this analysis, the *same condition* was defined as both a change condition in terms of relative contrast and as a no-change condition in terms of luminance. *Another condition* was defined as the opposite condition—as a no-change condition in terms of relative contrast and as a change condition in terms of luminance. Thus, effects of relative contrast and luminance had opposing influences on the results of this analysis, and the results indicate which attribute had the predominant effect.

Experiment 1

Method

The method for all the experiments was similar to the first experiment. Besides the different conditions, main differences in procedures among experiments involved equipment, calibration procedures, observers, and specific parameters, such as number of trials, absolute luminance, and contrast levels.

Participants. Five observers, 2 women (E.C.T., 23 years; S.E.D., 21 years) and 3 men (M.E., 26 years; M.J.H., 23 years; S.S.S., 29 years), participated in Experiment 1. All had normal or corrected-to-normal visual acuity and normal color vision as assessed by the Ishihara color blindness plates. Observers S.S.S. and M.E. are authors; the other observers were naive initially to the purpose of the experiment.

Apparatus. In Experiment 1, observers were placed on a headrest and they binocularly viewed stimuli presented on a CRT monitor (BARCO CDCT 5137, Duluth, Georgia) that was 26.6 × 21.0 cm in size, which was driven by a CAT 1631 24-bit (8 bits/channel) graphics systems on a Cromemco RS-2 computer. The stimuli were monochromatic, with CIE (Commission Internationale de l'Eclairage, 1932) coordinates of $x = .33$ and $y = .33$, which is approximately gray. Calibrations were performed with a Spectra Pritchard photometer (Model 1970-PR) calibrated with a standard illuminant (100 Footlambert Gamma Model 220 Standard Lamp source A; tungsten, color temperature 2854 K, 324.6 cd/m^2) and Wratten Filters #60 (red), #23A (green), and #47 (blue) closely matching the chromaticity of the phosphors of the monitor. Luminances of each phosphor were fit to polynomial and logarithmic polynomial functions that were similar to gamma functions, as described in Stanislaw and Olzak (1990).

Viewing distance was 120 cm, which gave a viewing size of 12.6° × 10° visual angle for the monitor. Experiments were performed in a darkened room with blackened walls to reduce spurious reflections.

Procedure. In the first experiment, observers viewed two displays per trial. In each display, there were two squares, each 1° of visual angle in size and 1° of visual angle apart, presented near the center of the display. The first display appeared for 300 ms; the next display appeared for 100 ms immediately following the first display, or with a delay of 16.7 ms (a single refresh of the computer display at 60 Hz).

The temporal and spatial arrangement of the two displays were designed to induce the apparent motion of two squares—either downward and to the left or downward and to the right (see Figure 2). The direction of apparent motion was controlled by the placement of the nontarget square; the spatial locations of all other squares were the same from trial to trial. The corners of the squares in the two display intervals abutted, but otherwise there was no spatial overlap between the squares in the two displays. The direction of apparent motion was randomized, with equal number of trials with leftward and rightward movement.

Observers were instructed to judge the luminance of the target square as either the darker or lighter target in the second display interval only. No specific instructions were given to the observer regarding the first display interval or regarding the perceived light intensity or the perceived surface reflectance of the target. The target square always was located horizontally between the two squares in the first display; thus, observers knew the location of the target on the basis of its position relative to the squares in the first display. In half the trials, the luminance of the target square was low (14.32 cd/m^2), and in the other half of the trials, the luminance of the target square was high (15.07 cd/m^2); the order of presentation was randomized. The background luminance was 18.84 cd/m^2, and the luminance of the nontarget square always equaled the mean (14.70 cd/m^2) of the low- and high-luminance values.

In all experiments, observers judged the luminance of the target square using a 4-point rating scale that indicated the luminance of the target and confidence of the judgment. For example, ratings could represent the following: 1 = *low luminance, high confidence,* 2 = *low luminance, low confidence,* 3 = *high luminance, low confidence,* and 4 = *high luminance, high confidence.* These data were analyzed by signal detection methods (Green & Swets, 1966) to give values of d', a measure of accuracy describing the distance between two hypothetical normal distributions representing the internal response to the two target stimuli. d' is in standard deviation units, or z scores, and typically varies between 0, which is chance performance, and 3, which is nearly perfect performance.

Figure 3 shows all the conditions for rightward movement in Experiment 1. In the first display interval, the luminances of the two squares were low and high. Locations of the low and high squares were randomized; for half the trials, the left square was low, and for the other trials the right square was low. The target square in the second display was linked by apparent motion either to a square of low or high luminance. Thus, the luminance of the object defined by the target square and its linked square in the first interval could either stay the same, from low → low or high → high, or change, from high → low or low → high. These two conditions were called no change and change, respectively.

During each session, the no-change and change conditions were intermixed randomly. Each session contained 160 trials, 80 trials for each condition. Trials with no response within 2 s were re-presented randomly later in the session. Each session was analyzed to give separate d' scores for the no-change and change conditions, and each observer participated in six sessions. An alpha level of .05 was used for all statistical analyses, which were

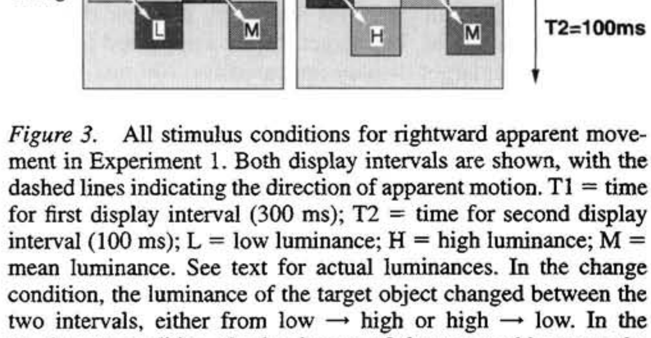

Figure 3. All stimulus conditions for rightward apparent movement in Experiment 1. Both display intervals are shown, with the dashed lines indicating the direction of apparent motion. T1 = time for first display interval (300 ms); T2 = time for second display interval (100 ms); L = low luminance; H = high luminance; M = mean luminance. See text for actual luminances. In the change condition, the luminance of the target object changed between the two intervals, either from low → high or high → low. In the no-change condition, the luminance of the target object was the same for the two intervals, low → low or high → high.

performed using the statistical package GANOVA (Woodward, Bonett, & Brecht, 1990).

Across all experiments, the relative contrasts of the stimuli (stimulus luminance–background luminance) varied from 0.745 to 0.800. Depending on the contrast level, targets could appear self-luminous, (contrasts levels above 1.7), white (contrasts from 1.1 to 1.7), gray (contrasts from 0.5 to 0.9), or black (contrasts below 0.5), for the relatively simple stimulus configurations in these experiments (Bonato & Gilchrist, 1994; Heggelund, 1974). The contrast levels were chosen to give the appearance of gray surfaces that were darker than the background and to avoid the percepts of luminous white and black objects. The perception of self-luminous objects qualitatively may differ from surfaces, and the percepts of white and black may hold unique status within the visual system (e.g., Bonato & Gilchrist, 1994; Gilchrist & Bonato, 1995).

Results and Discussion

Figure 4 and Table 1 summarize the results for the 5 observers in the first experiment. For all observers, there was a large difference in d' between the no-change and change conditions, with the no-change condition having better performance by about 0.7 to 2.0 d' units. As shown by the last column of Table 1, the results of t tests for each observer found that all differences were significant. Also, when comparing performance in the no-change and change conditions within each session, performance in the no-change condition was better relative to the change condition for 29 out of 30 sessions across all observers.

These data suggest that observers' judgments of luminance in the second display were biased by the initial luminance of the square linked to the target by apparent motion. It is possible but unlikely that the target object appeared on the same location on the retina across the two intervals in this paradigm. First, the spatial locations of the stimuli in the two intervals did not overlap. Second, the direction of motion was randomized, and the target duration was brief (100 ms), so it is unlikely that observers made predictive eye movements to track the moving target. Thus, the bias was probably not due to a simple integration of the luminance at a particular retinal location, and appears to be object specific. Experiment 2 tested the object specificity of the temporal integration more rigorously, and Experiment 3 tested the possibility of a simple integration process.

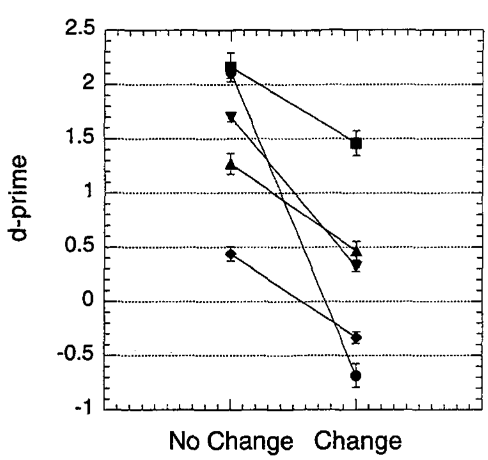

Figure 4. Mean performance in Experiment 1 for each observer: ME = circle, ECT = square, SED = diamond, MJH = upright triangle, and SSS = upside down triangle. The abscissa gives the condition (no change and change), and the ordinate gives performance as measured by d'. The vertical lines indicate standard errors of the mean.

A strong prediction would be that the initial estimate of luminance completely determines the judgment of the second interval. In this case, we would expect a positive d' in the no-change condition that is approximately equal to the discriminability of the low and high luminances presented for 300 ms in the first interval. For the change condition, we would expect d' to be equal in amplitude, but opposite in sign. Clearly, this was not the case. Three observers had positive d' in the change condition, and for the other 2 observers, the amplitudes of their negative d' in the change condition were less than the amplitudes for the positive d' in the no-change condition. Thus, observers maintained the ability to judge the luminance of the target in the second interval, and the effect of the first interval was not deterministic but instead reflected a bias towards the initial luminance.

Experiment 2

The results of Experiment 1 suggest that the previous absolute luminance of an object affects the current judgment of luminance such that the previous luminance value tends to be maintained across both intervals. Experiment 2 attempted to test the object specificity of this temporal integration more definitively.

