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Amodal representation depends on the object seen before partial occlusion

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Abstract

We demonstrate history-dependent effects in the amodal representation of partially occluded objects. The experience of seeing the fully visible objects before partial occlusion is shown to be influential in the way the objects are represented after occlusion has occurred. Using the method of ambiguous apparent motion correspondence to probe the extent of amodal continuation, bars of variable length were partly occluded by a moving rectangle. After a variable delay period, the part of the bars that remained visible underwent an apparent motion sequence. Subjects reported whether the perceived motion was horizontal or vertical. With a 1-s delay after occlusion, each of the five subjects tested showed a bias favoring motion in the direction of the elongated bars. These results indicate greater amodal continuation in the case of long bars after they have been occluded for an appreciable period of time. A control experiment varying the stereoscopic disparity of the occluder ruled out explanations based on two-dimensional effects, reinforcing the conclusion that the past history has a specific effect on amodal representations. With a delay of 2 s following occlusion, four of six subjects tested showed the history effect, indicating potentially longer durations for the effect, with individual differences in the duration. We conclude that the amodal representation of an object depends on the object seen before partial occlusion. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Amodal; Memory; Occlusion; Three-dimensional

1. Introduction

When one object is partially occluded by another, the occluded object is usually perceived to be larger than that portion which is visible. This has been termed ‘amodal presence’ or ‘amodal continuation’ (Michotte, 1963; Kanizsa, 1979; Michotte, Thinès & Crabbé, 1991). The actual size and shape of the object is often undetermined by the available image. This occurs when the observer steps out from an opening into a new vista (Gibson, 1966), in which case the occluded objects have never been fully visible. This is also the case when an experimenter presents a display that appears suddenly and contains a partial occlusion (Shimojo & Nakayama, 1990; Sekuler & Palmer, 1992). However, in some situations an object had at one time been fully visible to the observer, and was later partially occluded. This happens frequently during locomotion (Gibson, 1950). It is also a common occurrence for an object to become partly occluded upon moving behind another object. A moving object may also partially occlude a stationary object that was once fully visible. It is the latter case which is the topic of this study. We wish to ascertain whether the amodal representation of a partly occluded object is affected by the recent visual experience of seeing it when it was fully visible. In other words, we aim to determine whether amodal representations possess memory, in the empirical sense of being influenced by the previously visible attributes of the entire object.

Many aspects of amodal representations in static scenes have been studied by previous authors (Gerbino & Salmaso, 1987; Shimojo & Nakayama, 1990; Sekuler & Palmer, 1992; Kellman & Shipley, 1991; He & Nakayama, 1994a; Sekuler, 1994; Sekuler, Palmer & Flynn, 1994; Watanabe, 1995; Bruno, Bertamini & Domini, 1997). In dynamic scenes, the empirical question arises as to whether the amodal continuation of an

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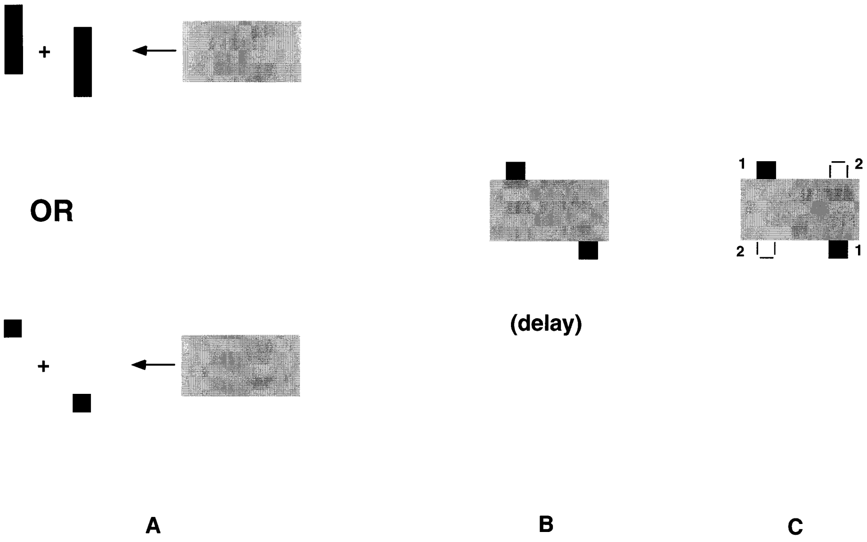

Fig. 1. Schematic of Experiment 1. Either long bars or short bars (A) were presented with a random horizontal displacement between them, while a stereoscopically-rendered rectangle moved from the side of the display into a position in front of the bars, partially occluding them. After a random delay time ranging from 0 to 2 s (B), the square tabs that remained visible underwent ambiguous apparent motion (C), with stimuli alternating between position 1 and 2. Subjects indicated whether the perceived motion was in the horizontal or vertical direction.

object depends on the perception of the full object before occlusion. Fig. 1A shows two possible scenes. The upper scene contains two long bars that are fully visible, and are then partially occluded by a rectangle that moves in front of them and comes to rest (Fig. 1B). The lower scene in Fig. 1A contains two short bars with the same moving rectangle that comes to rest in front of them (Fig. 1B). After partial occlusion, these two scenes are physically identical, although they have different histories. Yet it is possible that the amodal representations of the bars after partial occlusion are different in the two cases.

