

## Memory for Visual Motion

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Observers briefly viewed random dots moving in a given direction and subsequently recalled that direction. When required to remember a single direction, observers performed accurately for memory intervals of up to 8 s; this high-fidelity memory for motion was maintained when observers executed a vigilance task during the memory interval. When observers tried to remember multiple directions of motion, performance deteriorated with increasing number of directions. Still, memory for multiple directions was unchanged over delays of up to 30 s. In a forced-choice experiment, observers viewed 2 successive animation sequences separated by a memory interval; for both sequences, dots moved in any direction within a limited bandwidth. Observers accurately judged which animation sequence was more coherent, even with memory intervals of 30 s. The findings are considered within the context of cognitive bias and memory for other aspects of perception.

Effective visuomotor behavior often is guided by visual information acquired at some time prior to the execution of that behavior (e.g., visually checking for oncoming vehicles before crossing a street). Our actions, in other words, are often guided by previously experienced events. Because of the close link between perception and action, a complete understanding of various aspects of vision (e.g., motion perception) must include an account of the efficiency with which visual information is represented in and recalled from memory. After all, the time needed for execution of visually triggered action may be considerably longer than the time required for registration of the visual information eliciting that action. Consequently, we are often acting on a memorial representation of visual information. Surely biological systems are designed to deal with this constraint by including memory within the processes of sensorimotor integration. It was this general consideration that motivated our work on memory for visual motion, some of which was reported briefly in abstract form (Cepeda, Hiris, & Blake, 1994).

We felt that it would be particularly informative to study memory for motion for two reasons. One, several lines of evidence already implicate memorial processes in motion

perception. For instance, motion perception exhibits hysteresis (e.g., Williams, Phillips, & Sekuler, 1986), whereby the current perceived direction of semicoherent motion depends on the observer's immediate past history of exposure to motion. Also, the visual aftereffect of adaptation to motion—the so-called *waterfall illusion* (Hiris & Blake, 1992; Wohlgenuth, 1911; Sekuler & Ganz, 1963)—may be construed as a type of motion “memory,” in that one's current perception of motion is altered by prior, extended exposure to motion. A second reason for our interest in memory for motion centers around recent psychophysical and neurophysiological advances in our understanding of the neural representation of motion information (e.g., Salzman & Newsome, 1994) as well as the consequences of that representation for detection and discrimination performance (e.g., Wilson & Kim, 1994). Knowing something about how the brain initially registers information about motion provides a solid point of departure for exploring how accurately that information is maintained within the nervous system and, subsequently, deployed for cognitive judgments. This reasoning follows directly from the view that memory, rather than corresponding to storage in dedicated memory units, is the neurophysiological instantiation of information processing originally engaged at the time of a perceptual experience. To quote from a proponent of this view (Crowder, 1993, p. 115): “Where that original experience was played out, in brain activity, is where the memory for it will correspondingly reside afterwards.” Thus, our growing knowledge about the neural registration of motion information guides our search for the nature of memory for motion.

To pursue this question, we developed several procedures for exposing observers to motion sequences and, then, having them recall specifics about those sequences. These procedures involve either indicating the direction(s) in which translational motion was previously experienced or discriminating one motion sequence from another under conditions in which time elapses between the first and second presentations. The first procedure uses a technique that we term *point and click* because the observer uses a mouse cursor to

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indicate, on a video display, the direction of remembered motion. This procedure provides a measure of error, which should increase as the fidelity of the memorial representation of motion information decays. The second procedure, termed *delayed discrimination*, indexes memory in terms of discrimination performance on a two-alternative, temporal forced-choice task by which the animation sequences comprising the first and second intervals are separated by a time interval, thereby requiring the observer to compare the second animation sequence with the remembered version of the first.