The objects in Experiment 1 were defined by apparent motion, and Experiment 2 tested the importance of this linkage by adding a condition (unlinked) in which a third square was placed in the second display in the locations left unoccupied in Experiment 1 (see Figure 5). With the presence of the third square, the central test square in the second display could not be linked unambiguously to either square in the first display. If the effect in Experiment 1 was object specific and depended on clearly defined objects, judgments of luminance should not be biased by the first display in the unlinked condition. Performance in the unlinked condition should be better than in the change condition, as the judgment of the central square's luminance was not biased against the correct value. Analogously, the unlinked condition should be worse than the no-change condition because the central square's luminance was not biased toward the correct judgment. Performance for the unlinked condition, therefore, should be intermediate between the change and no-change conditions (no change > unlinked > change).

Method

Participants. Three observers participated, 2 men (H.R., 23 years; S.S.S., 30 years) and 1 woman (S.E.D., 23 years), all with normal color vision as assessed with the Ishihara color blindness

Table 1
Mean d′ and t Values in Experiment 1 for Change and No-Change Conditions

Observer	Change *M*	Change *SD*	No change *M*	No change *SD*	*t*(5) (change vs. no change)	*p*
ECT	1.371	.282	2.154	.329	3.53*	.017
ME	−0.603	.268	2.116	.138	9.03***	< .001
MJH	0.392	.210	1.269	.235	2.82*	.037
SED	−0.333	.133	0.440	.156	2.62*	.047
SSS	0.322	.113	1.700	.095	7.21***	.001

Note. $n = 6$ for each observer.
$*p \leq .05$. $***p \leq .001$.

plates, and normal or corrected-to-normal visual acuity. S.S.S., an author, and S.E.D., participated in the first experiment. Both S.E.D. and H.R. initially were naive to the purpose of the experiment.

Apparatus. Observers were placed on a headrest and they binocularly viewed a Conrac 2640 monochrome monitor at a distance of 60 cm. The size of the monitor was 13.5 × 18 cm, subtending 8.0° × 12.6° of visual angle. The room was darkened so that the display was the only noticeable source of light. The stimuli were generated using a Cromemco S-Series RGB graphics system. The outputs of two channels (6 bits/channel) of the graphics system were summed through a resistance circuit (Watson et al., 1986) to give 12 bits of luminance resolution.

Calibrations of the monitor were performed with the same apparatus as in the first experiment. The phosphor of the monitor was P45, with a listed chromaticity of $x = .27$ and $y = .31$ by Tektronix (Portland, OR), which is approximately gray.

Procedure. The procedure was identical to the first experiment, with the exception of an additional condition (unlinked). In this condition, there were two nontarget squares and a target square in the second interval, giving a total of three squares (see Figure 5). As before, the first display appeared for 300 ms, immediately followed by the second display, which appeared for 100 ms. Observers judged the luminance of the target square in the second display using a 4-point rating scale. There were 80 trials for each condition, randomly intermixed, giving 240 trials per session. Each observer participated in 10 sessions. Data were analyzed by signal detection methods to give values of *d′* for each condition in each session.

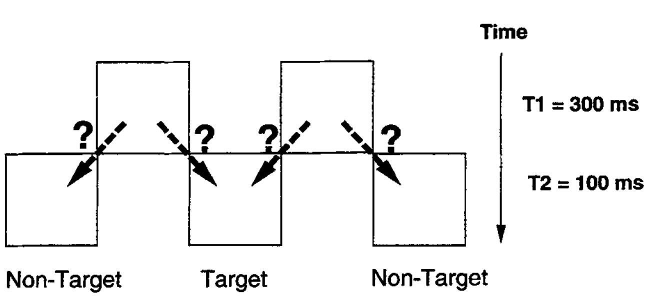

Figure 5. Stimulus configuration for the unlinked condition in Experiment 2. Each trial consisted of two display intervals shown in rapid succession; both display intervals are shown in the figure. T1 = time for first display interval (300 ms); T2 = time for second display interval (100 ms). Squares were 1° of visual angle. Three squares appeared in the second interval—the target square flanked by two nontarget squares. The ambiguous direction of motion is indicated by the question marks over the dashed lines.

The luminances were approximately 10 times the luminances in the first experiment. Luminance differences between the low and high targets were adjusted individually for each observer so that *d′* were between 1.0 and 1.5 for the unlinked condition in pilot studies performed prior to the experiment. Luminances for S.S.S. were 142.2 and 149.0 cd/m^2; for S.E.D. were 141.3 and 149.9 cd/m^2, and for H.R. were 140.5 and 150.7 cd/m^2. The background was always 188.4 cd/m^2, and the luminance of the nontarget square in the second display was the mean of the above luminances, or 145.6 cd/m^2.

Results and Discussion

Table 2 and Figure 6 describes the results from Experiment 2. For all observers, the no-change condition was better than the change condition, and, generally, performance in the unlinked condition was intermediate between the change and no-change conditions.

Column 1 of Table 3 gives the results for the main effects of the linking condition (change, no change, and unlinked), which were significant for all observers. To assess the predicted order of performance (no change > unlinked > change), columns 2, 3, and 4 of Table 3 give the pairwise comparisons between the conditions with a Bonferroni adjustment of $\alpha/3 = .0167$. For all observers, the data tended to follow the predicted pattern of results. For Observer H.R., only the comparison between the change and no-change conditions was significant, although the difference between the unlinked condition and the no-change condition was nearly significant. All pairwise comparisons for Observer S.E.D. were significant, and all comparisons for Observer

Table 2
Mean d′ in Experiment 2 for Change, Unlinked, and No-Change Conditions

Observer	Change *M*	Change *SD*	Unlinked *M*	Unlinked *SD*	No change *M*	No change *SD*
HR	1.002	0.420	1.334	0.667	1.782	0.456
SED	0.081	0.451	1.249	0.316	1.781	0.294
SSS	0.756	0.314	1.530	0.331	1.744	0.201
Overall	0.613	0.552	1.371	0.467	1.768	0.324

Note. $n = 10$ for each observer. $N = 30$.

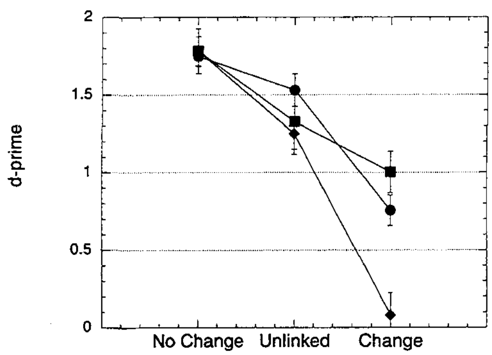

Figure 6. Mean performance in Experiment 2 for each observer: SSS = circle, HR = square, and SED = diamond. The abscissa gives the condition (no change, unlinked, and change), and the ordinate gives performance measured by d'. The vertical lines indicate standard errors of the mean.

S.S.S. were significant, except for the comparison between the unlinked and the no-change conditions.

For all observers, the no-change condition was significantly better than the change condition (column 4), replicating the results from Experiment 1.

For the data collapsed over all observers, a significant Observer × Condition interaction was found, $F(4, 54) = 5.71$, $MSE = 0.13$, $p < .001$, explained primarily by a larger simple main effect for S.E.D. compared with H.R. and S.S.S., $F(2, 54) = 9.49$, $MSE = 0.13$, $p < .001$. Also, a significant observer main effect was found, $F(2, 27) = 4.39$, $MSE = 0.24$, $p = .022$, which was due to slightly worse overall performance by Observer S.E.D. compared with H.R. and S.S.S.: S.E.D. versus H.R. + S.S.S., $F(1, 27) = 8.73$, $MSE = 0.24$, $p = .006$ (marginal *Ms*—H.R.: $M = 1.373$, $SD = 0.602$; S.E.D.: $M = 1.037$, $SD = 0.801$; S.S.S.: $M = 1.343$, $SD = 0.264$). As shown in the bottom row of Table 3, the main effect for the linking condition and all pairwise comparisons between linking conditions were significant for the data collapsed over all observers.

These results strongly suggest that the effect of the luminance of the previous display on the second display of the display was contingent on the unambiguous linkage of the target square with a square in the first display into a single coherent object. In other words, the effect is object specific. The intermediate results of the unlinked condition suggest a positive bias in the no-change condition and a negative bias in the change condition.

Results in the unlinked condition could reflect a lack of bias or, alternatively, a balance of positive and negative biases from the first display. This balance could have occurred across trials, in which the observer linked the target square randomly with just one of the squares in the first display, or within a trial, in which the observer perceived the target square linked to both squares in the first display simultaneously.

Experiment 3

The first 2 experiments strongly suggest a temporal integration of luminance for an object. While an object-specific effect is novel, other luminance integration effects have been described. A well-known example is Bloch's law (Barlow, 1958), which describes the ability to detect a luminance target in darkness. In Bloch's law, the total number of quanta striking the retina within a fixed period of time determines the detectability of the target. In mathematical terms, Bloch's law can be expressed as the following equation: Luminance × Time = Constant, to describe a stimulus of constant detectability. Note that within the temporal window of integration, the quanta are weighted equally with respect to time. In other words, as long as the quantum of light hits the retina within the temporal window of integration (about 500 ms), its contribution to detection does not depend on its time of impact.

Another temporal integration of luminance has been described for detecting luminance targets in dynamic noise (Eckstein et al., 1996). In these studies, observers attempted to detect targets defined by a distribution of luminances. This distribution had a higher mean luminance than the distribution of luminances that described the background. As these distributions were designed to overlap considerably, it was difficult to detect the target on the basis of a single image, which had the appearance of white noise (like a single frame of a snowy television set). If observers, however, could integrate information across several differ-

Table 3
Main Effects and Pairwise Comparisons for Experiment 2 (Unlinked)

	Main effect, linking condition			Pairwise comparisons								
				C vs. U			U vs. NC			C vs. NC		
Observer	$F(2, 27)$	*MSE*	*p*	$F(1, 9)$	*MSE*	*p*	$F(1, 9)$	*MSE*	*p*	$F(1, 9)$	*MSE*	*p*
HR	5.54	0.28	.01**	2.10	0.26	.179	6.85	0.15	.027	11.17	0.27	.009*
SED	58.21	0.13	<.001***	92.30	0.07	<.001**	43.11	0.03	<.001**	110.80	0.13	<.001**
SSS	32.62	0.08	<.001***	25.78	0.12	<.001**	3.06	0.08	.112	134.00	0.04	<.001**
Overall	81.30[a]	0.13	<.001***	57.16[b]	0.15	<.001**	28.06[b]	0.08	<.001**	136.90[b]	0.15	<.001**

Note. C = change; U = unlinked; NC = no change. Degrees of freedom are in parentheses in column heads. For main effect, $*p \leq .05$; $**p \leq .01$; $***p \leq .001$. For pairwise comparisons (Bonferroni adjustment), $*p \leq .0167$. $**p \leq .001$.
[a] $dfs = 2, 54$. [b] $dfs = 1, 27$.

ent images that are defined from the same distributions, detection would be possible. For an ideal observer integrating information perfectly, detectability would increase by the square root of the number of images, akin to the statistical attribute of increases in power with increases of sample size. Human observers were able to integrate the information across the images to detect the target within a temporal window of approximately 1 s, although less perfectly than the ideal observer. The observers' performances were fit well by a temporal Gaussian integration window, suggesting that this integration process is not weighted equally with respect to time, unlike Bloch's law. The assumption of a Gaussian window also suggests, however, that performance is determined by a temporal process that is symmetric with respect to time. Thus, similar to Bloch's law, the initial and latter halves within the temporal integration window contribute the same amount of information for detecting targets in visual noise.