The method we used to measure the extent of amodal continuation in each case, i.e. with each scene history before partial occlusion, is a method introduced by Shimojo and Nakayama (1990). In their work, square tabs behind an occluding rectangle underwent the bistable apparent motion sequence employed by Ramachandran and Anstis (1983). The configuration is illustrated in Fig. 1C. Motion tokens (the square tabs) alternate between positions 1 and 2 with no inter-stimulus interval. The motion correspondence in this situation is physically ambiguous, yet consistently there is a compelling perception of motion along only one of either the horizontal or vertical directions, which rarely if ever splits or switches between them. Fig. 2 illustrates that if the tabs are amodally extended to some degree behind the occluder, their centers-of-mass lie closer together along the vertical direction. Because the proximity of the motion tokens is a crucial determinant of which percept will be obtained (Burt & Sperling, 1981), the likelihood of a vertical motion percept is increased by the closer proximity of the centers-of-mass when there is a greater extent of amodal continuation. The competition between the two percepts can be biased by altering the horizontal displacement between the tabs. This gives a psychometric function for the probability of a horizontal motion percept as a function of the horizontal displacement. The ‘apparent motion bias’, the horizontal displacement at which the two percepts are equally likely, may be used as a measure of the correspondence strength. Shimojo and Nakayama (1990) used this measure to compare the correspondence strength between conditions under which the motion tokens could be amodally extended (behind a

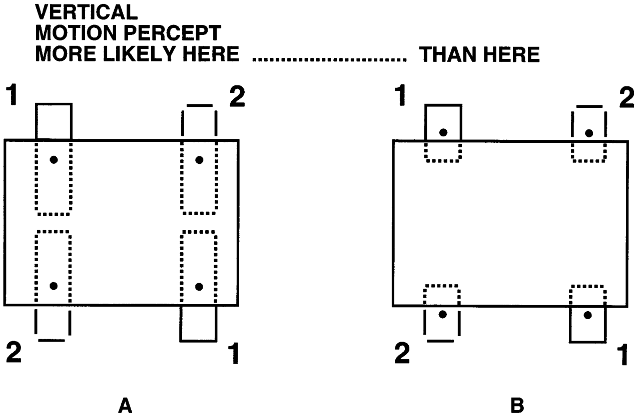

Fig. 2. The visible portion of a partially occluded object can be amodally continued behind the occluder. The amodal continuation (drawn as dotted lines) brings the centers-of-mass (drawn as dots) of the two objects closer together in the vertical direction. Greater amodal continuation makes the vertical motion percept more likely, because proximity is an important determinant of apparent motion correspondence.

rectangle in front of them) and could not be amodally extended (in front of a rectangle behind them). They found a bias favoring vertical motion in the condition in which amodal continuation was possible. This result can be attributed to a decreased vertical separation between the centers-of-mass of the motion tokens by virtue of their amodal extension.

We adapted this method to address the question of whether amodal representations of partially occluded objects depend on the objects seen when they were fully visible. A preliminary report of these results has been presented previously (Joseph & Nakayama, 1995a).

2. Experiment 1: amodal representation after partial occlusion

The logic of the experiment is straightforward. Two different visual experiences (long versus short bars) occur on different trials, but are always followed by a partial occlusion that results in physically identical stimuli. After some delay interval, we obtain a measure of the amount of amodal extension (apparent motion correspondence).

The method is schematized in Fig. 1. At the start of each trial, a pair of bars of variable length are on display, while a rectangle moves from the side of the screen into a position partially occluding them (Fig. 1A). Only square portions of the bars remain visible, and these are identical across trials which differ in the length of the bars as presented when they were fully visible. After the rectangle comes to rest, there is a variable delay period (Fig. 1B), followed by ambiguous apparent motion of the square tabs (Fig. 1C). The subjects reported whether the perceived motion was in the horizontal or vertical direction.

2.1. Methods

Stereoscopic stimuli were presented on a 120 Hz CRT display, 23.5×19 cm^2 with 640×512 resolution, equipped with an alternating liquid crystal circular-polarizing modulator. Subjects wore polarizing filters throughout the experiments. Therefore, the subjects were effectively exposed to a 60-Hz stereoscopically-rendered display. We used texture dots in the occluding rectangle to boost the three-dimensional percept resulting from the stereo rendering. Viewing distance was 57 cm. Luminances (cd/m^2) were approximately as follows: background, 2; bars, 15; rectangle (area between the texture dots), 8; texture dots, 30; and rectangle including texture dots (average), 10.