## Method

### Animation Sequences

In the manner of Williams and Sekuler (1984), our visual animation sequences consisted of random-dot cinematograms (RDCs) presented on a 12-in. (Ca. 30-cm) monochrome video monitor (66.7 Hz, P4 phosphor; 640 × 480 pixels; 76 pixels/in.) under control of a Macintosh computer. Except where otherwise noted, each sequence consisted of 300 randomly positioned, black dots (each dot 2 × 2 pixels) viewed against a white background. At the viewing distance of 80 cm, the visual angle subtended by each dot was 3 × 3 arc min, and the array of dots appeared within a circular region 3° in diameter. From frame to frame of an animation sequence, each dot was displaced to a new position, with the step-size adjusted to yield smooth apparent motion at an average speed of approximately 4°/s.<sup>1</sup> For most experiments, all dots moved in a given direction during the entire animation sequence (we term this type of display *coherent motion*). For one experiment (Experiment 3), each of the 300 dots chose a new direction from a range of possible directions specified by a rectangular distribution, the directional bandwidth (range of directions) and mean of which could be varied (we term this type of display *bandwidth motion*) (see Gilden, Hiris, & Blake, 1995, for mathematical description of this class of RDCs).

### Procedure

Schematics for the various procedures used in these experiments appear in Figure 1. In the interest of clarity, those procedures are detailed in the descriptions of specific experiments, and the reader will want to refer back to Figure 1 while reading those descriptions.

### Observers

A total of 12 individuals (5 women and 7 men ranging in age from 19 to 48 years) participated in one or more of these experiments. All had normal or corrected-to-normal vision, and 3 of the 12 were paid for their participation in the study. All experiments received prior approval from the Vanderbilt University Institutional Review Board.

## Results

### Memory for Single Directions of Motion

*Experiment 1.1: Memory over different delays.* This experiment used the point-and-click technique schematized in

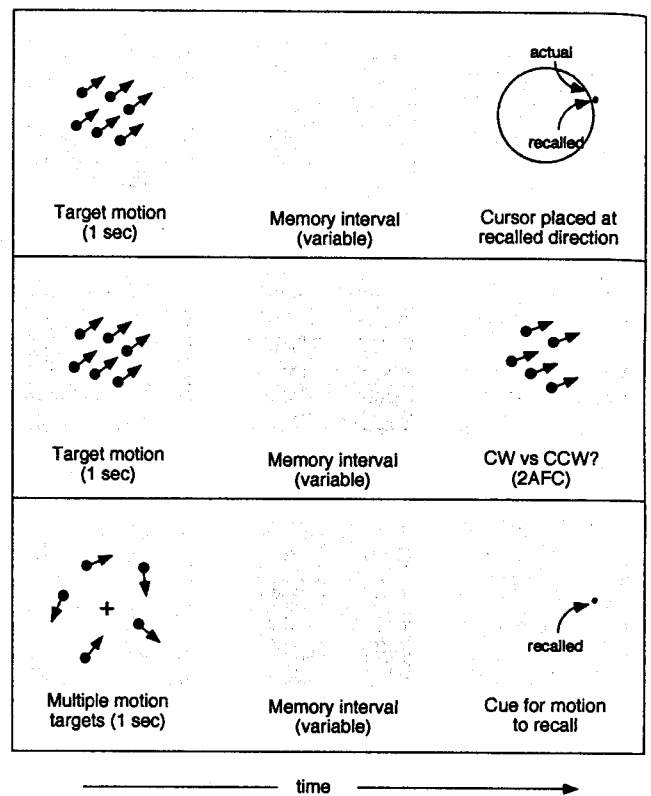


Figure 1. Schematics illustrating three techniques used in studying memory for motion. Upper panel: A point-and-click technique whereby the observer used the mouse to position the cursor at the position, on a circle, associated with the remembered direction of motion; angular difference between actual and remembered values indexes accuracy. Middle panel: A two-alternative, forced-choice task (2AFC) in which the observer indicates whether the direction of motion presented during the first interval was clockwise (CW) or counterclockwise (CCW) to that presented in the second interval. Lower panel: The point-and-click procedure adapted to a partial report technique whereby multiple patches of motion are presented simultaneously, with one patch subsequently cued for recall.

the upper panel of Figure 1. On each trial, the observer fixated a small mark in the center of the video display, used the mouse to position the on-screen cursor on this mark, and then clicked on this mark to trigger a trial. Each trial consisted of a single 1-s presentation of a RDC (i.e., coherent motion of all 300 dots in a single direction); neither the cursor nor the fixation mark was present during this 1-s display period. Following a blank interval of variable duration, a 3° circle (outlined by a thin, black line against a white background) appeared, thus cuing the observer to recall the direction portrayed in the RDC. Recall was ac-