If an object-specific integration process were used to explain the results of Experiments 1 and 2 the process would describe a qualitatively different phenomenon from the two examples described above, as both above examples describe effects on detection that are not object specific. The process may share the property of independence, however, in that the integration may not depend on the temporal sequencing of events. In terms of the task used in the previous experiments, it may not matter that the judgment occurs in the first or the second interval, only that the interval to be judged (i.e., 100 ms) is shorter than the nonjudged interval (i.e., 300 ms).

The integration process that is consistent with the object-file metaphor, however, suggests a different weighting function. Assigning and maintaining an attribute of an object to a file suggest that the initial intervals for an object are relatively more important than the later intervals. In other words, the object-file metaphor describes an integration process that is weighted in favor of the initial intervals of an object. As other luminance integration effects have been found that weight each interval equally or symmetrically with respect to its temporal window of integration, the possibility that the object-specific integration found in the previous experiments also is weighted equally or symmetrically with respect to time seems plausible. This would contradict an interpretation of this object-specific integration in terms of the object-file metaphor.

Experiments 3 tested the possibility of an object-specific integration of luminance weighted equally through time. In half the sessions, Experiment 2 was replicated with the change, no-change, and unlinked conditions, and the observers judged the luminance of the target in the second interval. These sessions were called the *second-interval-target* sessions in this experiment. In the other sessions, the first display was on for 100 ms and the second display for 300 ms, and observers judged the luminance of the target in the first display interval. These sessions were called the *first-interval-target* sessions (see Figure 7). As in the second-interval-target sessions, observers judged whether the luminance of the target was high or low, and there were three conditions: change, no change, and unlinked.

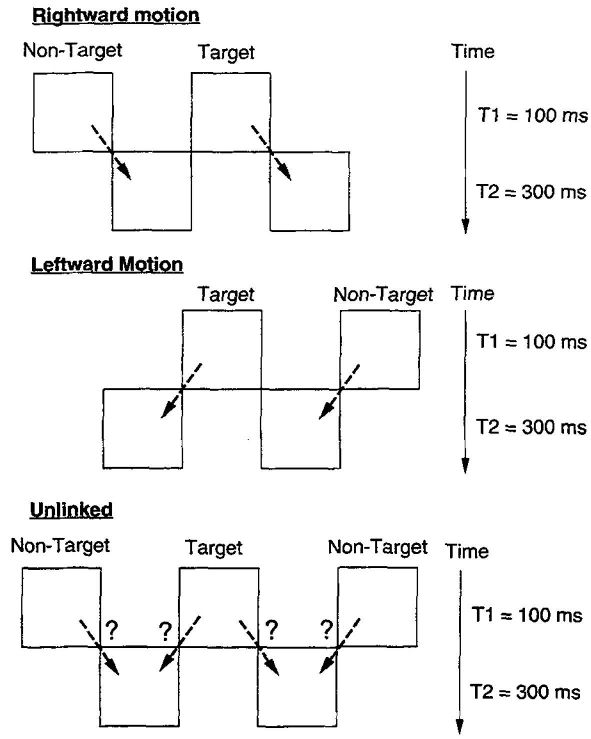

Figure 7. Stimulus configurations for first-interval-target sessions (Experiment 3). Each trial consisted of two display intervals shown in rapid succession; both display intervals are shown in the figure. T1 = time for first display interval (100 ms); T2 = time for second display interval (300 ms). Squares were 1° of visual angle. Dashed arrows indicate direction of apparent motion. The upper part of the figure shows conditions in which squares appeared to move to the right. The middle part of the figure shows conditions in which squares appeared to move to the left. For the rightward and leftward movement, all stimulus locations were identical except for the nontarget square in the first display interval. The lower part of the figure shows the unlinked condition, with three squares in the first interval—two nontarget squares and one target square. Direction of apparent motion is ambiguous, as indicated by the question marks. Observers judged the luminance of the target square in the first display interval.

An integration process weighted equally with respect to time would predict that the luminance of the longer interval would affect the luminance of the judged shorter interval, whether the shorter interval occurs before or after the longer interval. In other words, the biasing effects should be bidirectional with respect to time. For both the first- and the second-interval targets, the no-change condition should have better performance than the change condition, with the unlinked condition intermediate between the other conditions. If such an integration process were found, it would represent a clear violation of the object-file metaphor. An integration process that is more consistent with the object-file metaphor would predict an effect of the initial interval on the second interval but little or no effect of the second interval on the initial interval. Thus, the results of no change > unlinked > change should occur only for the second-interval targets.

Method

Participants. Three observers, 1 woman (D.B., 23 years) and 2 men (G.N., 45 years; S.S.S., 31 years), participated in this experiment. All had normal or corrected-to-normal visual acuity and normal color vision as assessed by the Ishihara color blindness plates. S.S.S. is the first author; the other 2 observers were initially naive to the purpose of the experiment.

Apparatus. Observers' chins were placed on a chin-rest from where they binocularly viewed an Apple computer color display that was driven by a Macintosh Quadra computer with a 48-bit (16 bits/channel) graphics system. The screen size was 26 × 35 cm, which subtended 18.7° × 24.7° of visual angle at a viewing distance of 80 cm. The monitor's chromaticity and luminance were calibrated with a Minolta Chromameter (CS-100); luminances for each gun were fit to gamma functions as described in Travis (1991). The chromaticities of all stimuli were $x = .305$, $y = .330$, which is approximately gray. The room was darkened so that the display was the only noticeable source of light.

Procedure. Each observer participated in eight repetitions of two different types of sessions. There were three conditions, change, no change, and unlinked, randomly intermixed in each session. In one session, observers judged the luminance of the target square in the first display interval (first-interval targets), and in the other session, observers judged the luminance of the target square in the second display interval (second-interval targets). Observers viewed two display intervals per trial in which the judged interval was always 100 ms, and the other nonjudged interval was always 300 ms.

The second-interval target conditions are equivalent to the change, no-change, and unlinked conditions of Experiment 2 and are shown in Figures 3 and 5. The change, no-change, and unlinked conditions for the first-interval target are described in Figure 7. Using a 4-point rating task, observers were asked to judge the luminance of the central square in whatever was the target interval. The conditions and direction of apparent motion were presented in random order in each session, as in the previous experiments. There were 80 trials per condition per session; therefore, each session contained 240 trials. Results were analyzed to give values of d' for each condition in each session.

For each observer, the luminance difference between the low and high targets were adjusted to give values of d' between 1.0 and 1.5 in the unlinked condition with the second-interval target. The values for SSS were 14.57 and 15.07 cd/m^2; for D.B., the values were 14.67 and 15.07 cd/m^2; and for G.N., the values were 14.32 and 15.07 cd/m^2. The luminance of the nontarget square in the target displays was the mean of the above luminances. The background luminance was 18.84 cd/m^2.

Results and Discussion

Table 4 gives the means and standard deviations for the 3 observers, and Figure 8 plots these means separately for each observer. In general, these results show that for all 3 observers, an integration process weighted equally through time was unlikely and that the integration process was more likely to be weighted in favor of the initial display of the target.

Table 5 gives the results for all observers for the Target Interval × Linking Condition (change, no change, unlinked) interactions, the simple main effects of linking condition for each target interval, and the main effects of the target interval. Inconsistent with the simple integration hypothesis, all observers showed a significant Target Interval × Linking Condition interaction that was due to a larger effect of the linking condition in the second-interval target sessions. All simple main effects of the linking condition were significant, except for S.S.S. in the first-interval-target sessions. Results for Observers D.B. and G.N. showed a significant main effect for the target interval, which was due to better performance overall in the second-target-interval conditions (Observer D.B.: first-interval target, $M = 0.982$, $SD = 0.428$, and second-interval target, $M = 1.419$, $SD = 0.460$; Observer G.N.: first-interval target, $M = 0.995$, $SD = 0.386$, and second-interval target, $M = 1.228$, $SD = 0.951$).

Table 6 gives the results of pairwise comparisons between linking conditions within both the first- and second-interval-target sessions for all observers, with a Bonferroni adjustment of $\alpha/3 = .0167$. For the first-interval-target sessions (first 3 rows of Table 6), results for D.B. indicate that the unlinked condition was significantly better than both the change and the no-change conditions. For Observer G.N., all comparisons except for unlinked versus no change were

Table 4
Mean d' in Experiment 3 (First-Interval Target) for Change, Unlinked, and No-Change Conditions

Observer	Change		Unlinked		No change	
	M	*SD*	*M*	*SD*	*M*	*SD*
First-interval target						
DB	0.790	0.362	1.393	0.221	0.764	0.366
GN	0.558	0.190	1.141	0.293	1.285	0.164
SSS	1.592	0.407	1.723	0.427	1.680	0.234
Second-interval target						
DB	0.946	0.352	1.753	0.311	1.559	0.265
GN	0.057	0.326	1.433	0.316	2.193	0.293
SSS	1.027	0.190	1.631	0.355	1.983	0.355

Note. $n = 8$ for each observer in each condition.