Spatial parameters of the stimuli were as follows. The bars were 35 min wide. The vertical length was 35 (short bars) or 255 min (long bars). The occluding rectangle was 230 min in height and 520 min wide, and was presented with a stereoscopic disparity of 13.2 min relative to the rest of the screen. Texture dots on the rectangle were 4.4 min square and had a density of 400 dots randomly distributed over the rectangle. Bars were vertically positioned so that in the case of short bars the occluding rectangle would just be flush with an edge of each bar (see Fig. 1). The center of the left bar always had a horizontal coordinate 44 min to the left of the fixation cross center. The arms of the fixation cross were 18 min in length. The horizontal placement of the right bar was chosen randomly on each trial from one of six equally spaced values. These were selected on the basis of the individual subject's performance in the first block of the first session, and were chosen with the aim of maximizing the statistical power of the test that was to follow. A probit fit (Finney, 1971) to the pooled responses from the first block for each bar length was used to determine the smallest range of horizontal displacements expected to yield at least 90% horizontal motion at the low end and at most 10% horizontal at the high end. Once chosen for any given subject, the values of the horizontal displacement between the bars remained constant throughout the two sessions of the experiment. (The first block of the first session was always conducted using horizontal displacements ranging from 110 to 308 min.) After moving onto the screen, the rectangle came to rest with its left edge 128 min to the left of the fixation point (66 min to the left of the left edge of the left bar).

The response on a given trial initiated the next trial after a 1-s blank interval, at which time the fixation cross and the bars were presented. The rectangle immediately began moving onto the display from the right at 8.8°/s (Fig. 1A). (The step-size of 4.4 min per 8.3 ms frame was small enough to mimic real motion.) Thus, the rectangle came to rest 125 ms after the bar lengths became completely concealed, which was 1570 ms after the rectangle began to appear at the start of the trial. After the rectangle stopped moving, there was a delay period chosen at random on each trial from the values 0, 1 or 2 s (Fig. 1B). The visible portion of the bars then underwent an apparent motion sequence (Fig. 1C) composed of three cycles, with an SOA or stimulus duration of 150 ms. There was no ISI; the total apparent motion duration was 900 ms. The first change in the display occurred 150 ms after the delay period elapsed, so for 0 delay, the first change was not simultaneous with the rectangle coming to rest After the ambiguous apparent motion sequence, the screen went blank, and the subject responded whether the perceived direction of the apparent motion was horizontal or vertical by pressing one of two keys.

Each of the three blocks in each session contained 144 trials and was balanced for delay period, horizontal displacement, and bar length, and randomly shuffled. Each subject participated in two sessions, held on separate days within 1 week of each other. Over the two sessions each subject performed 864 trials. Each session lasted about 45 min. Three naive subjects and one author (JSJ) participated. All had normal or corrected-to-normal vision, and performed 100% on the Stereo Optical four-alternative forced-choice disparity discrimination for 800, 400 and 200 s disparity.

If the extent of the bars continues to be represented even after it has been hidden for some time, a certain pattern of results is to be expected. The percentage of trials with a horizontal motion percept will be plotted against the horizontal displacement between the bars for both long and short bars. After a delay, the apparent motion bias (horizontal displacement at the 50% point) should be reduced for long bars compared to short bars. This is because a representation of longer bars is expected to have a smaller center-of-mass separation in the vertical direction, creating a greater tendency for a vertical motion percept. Reducing the horizontal displacement can make up for this tendency, so the horizontal displacement that yields 50% horizontal motion (the 'apparent motion bias') should be smaller for longer bars.

2.2. Results

The data are shown in Fig. 3. The first block of each session was considered practice to reduce apparent motion hysteresis and was discarded from the analysis. The two remaining blocks from each of the two sessions were pooled together, yielding 16 trials per combination of delay period, bar length, and horizontal displacement (576 total). The data for long and short bars have been plotted together for each subject and delay period. For each bar length, delay time, and subject, a probit analysis (Finney, 1971) was performed. The resulting cumulative normal psychometric curves are also shown. The horizontal displacement at which this curve passes through the 50% level (the apparent motion bias) was compared between the long and short bar conditions for each subject and delay period. Assuming the probit model, we computed the standard error of the difference, its normal deviate z, and the one-sided significance level P. Fig. 4 shows the apparent motion bias for each observer as a function of the time delay for both short and long bars.