<sup>1</sup> Given the discrete nature of the pixelated display, the actual speed which is governed by distance displaced from frame-to-frame, ranged from 3.8 to 4.2°/s depending on the particular direction in which dots moved. This variation in speed is close to the smallest difference in speed that humans can discriminate under optimal conditions (e.g., McKee, 1981).

completed by the observer using the mouse to place a small dot at the position on the circumference of the circle corresponding to the remembered direction of motion. When the observer clicked the mouse button, this angular direction was recorded and its deviation from the true direction was registered by the computer. Successive trials using this point-and-click technique were self-paced, and observers were encouraged to rest whenever they desired. Trials were typically administered in blocks of 40.

Eight observers were tested using delay intervals of 0, 1, 2, 4, or 8 s (where delay refers to the time elapsing between offset of the 1-s episode of target motion and onset of the circle used for registering responses). The actual direction varied randomly over trials, with each observer receiving a total of 200 trials (40 for each of 5 delays).

Figure 2 summarizes results from this experiment, with each histogram showing the average absolute error (i.e., absolute difference between actual and remembered direction) for a given delay; the short, vertical lines denote  $\pm 1$  SE of the mean. In substantiation of the general trends evident in these histograms, an analysis of variance (ANOVA) revealed no significant effect of delay [ $F(4, 35) = 0.27, p = 0.89$ ]. Evidently, observers are able to maintain a relatively high-fidelity representation of an animation sequence for at least a short time following termination of that sequence. Learning something about the nature of that representation was the goal of the next several experiments.

*Experiment 1.2: Noise during delay interval.* Is it possible that a 1-s exposure to a given direction of motion leaves a sensory aftereffect of that event, which the observer can then visually reference for performance of the point-and-click task? (An adaptational aftereffect, of course, would represent one particular form of visual memory, albeit one that has more the quality of an iconic afterimage.) To address this possibility, we repeated the point-and-click experiment on one observer, with one significant modification. On each trial, random motion (i.e., dots moving in all possible directions, with no net flow in any given direction) appeared during the previously blank interval. Following the same reasoning adopted in many other sorts of visual tasks involving sequential stimulation (Breitmeyer, 1984; Sagi & Julesz, 1985; Treisman, Russell, & Green, 1975), we reasoned that exposure to this noise display would effectively erase an iconic trace of the test motion. As may be seen in Figure 3, memory for motion does not decay with increasing delay interval. The top panel shows the average error for each memory delay (along with  $\pm 1$  SE, denoted by the short vertical line);  $t$  tests comparing the zero delay condition with each of the other delay conditions revealed no significant differences. To provide a feeling for the trial-to-trial variability on this task, we have plotted, in the bottom panel, individual error values for each of the five delay values.