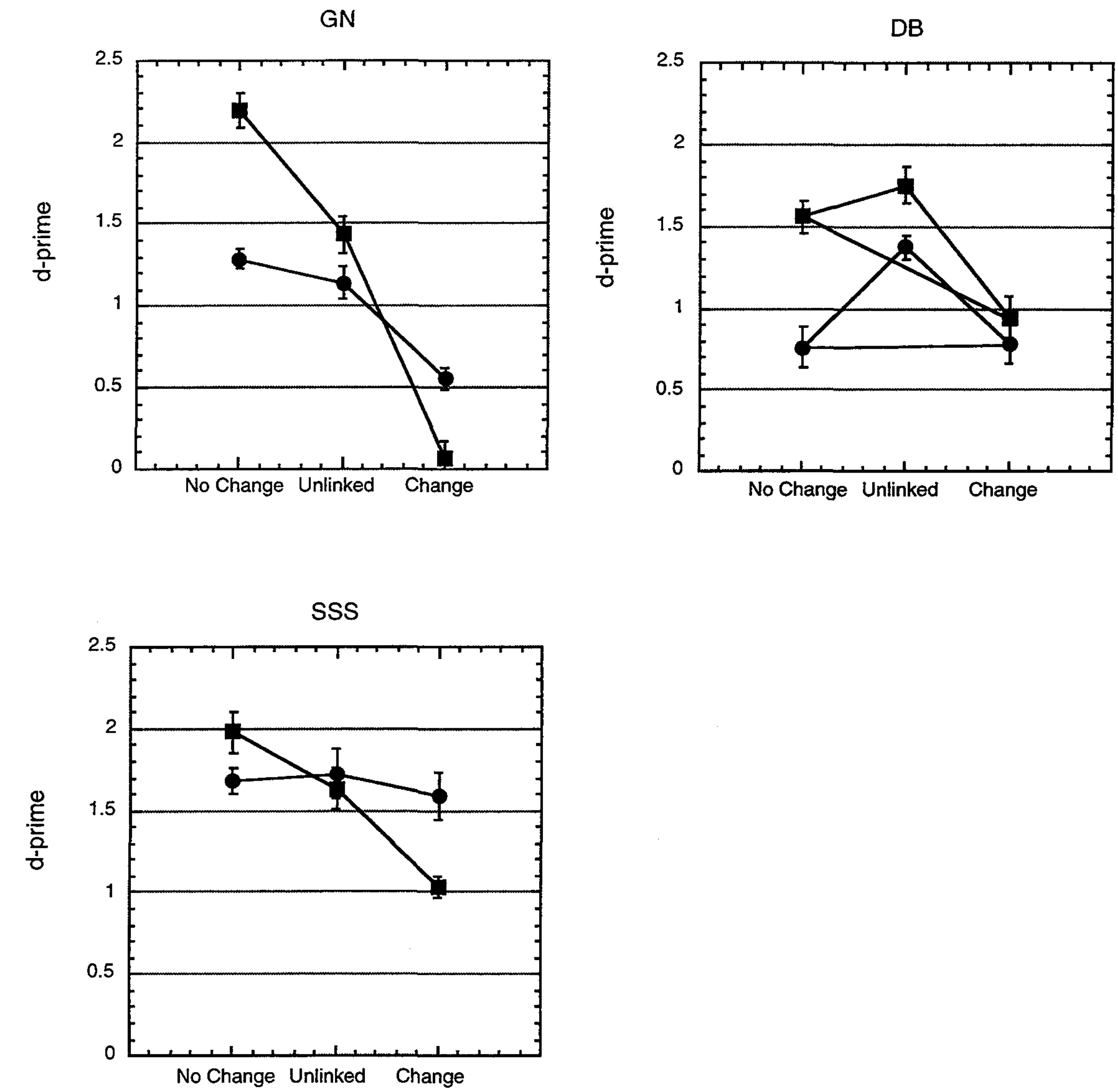

Figure 8. Mean performance in Experiment 3 for the first- and second-interval-target sessions (indicated by a circle and square, respectively), separated for each observer (indicated by initials). The abscissa gives the condition (no change, unlinked, and change), and the ordinate gives performance as measured by d'. The vertical lines indicate standard errors of the mean. The first-interval-target conditions are indicated by the circles, and the second-interval-target conditions are indicated by the squares. Additional lines for Observer D.B. compare performance in the no-change and change conditions.

significant, and the results tended to follow the predicted pattern (no change > unlinked > change). For Observer S.S.S., none of the pairwise comparisons were significant, which is consistent with his lack of a simple main effect for the first-interval target.

Overall for the first-interval-target sessions, the results for only Observer G.N. appeared to follow the predicted pattern for an equally weighted integration hypothesis (no change > unlinked > change). Observer D.B. had unusually high performance in the unlinked condition, suggesting that displays with unambiguous apparent motion of objects may cause interference in performing the task for this observer. Both D.B. and S.S.S., however, did not have a significant difference between the change and no-change conditions, unlike the results from the previous experiments with the target in the second interval.

The pairwise comparisons for the second-interval-target sessions are summarized in the last three rows of Table 6. For Observer D.B., the change condition was significantly worse than both the unlinked and the no-change conditions. For Observers G.N. and S.S.S., the results tended to follow the pattern of the previous experiments (no change > unlinked > change). All pairwise comparisons for G.N. and S.S.S. were significant, except for the comparison between

Table 5
Main Effects, Interactions, and Simple Main Effects for Experiment 3 (First-Interval Target)

	Target interval × linking condition			Simple main effect of linking condition, first-interval target			Simple main effect of linking condition, second-interval target			Main effect of target interval		
Observer	$F(2, 14)$	*MSE*	*p*	$F(2, 14)$	*MSE*	*p*	$F(2, 14)$	*MSE*	*p*	$F(1, 7)$	*MSE*	*p*
DB	4.15	0.10	.038*	15.17	0.07	<.001***	14.26	0.10	<.001***	25.66	.09	.002**
GN	27.85	0.07	<.001***	34.59	0.03	<.001***	106.90	0.09	<.001***	12.66	.05	.009**
SSS	12.44	0.06	.001***	0.50	0.07	>.500	25.37	0.07	<.001***	0.58	.28	.475

Note. Degrees of freedom are in parentheses in column heads.
$*p \leq .05$. $**p \leq .01$. $***p \leq .001$.

the unlinked and the no-change conditions for S.S.S., which was nearly significant.

Thus for the second-interval-target sessions, Observers G.N. and S.S.S. replicated the pattern of results for the previous experiments with the target in the second interval. Results for Observer D.B. indicate a higher level of performance in the unlinked condition than predicted, similar to her performance in the first-interval-target sessions. All observers including D.B., however, were better in the no-change condition than in the change condition, which is consistent with the previous experiments.

For observers S.S.S. and D.B., the predicted pattern of results (no change > unlinked > change) were found only for the second-interval-target sessions, which is inconsistent with an equally weighted integration hypothesis, whereas results for G.N. found the predicted pattern for both the first- and second-interval-target sessions. As indicated by the significant Interval Target × Linking Condition interaction; however, the simple main effect of the linking condition for the first-interval-target sessions was significantly different from the simple main effect for the second-interval-target sessions for Observer G.N. This difference in simple main effects for G.N. can be explained mostly by a greater difference between conditions in the second-interval target sessions compared with the first-interval-target sessions. This is true for both the differences between the change and no-change conditions, $F(1, 7) = 109.49$, $MSE = 0.04$, $p < .001$, and the differences between the change and unlinked conditions, $F(1, 7) = 13.30$, $MSE = 0.10$, $p = .008$. Thus, for G.N. the linking condition had a stronger effect in the second-interval target sessions, which again is inconsistent with an equally weighted integration hypothesis.

These results suggest that, as before, the luminance of the first display interval has a strong effect on the judged luminance when the target is in the second display interval. The second display interval, however, has much less effect on the judged luminance when the target is in the first display interval. An integration process weighted equally or symmetrically with respect to time would predict that the presentation duration would affect the judgment of luminance, regardless of its temporal sequencing with respect to the target. Clearly, the results are inconsistent with such an integration process. The results are more consistent with a weighted integration process that favors the initial interval over the later intervals. Such a weighted integration process is congruent with an integration process suggested by the object-file metaphor.

It should be mentioned that this experiment cannot be regarded as strong evidence in favor of the object-file hypothesis. For the second-interval-target conditions, the decision must occur logically after the observer views both display intervals. Thus, both intervals can affect the decision. For the first-interval-target conditions, the observer's decision could occur logically after the first interval, preempting any possible effect of the second interval on the first. For example, the observer may choose to shut his or her eyes after the first interval. It is clear, however, that the results do not favor an interpretation of an integration that is weighted equally or symmetrically with respect to time,

Table 6
Pairwise Comparisons for Experiment 3 (First-Interval Target)

	C vs. U			U vs. NC			C vs. NC		
Observer	$F(1, 7)$	*MSE*	*p*	$F(1, 7)$	*MSE*	*p*	$F(1, 7)$	*MSE*	*p*
First-interval target									
DB	9.13	0.08	.004*	29.16	0.05	.001**	0.04	0.07	> .500
GN	56.36	0.02	< .001**	1.64	0.05	.241	76.54	0.03	< .001**
SSS	1.30	0.05	.292	0.08	0.10	> .500	0.491	0.06	> .500
Second-interval target									
DB	34.23	0.08	< .001**	1.74	0.09	.227	11.04	0.14	.013*
GN	55.90	0.14	< .001**	29.54	0.08	.001**	67.96	0.05	< .001**
SSS	19.67	0.07	.003*	9.13	0.05	.019	39.43	0.09	< .001**

Note. C = change; U = unlinked; NC = no change. Degrees of freedom are in parentheses in column heads.
$*p \leq .0167$. $**p \leq .001$.

which clearly would be a violation of the object-file hypothesis.

Experiment 4a

The first 3 experiments suggest an object-specific temporal integration of luminance that is weighted in favor of the initial interval. The question arises as to what the purpose of such a mechanism may be. For a possible explanation, it is relevant to understand how luminance is represented, both internally and in the environment.