An effect was observed in each of the four subjects for the 1-s delay period ($z = 6.23$, 4.18, 3.06, 2.85; $P < 0.05$). This corresponds to a reduced apparent motion bias for long bars compared to short bars (curves shifted to the left). The effect size was on the order of a 25% increase in the apparent motion bias for short bars relative to long bars (although this ranged from about 45 ± 20% in MMC to about 15 ± 6% in JNJ). Three of the four subjects (JSJ, VM and JNJ) showed an effect for the 2-s delay ($z = 4.88$, 2.38, 2.89; $P < 0.05$, MMC: $z = 0.84$, $P > 0.1$), indicating that while there may be individual differences in the duration of the memory effect, it can persist for even longer than the 1-s delay period that consistently showed the effect. We can take 1 s as a lower bound for the effect's duration, although an upper bound (a delay period beyond which virtually no subjects show an effect) remains to be observed. Analysis of the subject-averaged shift in the apparent motion bias by paired-difference one-sided t-test reveals an overall effect for both 1- ($t(3) = 4.79$; $P < 0.05$) and 2-s delays ($t(3) = 7.44$; $P < 0.05$).

We also see effects in all four subjects at 0 time delay ($z = 4.09$, 5.18, 2.83, 2.37; $P < 0.05$); the subject-average was also significant ($t(3) = 3.19$; $P < 0.05$). The time delay which has been plotted is the time from the rectangle coming to rest until the beginning of the apparent motion sequence, which starts with the tabs in their original positions for 150 ms. Recall that the occlusion is final (the bar length is completely hidden) 125 ms before the rectangle comes to rest. The experiment was so arranged in order to avoid an 'accidental' configuration in which the rectangle came to rest flush with a bar on its left edge. There is therefore a 275-ms interval between the concealment of the length of the bars and the first stimulus change of the apparent motion sequence. The presence of an effect after such a short time could easily be due to short-term visual storage persisting on the order of 250–300 ms (Sperling, 1960; Coltheart, 1980; Long, 1980). This time is also long enough for completion processes to occur (Sekuler & Palmer, 1992; Bruno et al., 1997). The first experiment alone does not determine whether the effect at 0 delay is due to amodal continuation or visual persistence.

3. Experiment 2: control for vertical perceptual organization and other 2-D explanations

In Experiment 1, we consistently observed memory effects of object length after temporal delays of 1 s and longer. Our interpretation of these results is that the amodal extension of a partly occluded object contains some memory of past visual experience of the object's length.

While we consistently observed effects of visual experience in the last experiment, there is conceivably an alternative explanation for these data, in which the phenomenon is unrelated to the amodal representation of a partially occluded object. It is possible, one might argue, that there is a greater 'vertical perceptual organization' of the display when the longer vertical bars had been present. That is, in trials that had longer bars in the display, the bars may have induced a perceptual organization in the vertical direction, and that is why