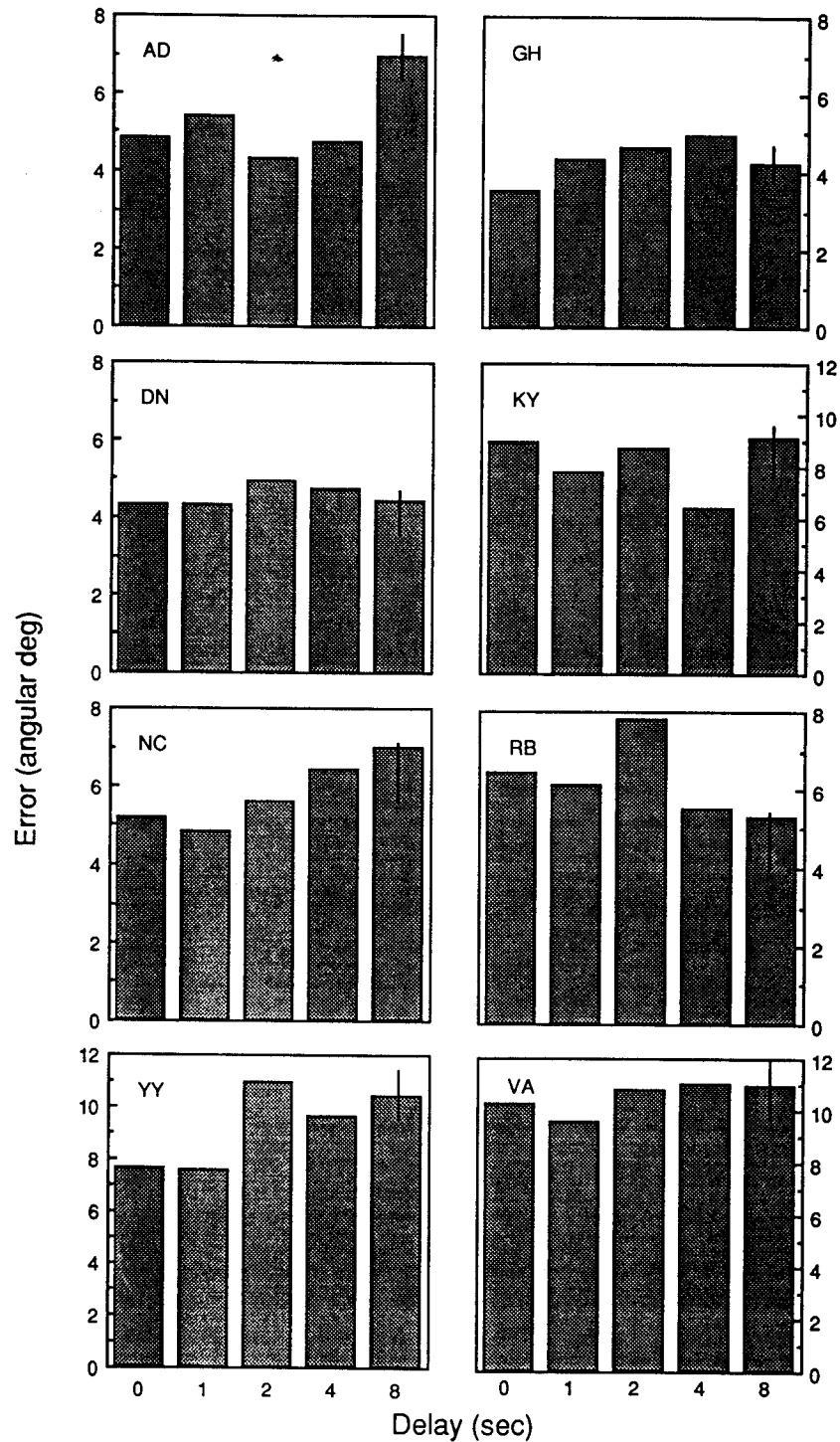
So, these results imply that the memorial representation of visual motion is not a literal, iconic leftover that can be masked by noise; this conclusion is substantiated further by results from Experiment 2.2, described in the following section. Rather, we are led to entertain other hypotheses

about the nature of this visual memory, hypotheses tested in the following experiments.

*Experiment 1.3: Tracking task during memory interval.* In the above experiments, no specific instructions concerning fixation were given to observers. So, it is conceivable that their eyes tended to track the path of coherent motion during the 1-s presentation, a natural tendency when viewing these kinds of displays. Perhaps, then, observers were remembering something associated with eye movements engendered by the test display. This motoric information could include command signals associated with the generation of the tracking eye movements or the proprioceptive signals within the oculomotor system produced as the eyes actually moved. To assess the possible role of eye movement-related information, we modified the task to include a vigilance task during the blank interval between the offset of the 1-s test stimulus (an RDC depicting motion in a randomly selected direction) and the introduction of the point-and-click task. This vigilance task required the observer to fixate a single, small ( $5 \times 5$  pixel) dot that changed position within the circular display area 8 times/s, with a constant step size of 10 pixels (which yielded the appearance of slightly jerky movement). Because the frame-to-frame direction of dot position was random, the observer could not predict its path. At any time during this tracking episode, the dot's size could abruptly shrink to  $3 \times 3$  pixels and then continue its random path of movement; the observer was instructed to tap the spacebar on the keyboard as quickly as possible whenever a size change was detected. The change in size was sufficiently small that foveal viewing was required to detect it accurately, thus forcing the observer to track the dot with the eyes at all times. Being stochastically determined by the computer, size changes did not occur on all trials, but failures to react within 750 ms to a size change when it did occur was defined as an *error*. Once a size change occurred, the dot remained small and continued its random walk until the memory interval was over; observers knew that only one size change, at most, would occur during a given memory interval. A total of 40 trials was administered at each of five delay intervals (0, 1, 2, 4, and 8 s), with the order of trials randomized over the 200 total trials. The three observers were encouraged to rest whenever they desired.