Here, it is useful to think in terms of the intrinsic properties of an object, or those properties inherent to the object, and the extrinsic properties of an object, or those properties inherent to the particular viewing conditions. An object's surface reflectance, or roughly speaking, its "color," is an intrinsic property of the object and is usually invariant (e.g., that car is "red," the banana is "yellow"). The illumination shining on an object is an extrinsic property that varies with viewing environment. The light intensity along the visible spectrum reflected from an object and hitting the retina is a function of both the spectral surface reflectance properties of the object and the spectral power distribution of the illumination. Other factors, such as orientation, specularity, and atmospheric conditions, also have an effect. This is analogous to the retinal image of an object being affected by the intrinsic properties of an object's size and shape, as well as by its extrinsic properties of distance and orientation from the viewer. For all three of these dimensions, color, size, and shape, often it is assumed that retrieving the relevant intrinsic property from the retinal image is paramount to object perception and recognition. These computations are termed problems of *constancy.* Hence, determining the surface reflectance properties of an object from the retinal image is *color constancy,* and, analogously, we have the problems of *size constancy* and *shape constancy* (see Brainard, Wandell, & Chichilnisky, 1993).

The property of color typically is described as a three-dimensional space, such as the Commission Internationale de l'Eclairage (CIE; 1932) color-coordinate space, with one axis representing luminance and the other two axes composing a chromatic plane. (In some color spaces, the chromatic plane is described by two chromatic dimensions resembling the opponent-color processes: a blue–yellow [b-y] axis and a green–red [g-r] axis [e.g., Derrington, Krauskopf, & Lennie, 1984].) Thus, luminance is a single dimension of color and has the corresponding intrinsic and extrinsic properties associated with it. Again, the extrinsic property is the illumination, the intrinsic property is surface reflectance, and the light intensity from an object is a function of both properties. This can be described as encompassing a black–gray–white dimension of color but includes changes in luminance for any single chromaticity (i.e., a point on the chromatic r-g, b-y plane). In theory, we can divide these two properties into separate percepts. Considering only luminance, the percept of light intensity is defined as *brightness,* and the percept of surface reflectance is *lightness.* Analogous to the above definitions, the problem of extracting the intrinsic property of surface reflectance from the retinal image is called *lightness constancy.*

As stated before, extracting the intrinsic properties of an object from its retinal image is considered crucial for object perception and recognition, specifically because it is these properties that define an object. In large part, this is due to the fact that these properties are invariant or slowly variant through time. Another aspect of these invariant properties is that they must be computed from the retinal image, if they are unknown. These computations can be demanding for shape, size, and particularly for color (see Brainard & Freeman, 1997, for a discussion). Given the difficulties in these calculations, and the invariances in these properties, a useful heuristic might be to assume that the intrinsic properties of an object do not change for relatively short periods of time. Such a heuristic would save time calculating updated values for these properties yet would be accurate for almost all cases because of their invariance. This strategy would be less useful for the extrinsic properties of an object, which change from moment to moment and do not define the object's identity. From these considerations, we suggest that humans should maintain the intrinsic properties of an object, rather than its extrinsic properties.

By extension to the case of luminance, such a strategy would assume that the intrinsic property of surface reflectance should be maintained through time. The conditions of the previous experiments, however, do not allow a distinction between the extrinsic and intrinsic properties of luminance associated with this effect. The previous luminance manipulations of the target across the first and second displays clearly affect the perceived light intensity but almost certainly also affect the perceived surface reflectance. As mentioned before, there are many cues to surface reflectance in a natural viewing environment, but within a limited viewing environment such as the one simulated by the experimental displays, the predominant cue to surface reflectance is the relative contrast of the target to the background (Shapley, 1986; Wallach, 1948). Note that the equivalence of perceived surface reflectance to relative contrast is true only for an extremely simple viewing environment, in which the objects are the same color, coplanar, two dimensional, and equally illuminated by a single illuminant. Thus, the previous manipulations of absolute luminance of the target also changed the relative contrast of the target with the background and most likely the perceived surface reflectance of the target as well. In other words, the effects of the no-change, unlinked, and change conditions could have been due to either the perceived light intensity or the perceived surface reflectance of the target.

In Experiment 4, we attempted to determine whether the results of the previous experiments could be attributed to the perceived light intensity or the perceived surface reflectance of the target. This was done by simulating surface reflectance changes of an object that were analogous to the luminance changes of an object in the previous experiment. A simple lighting condition was assumed—a single, uniform, achromatic illuminant—such that surface reflectance could be simulated by the relative contrast of the target with the background. Note that such assumptions would be in error if we were studying lightness perception in its entirety. In this case, however, the goal was to simulate surface reflectance within the simple displays of the first three experiments in which the effect was found.

The design of Experiment 4a (Figure 9) was similar to Experiment 2, except that the luminance of the background always changed between the first and the second display. This change was either from a lower to a higher luminance background, or vice versa (only changes from a higher to a lower luminance are shown in Figure 9). Thus, absolute luminance could not be used as a discrimination cue. The luminance of the squares also changed concurrently, so that the relative contrasts between the background and the two squares remained consistent, which made relative contrast the relevant discrimination cue. Also, the relative contrasts of the target were manipulated across conditions, such that the relative contrast of the target square could either change or not change across the two intervals. Thus, the change and no-change conditions refer to the status of the relative contrast of the target object with the background. As before, the prediction was that discrimination in the change condition would be worse than discrimination in the no-change condition. Also, performance in the unlinked condition would be intermediate between the change and no-change conditions (no change > unlinked > change).

In Experiment 4a, the background and target luminances always changed from the first and second interval. Theoretically, the change in absolute luminance across the background could be attributed to either a change in illumination

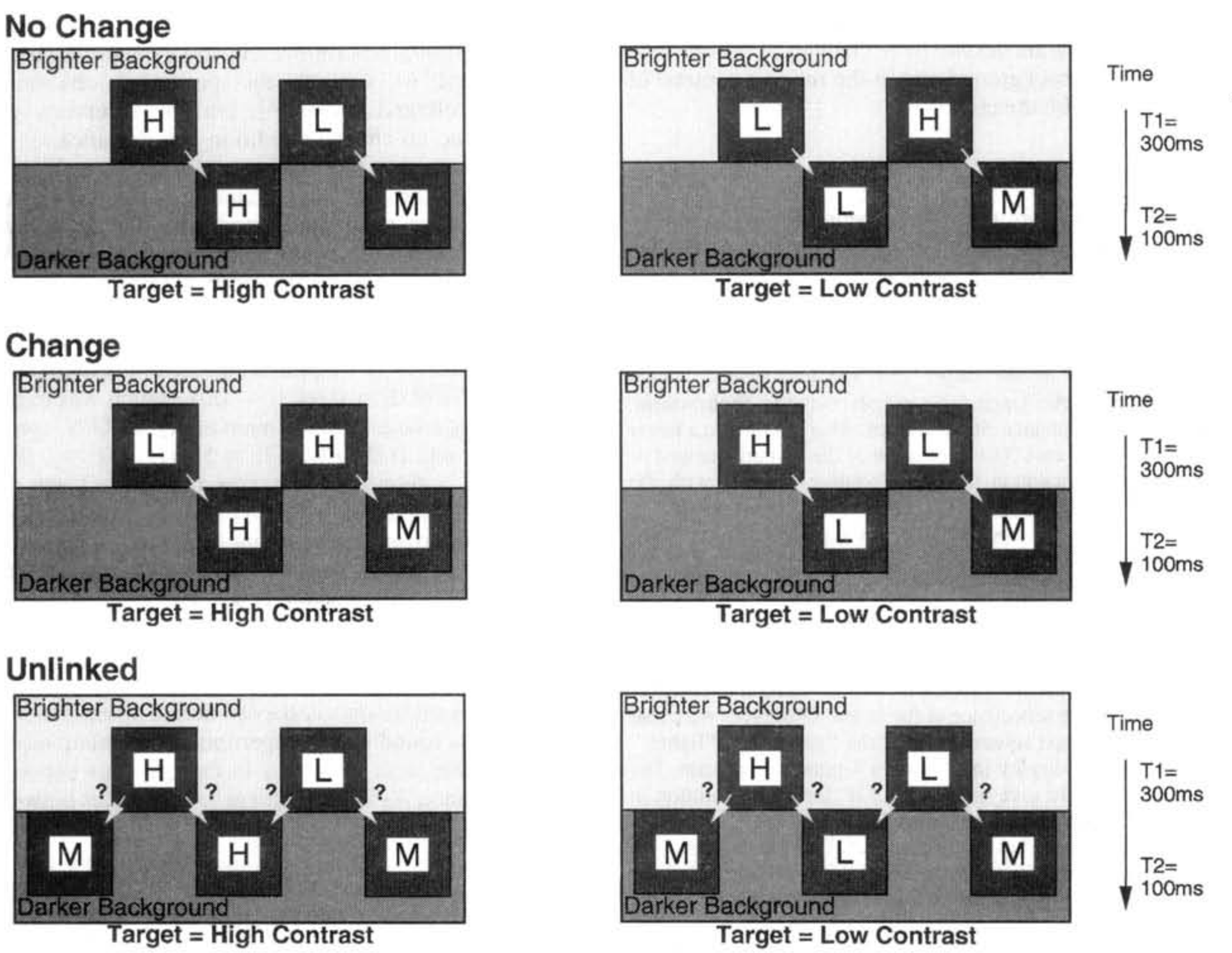

Figure 9. Stimulus configurations for Experiment 4a's (relative contrast), no-change, change, and unlinked conditions. The background luminance changed from either a lower to a higher luminance, or a higher to a lower luminance. Only rightward apparent motion and changes from the brighter to the darker background are shown. Each trial consisted of two display intervals shown in rapid succession; both display intervals are shown in the figure. Squares were 1° of visual angle. The luminances of the stimulus squares changed accordingly so that the relative contrast with the background remained constant. T1 = time for first display interval (300 ms); T2 = time for second display interval (100 ms); H = high relative contrast; L = low relative contrast; M = mean relative contrast. Refer to Table 7 for the luminances and contrasts.

Table 7
Luminances and Relative Contrasts for Stimuli in Experiment 4a (Relative Contrast)

	Darker background			Brighter background			Relative contrast	
Observer	Low	High	Background	Low	High	Background	Low	High
DB	14.67	15.07	18.84	15.07	15.48	19.35	0.779	0.800
GN	14.32	15.07	18.84	15.07	15.86	19.83	0.760	0.800
SSS	14.57	15.07	18.84	15.07	15.59	19.49	0.773	0.800

Note. Luminances are in cd/m^2. Relative contrast = target luminance ÷ background luminance.

or a change in the reflectance of the background. A study by Bonato and Gilchrist (1994) suggested, however, that observers interpret the absolute change of luminance across the background as a change of illumination. Using a stimulus configuration similar to this experiment, a single central target either on a large background surround or on a ganzfeld surround, they found that the background tended to maintain an appearance of white despite large changes in the absolute luminance of the background and in the relative contrast of the background with the target.