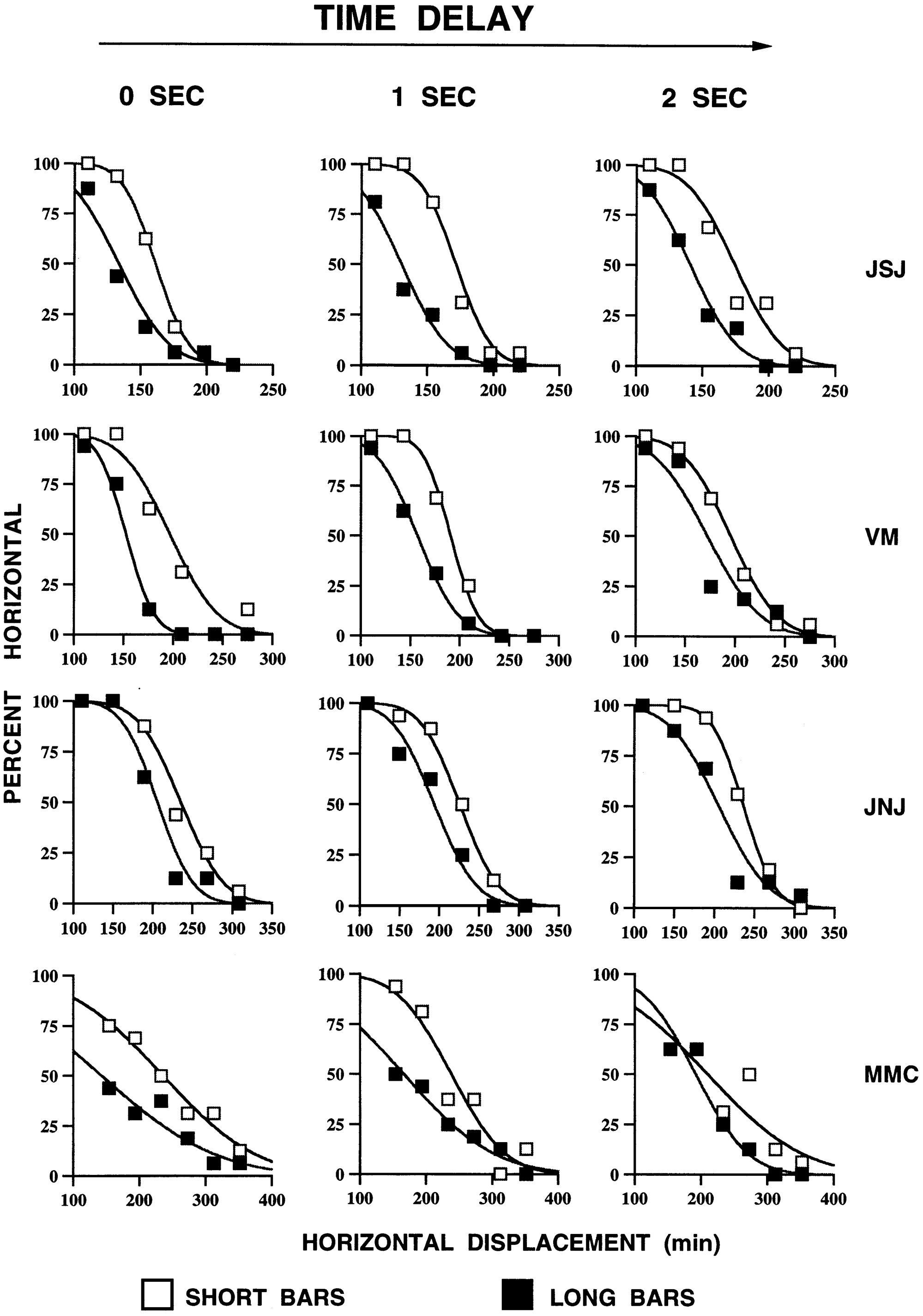

Fig. 3. Results of Experiment 1. For each of the four subjects and each delay time (0, 1 and 2 s), we have plotted the percent of the trials on which horizontal motion was perceived as a function of the horizontal displacement. In each graph, this is shown for long bars and short bars. All four subjects showed a bias towards vertical motion in the case of long bars at the 1-s delay period ($P < 0.05$). This indicates that the amodal representations of the bars are influenced by the past visual experience of bar length 1 s after it has become hidden. Three of the four subjects showed effects at the 2-s delay.

the subjects showed a tendency to perceive the ambiguous apparent motion in the vertical direction. It is also conceivable that for some reason visual persistence of these stimuli endures for the unusually long timescale of 1 s or longer.

3.1. Methods

We can reject these explanations by reversing the binocular disparity of the rectangle relative to the remainder of the screen. Because the 2-D configuration is

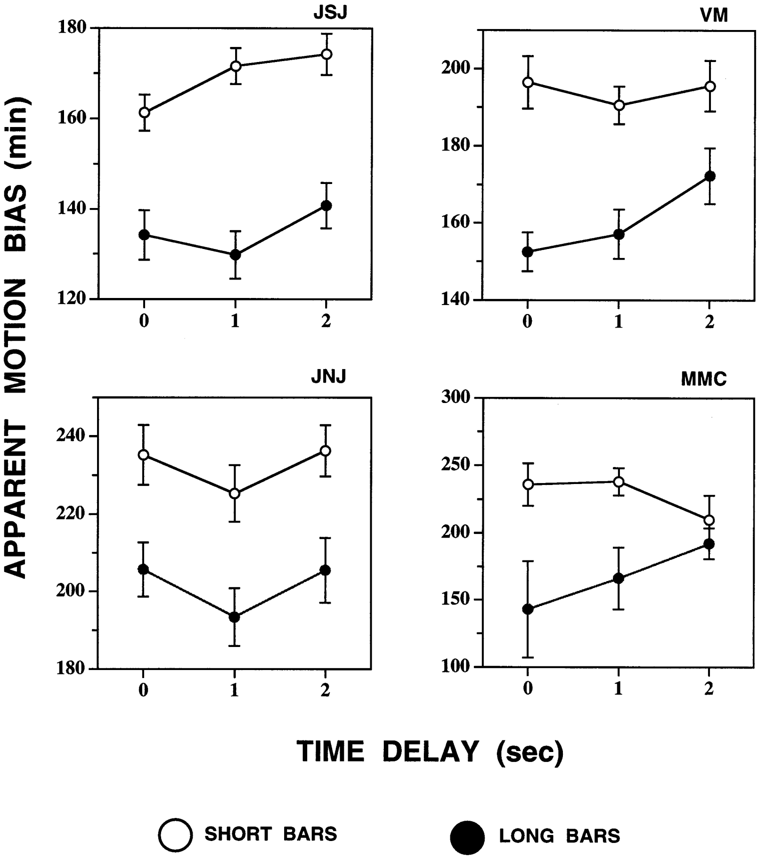

Fig. 4. The apparent motion bias (the horizontal displacement giving 50% horizontal motion on the psychometric curve) measured in Experiment 1 as a function of time delay for long and short bars. The effect size for a 1-s delay is on the order of a 25% increase in the apparent motion bias in the case of short versus long bars. The smaller apparent motion bias for longer bars reflects the greater tendency for a vertical motion percept. Error bars represent 1 S.E.

then the same, still containing the various lengths of the bars, we would predict the same result as found in the previous experiment if the hypotheses regarding the vertical organization or visual persistence were true. In contrast, according to the hypothesis that it is the amodal representations that are affected by previously seeing the fully visible objects, reversing the disparity leaves no opportunity for the visible tabs to be amodally extended. As such we should expect the abolition of the history effect.

The experiment was identical to Experiment 1 in every respect, except for the rectangle's reversed stereoscopic disparity of 13.2 min relative to the bars, making it appear farther away. In particular, the two-dimensional properties of the stimulus were the same. This was achieved by drawing the bars followed by the rectangle to the graphics board on each frame, as in Experiment 1, thus overwriting any portion of the bars sharing the same x–y coordinates with part of the rectangle. This prevents the presentation of any part of the bars overlapping with the rectangle, even though the rectangle is perceived as farther away than the bars. The same subjects participated in this experiment as in Experiment 1. As in Experiment 1, the first block of the first session was used to determine an adequate range of horizontal displacements for each subject, and the first block of each session was discarded as practice.

3.2. Results

The psychometric functions are shown in Fig. 5. None of the four subjects showed a significant effect for either the 1-s ($z = -1.33, -0.44, -0.48, 0.54$; $P > 0.1$) or the 2-s time delays ($z = -1.01, 0.77, 0.11, 1.28$; $P > 0.1$). There was no significant subject-averaged shift at either 1 s ($t(3) = -1.14$; $P > 0.1$) or 2 s ($t(3) = 1.05$; $P > 0.1$).

The absence of any effects at these delays rules out any explanation in terms of 'vertical organization' of the display, as well as any other 2-D effects. The different results in the two experiments are reflected in the interaction between rectangle disparity (front/back) and the bar length, which was significant for both 1 s ($t(3) = 6.98$; $P < 0.05$) and 2 s ($t(3) = 3.11$; $P < 0.05$).

At 0 time delay, there was an overall effect ($t(3) = 3.06$; $P < 0.05$), although two subjects (VM and MMC) individually showed an effect ($z = 3.02, 2.05$; $P < 0.05$)