Method

Participants and apparatus. This experiment was run concurrently with the previous experiment. The apparatus, calibration procedure, and the observers were the same.

Procedure. Conditions were similar to Experiment 2; there were three conditions: change, no change, and unlinked (see Figure 9). In this experiment, however, the conditions referred to the status of relative contrast of the target with the background, which simulated surface reflectance for a simple viewing environment. The background luminance changed from either a higher to a lower luminance, or vice versa. The luminance of the stimuli changed as required either to maintain the same relative contrast with the background, or to make the desired change in relative contrast.

There were 160 trials per session, for each condition, which yielded 480 trials total per session. The conditions (change, no change, and unlinked), background luminance change (darker to brighter, or vice versa), and direction of apparent motion were intermixed randomly in each session. As in the previous experiments, no specific instructions were given to the observer regarding the first display interval or regarding the perceived light intensity or the perceived surface reflectance of the target. Observers were told only to judge the target square as either the "darker" or "lighter" target in the second display interval on a 4-point rating scale. The data were analyzed to give one value of d' for each condition in each session. Each observer participated in 8 sessions.

The differences in relative contrast between the targets were determined separately for each observer. In pilot studies of the unlinked condition with no background changes (equivalent to the unlinked condition of Experiment 2), these differences gave d' values between 1.0 and 1.5. The luminances are summarized in Table 7 and are similar to the luminance values for the first experiment.

Results and Discussion

The means for each observer of Experiment 4a are shown in Table 8 and Figure 10. In general, the results were similar to the luminance results of Experiment 2 and followed the predictions that the no-change condition would have better performance than the change condition, with the unlinked condition being intermediate between the other two conditions.

Table 9 gives the results for each observer for the main effects of the linking condition and for all pairwise comparisons between linking conditions, with a Bonferroni adjustment of $\alpha/3 = .0167$. For all observers, the main effect of the linking condition was significant, and the pairwise comparisons tended to support the predicted outcome (no change > unlinked > change). For all observers, performance in the no-change condition was significantly better than performance in the change condition. Also, all comparisons among the unlinked condition and the other two conditions were significant, except for the difference between unlinked and change for S.S.S. ($p = .084$) and between no-change and unlinked for D.B. ($p = .057$), both of which were nearly significant.

When we collapsed the results across observers, a significant Observer × Condition interaction was found, $F(4, 42) = 29.77$, $MSE = 0.04$, $p < .001$, which was explained primarily by a larger simple main effect for G.N. compared with S.S.S. and D.B., $F(2, 42) = 56.57$, $MSE = 0.04$, $p < .001$. Also, a significant observer main effect was found, $F(2, 21) = 3.75$, $MSE = 0.09$, $p = .039$, which was due to slightly better overall performance by S.S.S. compared with D.B. and G.N.: S.S.S. versus D.B. + G.N., $F(1, 21)$, $MSE = 0.09$, $p = .012$ (marginal *M*s, D.B.: $M = 1.027$, $SD = 0.385$; G.N.: $M = 1.059$, $SD = 0.815$; S.S.S.: $M = 1.252$, $SD = 0.320$). Finally, as shown in the last row of Table 8, the main effect of the linking condition and all pairwise comparisons were significant for data collapsed across observers.

The effect found in this experiment with relative contrast is comparable with the effect in the previous experiments with luminance. As in Experiment 1, differences between the

Table 8
Mean d' in Experiment 4a (Relative Contrast) for Change, Unlinked, and No-Change Conditions

	Change		Unlinked		No change	
Observer	*M*	*SD*	*M*	*SD*	*M*	*SD*
DB	0.623	0.261	1.133	0.237	1.326	0.249
GN	0.078	0.152	1.146	0.217	1.955	0.294
SSS	1.014	0.148	1.190	0.261	1.551	0.274
Total	0.572	0.434	1.156	0.228	1.611	0.373

Note. $n = 8$ for each observer. $N = 24$.

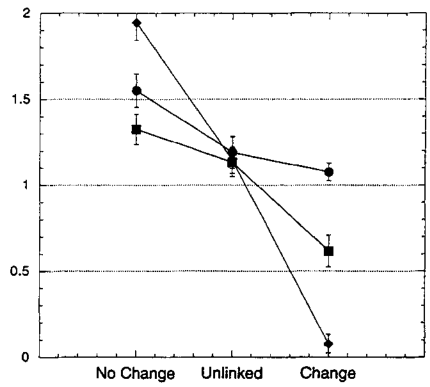

Figure 10. Mean performance in Experiment 4a (relative contrast) for each observer: SSS = circle, DB = square, and GN = diamond. The abscissa gives the condition (no change, unlinked, and change), and the ordinate gives performance as measured by d'. The vertical lines indicate standard errors of the mean.

change and no-change conditions ranged from 0.5 to 2.0 d' units. The stimulus conditions simulated changes in illumination over the target objects differing in reflectance by maintaining the relative contrast between the background and the targets. Thus, these results suggest that the results of the previous experiments are due to the percept of surface reflectance, and not the percept of light intensity.

Experiment 4b: Relative Contrast Versus Luminance

Method

For all observers in Experiment 4a, the luminance of the high-relative-contrast target with the darker background was the same as the low-relative-contrast target with the brighter background (15.07 cd/m^2; see Table 7). By analyzing a subset of the trials in Experiment 4a, we could compare directly the effects of the initial absolute luminance of the target against the initial relative contrast of the target. Figure 11 gives the absolute luminances for this comparison for Participant D.B. (rightward motion only), with the designations of the stimuli with respect to relative contrast in parentheses.

In the no-change-relative-contrast–change-luminance condition described in the first row of Figure 11, the high-relative-contrast target first appears against the brighter background (19.35 cd/m^2), then against the darker background (18.84 cd/m^2), and the luminance of the target changes from 15.48 cd/m^2 to 15.07 cd/m^2. Because of the change in luminance of the background, the relative contrast stays the same across the two intervals. For the low-relative-contrast target, the background goes from the darker to the lighter background, and the luminance of the target goes from 14.67 cd/m^2 to 15.07 cd/m^2. Again, the absolute luminance of the target changes and the relative contrast is constant across the two intervals. Thus, same condition could be described as either a no-change condition for relative contrast or a change condition for luminance.

For the change-relative-contrast–no-change-luminance condition (second row, Figure 11), the high target first appears on the brighter background (19.35 cd/m^2) and then on the darker background (18.84 cd/m^2). The luminance is constant across the two intervals (15.07 cd/m^2), and therefore the relative contrast changes across the two intervals. For the low target, it appears first on the darker background and then on the lighter background. Again, the luminance does not change across the two intervals (15.07 cd/m^2), so that the relative contrast changes. In opposition to the previous condition, this condition could be considered either as a change condition in relative contrast or as a no-change condition in luminance.

The last row of Figure 11 gives the unlinked condition (both for relative contrast and luminance) for this analysis. As in the other experiments, a third square added to the second display makes ambiguous the linkage of the squares in the initial display to the squares in the second display.

A predominance of the effect by the initial relative contrast of the target square predicts that the no-change-relative-contrast condition would show better performance than the change-relative-contrast condition, with performance in the unlinked condition intermediate between the change and no-change conditions. A predominance of the initial absolute luminance of the target square predicts that the no-change-luminance condition would show better performance than the change-luminance condition, again with performance in the unlinked condition intermediate between the change and no-change conditions. Because the no-change-relative-contrast condition and the change-luminance conditions are equivalent, and vice versa, the predicted effects of relative contrast and luminance are exactly opposed in this analysis.

Results and Discussion for the Relative Contrast Versus Luminance Analysis

Table 10 and Figure 12 give the results for the relative contrast versus luminance analysis for all 3 observers. The abscissa gives the conditions with respect to both relative

Table 9
Main Effects and Pairwise Comparisons for Experiment 4a (Relative Contrast)

	Main effect, linking condition			Pairwise comparisons								
				C vs. U			U vs. NC			C vs. NC		
Observer	$F(2, 21)$	*MSE*	*p*	$F(1, 7)$	*MSE*	*p*	$F(1, 7)$	*MSE*	*p*	$F(1, 7)$	*MSE*	*p*
DB	17.04	0.06	<.001***	23.72	0.04	.002*	5.12	0.03	.057	122.70	0.02	<.001**
GN	135.10	0.05	<.001**	99.52	0.05	<.001**	143.00	0.02	<.001**	181.30	0.08	<.001**
SSS	10.90	0.06	<.001**	3.991	0.03	.084	16.70	0.03	.005*	5.74	0.05	.002*
Overall[a]	173.30	0.04	<.001***	101.90	0.04	<.001**	94.48	0.03	<.001**	280.30	0.05	<.001**

Note. C = change; U = unlinked; NC = no change. Degrees of freedom are in parentheses in column heads. For main effect, $*p \leq .05$; $**p \leq .01$; $***p \leq .001$. For pairwise comparisons (Bonferroni adjustment), $*p \leq .0167$; $**p \leq .001$.
[a]For all *F*s in this row, $df = 1, 21$.