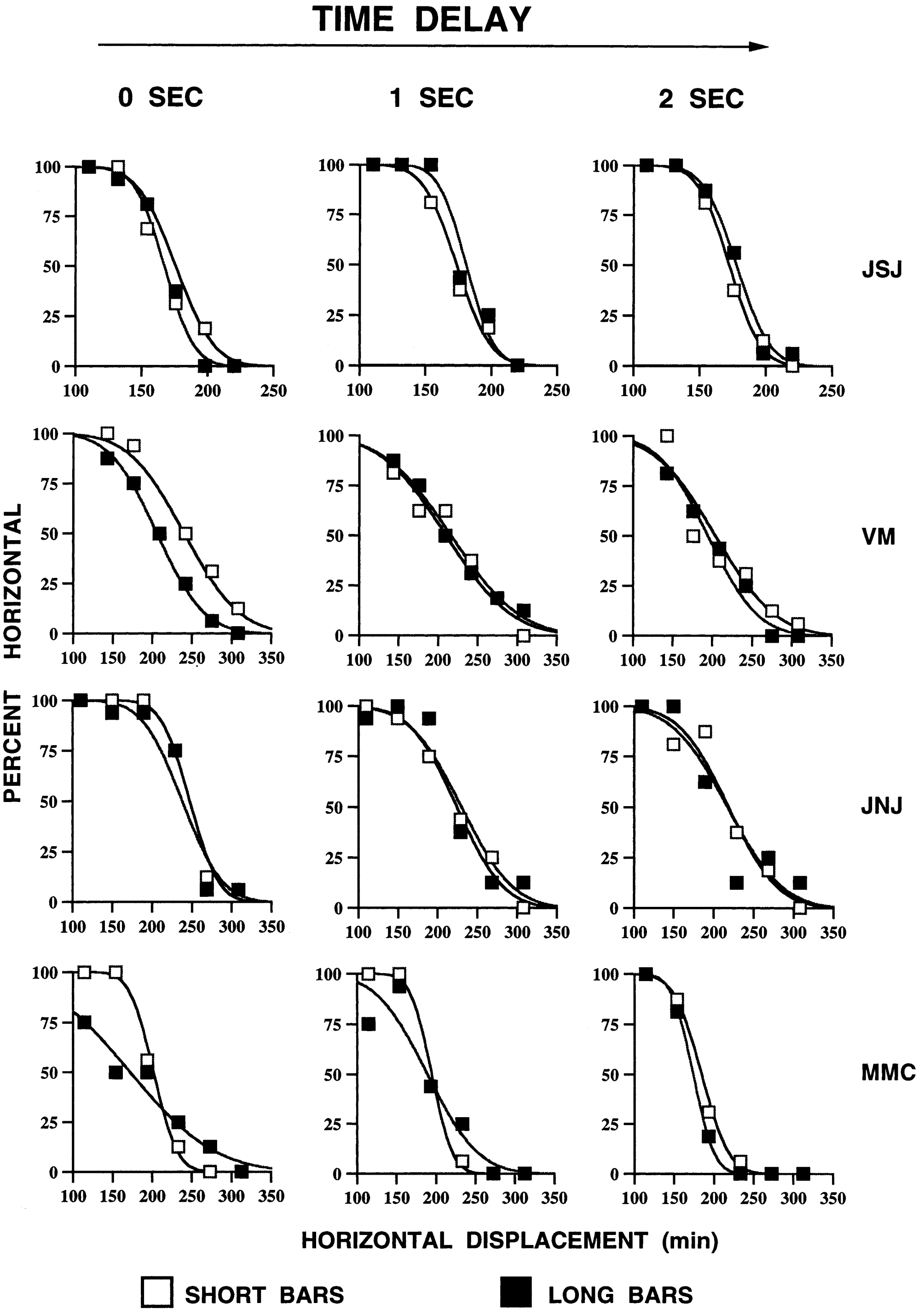

Fig. 5. Results of Experiment 2. The experiment rules out the possibility that the effects of Experiment 1 were simply due to an increased 'vertical organization' of the display in the case of long bars, or any other two-dimensional effect. The stereoscopic disparity of the rectangle relative to the bars has been reversed. This makes the rectangle appear farther than the bars, rendering the stimulus inconsistent with a 3D layout of bars behind a rectangle. At the same time, it does maintain the same exposure to the bars, and thus the degree of 'vertical organization', as in Experiment 1. Upon reversing the disparity, the history effect disappears. None of the four subjects showed a significant difference in the apparent motion bias between the long and short bar trials at either the 1- or the 2-s delay periods. This is in sharp contrast to the results of Experiment 1.

while two did not ($z = 1.44$, 0.98; $P > 0.1$). The mean effect here was weaker than that found at 0 delay with the rectangle in front in Experiment 1, as seen from the interaction between rectangle disparity and bar length ($t(3) = 2.38$; $P < 0.05$). This suggests that the effect at 0 time delay observed in Experiment 1 was due to a combined effect of amodal continuation and visual persistence.

With the data from this experiment, we can also determine which bar length, long or short, dominated the effects that were observed in Experiment 1. The shift between the psychometric curves found in the two experiments at the 1-s delay was significant for the long bars ($t(3) = 5.30$; $P < 00.05$) but not for the short bars ($t(3) = -0.44$; $P > 0.1$). This shows that the long bars were chiefly responsible for the effects of previous experience exhibited in the first experiment. The long bar is treated by the visual system like a short bar when the 'occluding' rectangle is farther than the visible pieces, but not when the rectangle is in front as a natural occluder.

The marked distinction between the results of this experiment and those of Experiment 1 at the 1- and 2-s delays demonstrates that the results of the first experiment are not due to any 2-D effect such as perceptual organization or visual persistence. Instead, the results lead to the more specific conclusion that the amodal representation of a partially occluded object depends on the previously seen fully visible object for more than 1 s after it has been occluded. The overall pattern of results is summarized in Fig. 6.

4. Discussion

These results demonstrate that the amodal representation of a partly occluded object depends on the previous experience of seeing the object before the occlusion event, when it was fully visible. Objects that are seen before partial occlusion to have different lengths, but that present physically identical stimuli after occlusion, are amodally represented differently after occlusion. This effect of previous visual experience, or 'memory' in the empirical sense, persists for at least 1 s, and in some naive subjects for as long as 2 s or potentially longer.

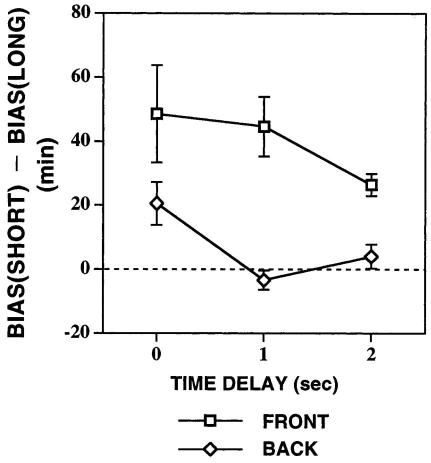

Fig. 6. Summary of the results. The difference between the subject-averaged apparent motion biases in the short and long bar conditions is plotted, for the case of the rectangle in front, in which amodal continuation is possible, and for the case of the rectangle in back, in which no amodal continuation can occur.

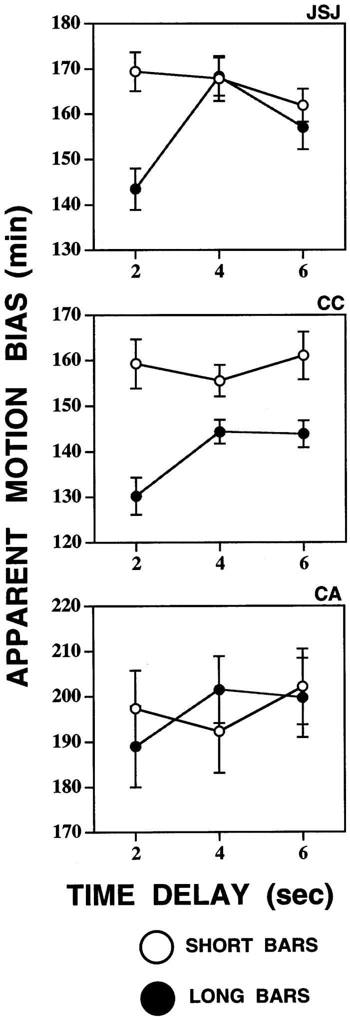

Fig. 7. The apparent motion bias at longer time delays (2, 4 or 6 s) for long and short bars.

As a first step toward determining the maximum duration of the effect, we tested the longer time delays of 2, 4 and 6 s following occlusion. The results from one author and two new naive subjects are summarized in Fig. 7, which shows the apparent motion bias as a function of the time delay. At the 2-s delay, observers JSJ and CC showed an effect ($P < 0.05$), although CA did not ($P > 0.1$). Putting these results together with the results of Experiment 1 for a 2-s time delay, we find that four of six subjects tested with this delay showed the history effect. This indicates that the effect can persist for longer than the 1-s delay for which all subjects showed the effect in Experiment 1, although there are individual differences in the effect's duration.

Examination of performance at even longer time delays shows further indication of individual differences in the duration. Neither JSJ nor CA showed an effect at the 4- or 6-s time delays ($P > 0.1$), while CC showed the effect at all time delays tested ($P < 0.05$). Thus, we can place a lower bound of 1 s on the effect's duration, but an upper bound at which no subjects show the effect remains to be found. Because observer CA showed no effect at either 2-, 4- or 6-s delays, this observer was subsequently tested with the 0-, 1- and 2-s delays presented to observers in Experiments 1 and 2 (see Fig. 8). Again, CA showed no effect at 2 s ($P > 0.1$), but like the subjects in Experiment 1, displayed the memory effect for the 0- and 1-s delays ($P < 0.05$). Thus, all five of the subjects tested at the 1-s delay showed an effect.

Our findings demonstrate that the visual system maintains a representation of the attributes of an object that are concealed by partial occlusion. These results extend the idea of phenomenal permanence, the perception of continuity of the existence of objects, enunciated by Michotte and others (Michotte, 1950; Burke, 1952; Michotte, 1963; Michotte et al., 1991; Yantis, 1995). Our results can be thought of as an expression of the perceptual persistence of an object's attributes, beyond the object's existence. We postulate that while the objects in a scene are fully visible, the resulting image is parsed into surfaces or objects (Gibson, 1950, 1966, 1979; Marr, 1982; He & Nakayama, 1992; Nakayama & Shimojo, 1992; He & Nakayama, 1994b). These are tagged in some way, perhaps by the creation of object files (Kahneman & Treisman, 1984) or by some other identity maintenance mechanism (Pylyshyn & Storm, 1988). When the partial occlusion occurs, the scene does not need to be parsed again, for the tagged objects are imbued with permanent existence, unless events indicate otherwise (as in Experiment 2). The present study shows that the contents of the object file, and not just its existence, survive the occlusion event and are reflected in the way the object is amodally represented. These contents consist of the object's attributes, such as shape or size. In this sense, the amodal representation of the object reflects the attributes of the formerly completely visible object. The assignment of attention to the object before occlusion, and the maintenance of that assignment, may be involved in the representation of those attributes (Joseph & Nakayama, 1995b).

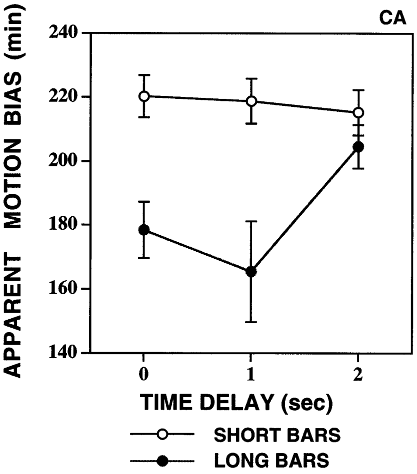

Fig. 8. Results for subject CA, showing the effect at the 1-s delay.

The history dependence of the amodal representation following partial occlusion adds another dimension to the problem of understanding how partly occluded objects are represented by the visual system, and forces us to consider the more complete problem of dynamic scenes. As a result, modeling efforts may have to be extended beyond completion rules for partially occluded objects in static scenes.

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