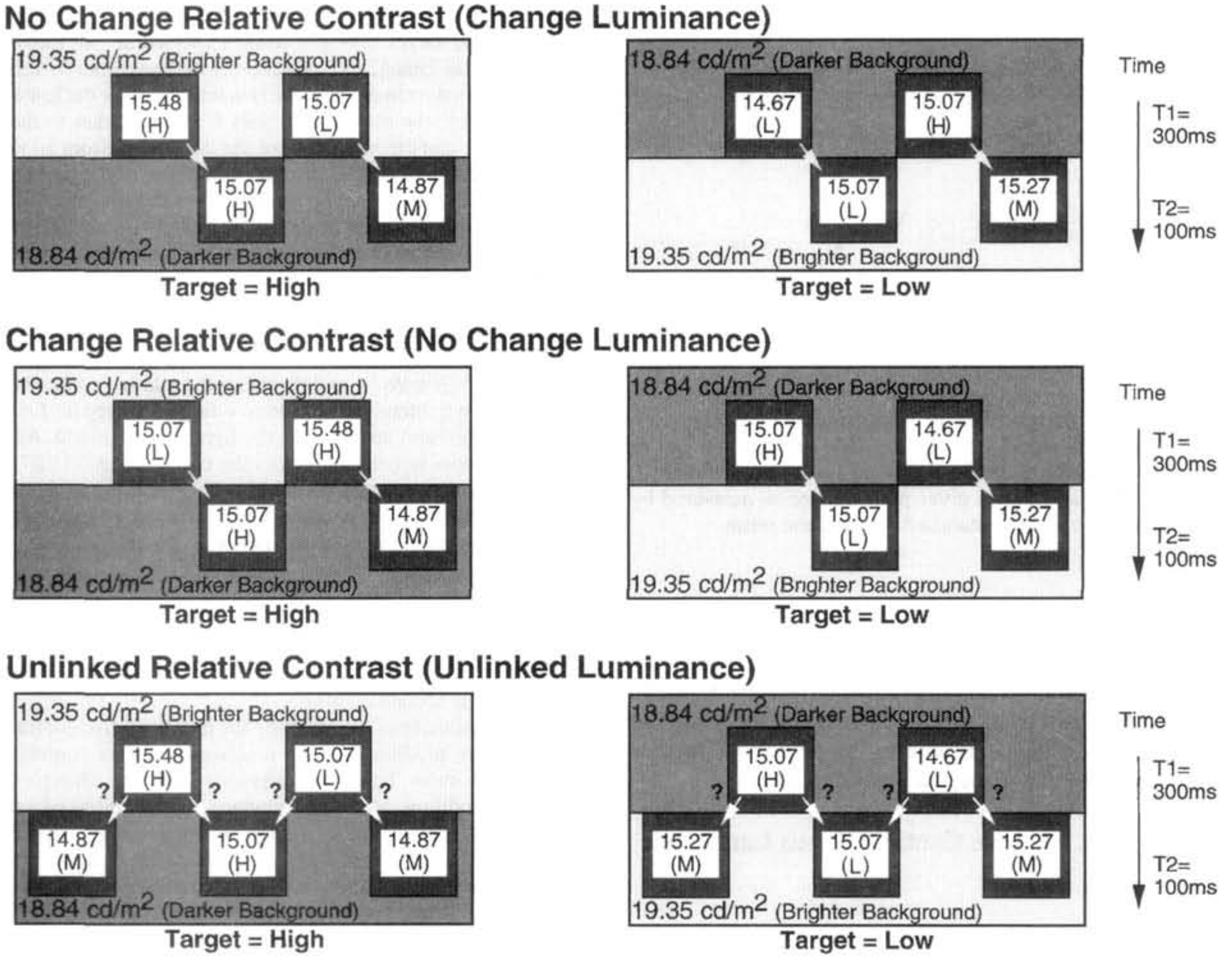

Figure 11. Stimulus conditions for Experiment 4b's (relative contrast) relative contrast versus luminance analysis. The conditions in this analysis are a subset of the stimulus conditions of Experiment 4a, as described in Figure 9. The figure lists the absolute luminances in cd/m^2 for Observer D.B. and the relative contrasts (low or high) in parentheses. Each trial consisted of two display intervals shown in rapid succession; both display intervals are shown in the figure. Only rightward movement is shown. Squares are 1° of visual angle. Targets are defined in terms of relative contrast to the target. T1 = time for first display interval (300 ms); T2 = time for second display interval (100 ms); H = high-relative-contrast target; L = low-relative-contrast target; M = mean (of high and low) relative contrast. Refer to Table 7 for the luminances and contrasts for the other participants.

contrast and luminance, and the ordinate gives mean values of d'. Results clearly show a predominance of the effect of relative contrast, with the no-change-relative-contrast (change luminance) condition having better performance than the change-relative-contrast (no-change luminance) condition.

Table 11 gives the results with respect to relative contrast for each observer. The table lists the main effects of the linking condition and for all the pairwise comparisons between the conditions with a Bonferroni adjustment of $\alpha/3 = .0167$. As indicated by column 1, the main effects of linking condition were significant for all observers. For G.N., all pairwise comparisons were significant and matched the predicted pattern of no-change relative contrast > unlinked > change relative contrast. For D.B., only the comparison between change relative contrast and no-change relative contrast was significant, again with the no-change-relative-contrast condition having better performance than the change-relative-contrast condition. For S.S.S., only the difference between the unlinked and the no-change-relative-contrast conditions were significant. Similar to the other observers, performance in the change-relative-contrast condition was lower than performance in the no-change-relative-contrast condition, but this difference was not significant.

For the results of the data collapsed across observers, a significant Observer × Linking Condition interaction was found, $F(4, 42) = 29.77$, $MSE = 0.12$, $p < .001$, which was due to a larger simple main effect for G.N. compared with both S.S.S., $F(2, 42) = 15.26$, $MSE = 0.12$, $p < .001$, and

Table 10
Mean d′ in Experiment 4b (Relative Contrast) for the Same-Luminance–Different-Contrast Analysis

Observer	Change, relative contrast		Unlinked, relative contrast		No change, relative contrast	
	M	*SD*	*M*	*SD*	*M*	*SD*
DB	0.562	0.385	0.872	0.230	1.113	0.232
GN	0.507	0.251	1.308	0.251	2.111	0.556
SSS	1.610	0.425	1.345	0.311	1.968	0.409
Total	0.893	0.636	1.175	0.336	1.730	0.603

Note. $n = 8$ for each observer. $N = 24$ overall.

D.B., $F(2, 42) = 9.35$, $MSE = 0.12$, $p < .001$. A significant observer main effect was found, $F(2, 21) = 23.81$, $MSE = 0.16$, $p < .001$, because overall performance differed among all observers: D.B. versus S.S.S., $F(1, 21) = 15.89$, $MSE = 0.16$, $p < .001$; and S.S.S. versus G.N., $F(1, 21) = 8.32$, $MSE = 0.16$, $p < .001$, (marginal *M*s, D.B.: $M = 0.849$, $SD = 0.131$; G.N.: $M = 1.308$, $SD = 0.773$; S.S.S.: $M = 1.641$, $SD = 0.451$). As indicated by the last row of Table 11, the main effect of the linking condition and all pairwise comparisons of the linking conditions were significant for the results collapsed across observers.

Results for the relative contrast versus luminance analysis over all the observers demonstrated better performance in the no-change-relative-contrast condition compared with performance in the change-relative-contrast condition. Because the no-change-relative-contrast condition is equivalent to the change-luminance condition, and the change-relative-contrast condition to the no-change-luminance condition, the results also showed better performance in the change-luminance condition compared with performance in the no-change-luminance condition. This result, in terms of luminance, is clearly incongruent with the results from the previous experiments, which consistently found better performance in the no-change condition. Thus, the results indicate that the effect in the previous experiments was due to the relative contrast of the target in the initial display and not its absolute luminance. As discussed earlier, relative contrast simulates the surface reflectance of an object for simple viewing conditions, which suggests that the effect found in the previous experiments was due to the percept of surface reflectance.

General Discussion

In Experiments 1 and 2, we found that the luminance of an object was integrated through time, such that the initial luminance biased the succeeding luminance judgments. Results from Experiment 3 suggest that this integration was unidirectional such that the succeeding luminance did not affect the initial judgment of luminance of the object. In other words, the integration appears to have been weighted to favor the initial moments of viewing an object. In Experiment 4a, we found a similar effect when the relative contrast of the object with the background was manipulated. In Experiment 4b, we directly compared effects of the initial relative contrast of the target object with initial luminance of the target object, and we found relative contrast as the predominant cue. Because relative contrast simulates sur-

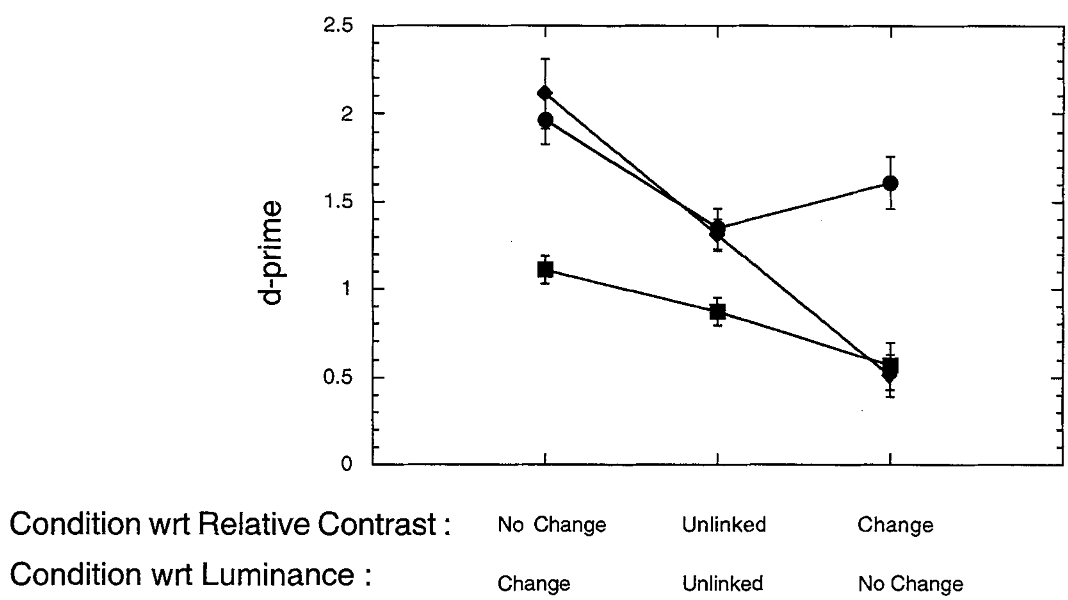

Figure 12. Mean performance in Experiment 4b's relative contrast versus luminance analysis, for each observer: SSS = circle, DB = square, and GN = diamond. The abscissa gives the condition with respect to either the relative contrast or the luminance of the target square in the first interval. The ordinate gives performance measured by *d′*. The vertical lines indicate standard errors of the mean. wrt = with respect to.

Table 11
Pairwise Comparisons for Experiment 4 (Relative Contrast) for the Relative Contrast Versus Luminance Analysis

Observer	Main effect, linking condition			Pairwise comparisons for conditions defined by relative contrast								
				C vs. U			U vs. NC			C vs. NC		
	$F(2, 14)$	*MSE*	*p*	$F(1, 7)$	*MSE*	*p*	$F(1, 7)$	*MSE*	*p*	$F(1, 7)$	*MSE*	*p*
DB	8.65	0.07	.004**	3.95	0.10	.085	5.15	0.05	.056	17.51	0.07	.004*
GN	28.21	0.18	<.001***	19.28	0.11	.004*	30.99	0.08	.001**	31.10	0.33	.001**
SSS	7.52	0.10	.006**	3.23	0.09	.113	33.37	0.05	.001**	2.88	0.18	.132
Overall	36.66[a]	0.12	<.001***	9.03[b]	0.11	.007*	63.58[b]	0.06	<.001**	43.67[b]	0.19	<.001**

Note. C = change, relative contrast (no-change luminance); U = unlinked, relative contrast (unlinked luminance); NC = no-change, relative contrast (change luminance). Degrees of freedom are in parentheses in column heads. For main effect, $*p \leq .05$; $**p \leq .01$; $***p \leq .001$. For pairwise comparisons (Bonferroni adjustment), $*p \leq .0167$; $**p \leq .001$.
[a] $df = 2, 42$. [b] $df = 1, 21$.

face reflectance for simple displays, the results from Experiment 4a suggest that the effect was due to the perceived surface reflectance and not the perceived light intensity.

The results from the unlinked condition in Experiments 2, 3, and 4a suggest that the integration was contingent on the percept of a coherent object by apparent motion across the two displays. In other words, the effect appears to have been object specific. This is an important distinction, as object specificity has not been demonstrated for other instances of luminance integration (e.g., Barlow, 1958; Eckstein et al., 1996).

This effect appears not to be explained by other factors such as retinal location or local contrast. Integration over the same retinal location appears unlikely because of the absence of overlap of the target square across the two intervals and the randomized apparent motion and the presentation duration of 100 ms not allowing for predictive eye movements. Local contrast does not appear to have been a factor, as the squares defining the target across the two displays did not share any borders. Also, the local contrast information for each target across the two displays in each experiment was the same under all conditions, as the two squares appearing in the first display always had the low and high target contrasts.

The object-specific integration effect in these experiments also could be described as a "hysteresis effect," as suggested by A. Gilchrist (personal communication, 1996). He reported that he has observed informally several cases of analogous effects in his studies of lightness perception.

Relation to the Object-File Metaphor

In the original experiments of Kahneman et al. (1992), the authors proposed the metaphor of an object file to describe their results (see also Kahneman & Treisman, 1984). This metaphor suggests that for each object, there exists a representation (a file) listing its characteristics, such as its identity, its color, and its shape. In terms of this metaphor, one can imagine that these files initially could be empty of data and that such information would have to be filled by an assignment process. The empty files could be similar to the object tokens described by Marr (1982) and Treisman and DeSchepper (1996), and the process of filling these files would be equivalent to recognizing and identifying the object.

A similar metaphor to object files was suggested by Ballard (1993), who proposed the existence of internal markers to keep track of relevant objects. Each marker would operate like a pointer to a structure in the programming language C, with the structure holding information concerning the object. Such a design allows operations on a single object through the marker or pointer without referencing all the information attached to the object. The relevant information would be maintained within the structure or could be accessed directly from the visual input so that the environment would act as an "external memory." Similar to the object file, this data structure could be construed as being empty of data initially, and its creation would be analogous to the memory allocation function in C (malloc). Assigning values to the variables within the structure would constitute object identification and recognition.

Thus, both metaphors for objects above could suggest a representation of an object initially empty of object descriptors and an assignment process filling the representation with these descriptors. As discussed earlier, the descriptors represented for an object should be the defining intrinsic properties of the object, such as its shape, size, and surface properties, as opposed to its extrinsic properties, such as its orientation, distance, and the illumination. Thus, logically an object file should contain at least some of these intrinsic properties. Because intrinsic properties tend to be invariant or constant and because the computational cost of assigning values to these attributes may be high, an assumption that these properties remain constant would achieve relatively high accuracy at relatively low computational cost. Such a strategy might be called a "perceptual heuristic," which would be similar to the cognitive heuristics described by Kahneman and Tversky (1973, 1982a, 1982b; Tversky & Kahneman, 1974).

The results of the current experiments suggest a weighted integration of the perceived surface reflectance that favors the initial moments of an object. Taken to an extreme, an assignment process, such as that suggested by the object-file metaphor, is equivalent to a weighted integration that completely favors the initial interval. Thus, the results are consistent with the object-file metaphor in which the initial perceived surface reflectance is assigned to an object file and maintained through time.

Lightness and Brightness

Lightness typically is defined as the perceived surface reflectance of an achromatic object, whereas brightness typically is defined as the perceived light intensity. In the first 3 experiments, the manipulations of absolute luminance affected both the perceived surface reflectance (lightness) and the perceived light intensity (brightness) of the target. Therefore, it is completely ambiguous from Experiments 1 to 3 whether the effect was due to the percept of lightness or brightness. In Experiment 4a, an effect of relative contrast nearly equal to the luminance effect was found, and in Experiment 4b, the effects of the previous luminance and the previous relative contrast of an object were compared directly, with the previous relative contrast having the predominant effect. As described earlier, relative contrast simulates surface reflectance for extremely simple viewing conditions. Thus, the results of Experiment 4 suggest that the effect is based on the perceived surface reflectance (lightness) and not the perceived light intensity (brightness).

Thus, these experiments suggest the predominance of perceived surface reflectance (lightness) over the perceived light intensity (brightness). Several authors have suggested that these two percepts are difficult for observers to distinguish, despite their relatively straightforward definitions (Jacobsen & Gilchrist, 1988; Sewall & Wooten, 1991; Whittle, 1991). Results from Whittle (1986), however, suggest that perceived surface reflectance predominates under certain conditions. In his experiment of brightness matches, under no conditions were observers able to overcome the cue of relative contrast in order to make a correct luminance match. Also, several studies have shown that, generally, humans can perceive the surface reflectance of an object despite changes in illumination (e.g., Arend & Goldstein, 1987; Arend & Reeves, 1986; Blackwell & Buchsbaum, 1988; Brainard & Wandell, 1992; Land, 1959; McCann, McKee, & Taylor, 1976).

The Problem of Lightness Constancy

Individuals' ability to perceive accurately the surface reflectance of an object suggests that people are able to make the necessary computations to extract the correct surface color from the retinal image. In other words, humans have the ability to solve the problem of color and lightness constancy described earlier. Models of how these computations can be done rely on a number of strategies and cues, and studies of color and lightness perception have found that humans can use some of these strategies and cues to varying degrees. These include local contrast (Shapley, 1986; Shapley & Enroth-Cugell, 1984), other surfaces in the environment (Buchsbaum, 1980; Land, 1983; Maloney & Wandell, 1986), adaptation (von Kries, 1905; Worthey & Brill, 1986), specularity (Lee, 1986), changes in illumination (D'Zmura, 1992; D'Zmura & Iverson, 1994), and prior probabilities of surfaces and illuminations (Brainard & Freeman, 1997).

Humans are also able to use other cues to surface reflectance not directly related to the illumination or the surface reflectance properties of the objects. For example, lightness perception can depend on the geometric interpretation of a visual scene, such as curvature (Knill & Kersten, 1991; Pessoa, Mingolla, & Arend, 1996), transparency (Adelson, 1993), and depth (Gilchrist, 1977; Schirillo & Arend, 1995; Schirillo, Reeves, & Arend, 1990). Also, simply inducing the observer to interpret a scene differently (whether a luminance boundary is a shadow or an object border) affects lightness accordingly (Gilchrist, Delman, & Jacobsen, 1983).

These effects on lightness perception by geometric or configural cues are sometimes called contextual lightness effects, because they are based on cues that give the context of the viewing environment and not the actual surface reflectance or illumination. In this sense, the object-specific temporal integration in the current experiments may also have been considered as using a contextual cue, the recent history of the object. This cue, therefore, appears to be one of a battery of possible cues that humans use to solve the problem of lightness constancy. In this way, lightness perception appears to be similar to depth perception in that a large number of cues (e.g., stereopsis, motion parallax, and texture gradients) can be used to solve the task (e.g., Landy, Maloney, Johnston, & Young, 1995).

Unanswered Questions

The present experiments did not explore the problem of how lightness is determined initially, only how that information appears to be maintained after the initial determination. Also, because the task of the observers was to discriminate the relative luminance or relative contrast of the targets, these experiments did not explore the determination of absolute lightness, or the "anchoring problem." As suggested by Gilchrist and Bonato (1995), objects have absolute values of lightness, such as black, gray, and white, which must be determined beyond values of relative lightness by a rule assigning or anchoring a particular stimulus to an absolute lightness value. For relatively simple displays of single targets against a large uniform surround, the absolute lightness of the target appears to be determined by the assignment of white to the background (see also Bonato & Gilchrist, 1994).

One question not addressed in this study is the time course of an object-specific integration of luminance. The duration of the displays in the current experiments were relatively brief, 300 ms and 100 ms, and it is unclear what effects might be found for longer durations. Presumably, this time course is related to formation and maintenance of the internal representation of objects. Another issue that needs exploration is the differences in luminance over which this effect would be found, because the differences used in this study were relatively small for both the targets in all experiments, and for the background change in Experiment

4a. It is unclear whether the same effect could be found for larger luminance differences.

The observers performed a perceptual judgment throughout these experiments, and the biasing suggested by the results may occur at any point within the entire decision process incorporated in performing the judgment. This would include lower level perceptual processes and higher level decision, cognitive, processes. The results of these experiments imply that the bias is contingent on the unambiguous identity of the target object across the two intervals and the relative contrast of the target, but a more specific locus (or loci) of the effect cannot be specified.

Because the problem of color constancy is equivalent to the problem of lightness constancy extended to chromatic stimuli, it seems likely that there is a bias for color appearance that is similar to the bias found for lightness. Finally, as mentioned before, the problems of lightness and color constancy are analogous to other problems of object constancy. An object's intrinsic properties remain constant along a number of different dimensions, such as size and shape, even though the retinal image may change along these dimensions as an object moves and rotates in the environment. It is plausible, therefore, that a similar process applies to other dimensions, as well as those of luminance and color.

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