This tracking task during the memory interval, we reasoned, should effectively override any oculomotor cues associated with viewing the 1-s test sequence. Moreover, the vigilance needed to monitor this event for a size change required considerable attentive effort, thus precluding mental rehearsal of the RDC test sequence.<sup>2</sup> In spite of these increased cognitive demands, performance on the recall portion of the test was good and was constant for the delay intervals tested. The set of histograms in Figure 4 shows

<sup>2</sup> This task, the presentation of an item (i.e., an RDC) to be remembered for a short time, with a distractor task intervening between the presentation and the test, could be construed to be a modified version of the Brown-Peterson paradigm popularized in the mid 60s and early 70s as a technique for studying short-term memory.



*Figure 2.* Average absolute error for each of eight observers tested at five memory delay intervals. For each observer, 40 trials were devoted to each delay. The vertical lines superimposed on the histograms associated with a delay of 8 s denote plus or minus the average standard error for that observer. deg = degree.

average errors for each of the five delay intervals tested; these data summarize results from all the trials, regardless of whether or not the observer responded within the specified

750 ms period on the vigilance task. Error rate (i.e., proportion of trials on which a size change was missed or detected after more than 750 ms) ranged from 0.20 to 0.28

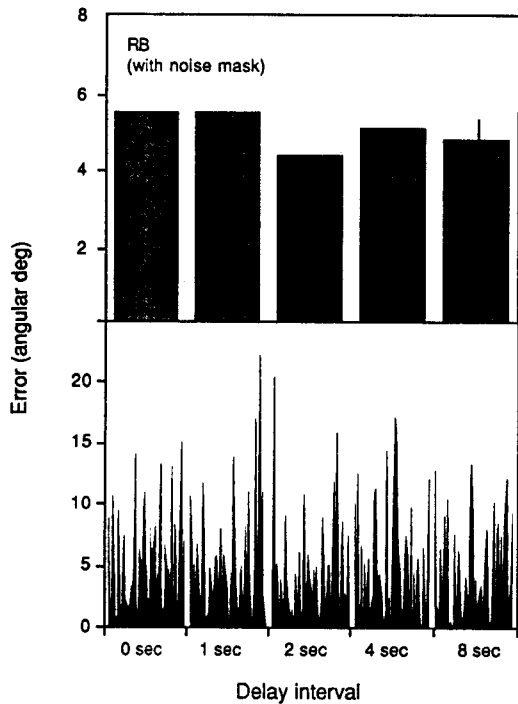


Figure 3. Upper panel: Average absolute error for observer RB tested at five memory delay intervals, in a condition in which random noise was presented during the memory interval. Each histogram is the average of 50 observations. Lower panel: Distribution of errors on a trial-by-trial basis, segregated here as the function of delay interval (the actual sequence of trials was randomized over delay). deg = degree.

among the three observers tested, confirming the difficulty of the task. Analyzing angular settings on "hit" and "error" trials revealed no evidence that observers were better at remembering motion direction on trials producing errors versus trials yielding correct detections (see Figure 5). There were, of course, more errors on trials associated with longer memory delays, as one would expect on the basis of probability alone. The important finding, however, is the constancy of memory accuracy over delays ranging from 0 to 8 s, even when observers were distracted during the memory interval. The statistical insignificance of delay interval was confirmed both by ANOVA [ $F(4, 10) = 0.27$ ,  $p = 0.89$ ] and by individual  $t$  tests comparing the zero delay results with those for delays of 1, 2, 4, and 8 s. We interpret these results to be evidence against hypotheses attributing memory accuracy to eye movement-related cues or to active rehearsal of motion during the interval between test and recall.

*Experiment 1.4: Forced-choice testing of memory for motion.* The final experiment in this series sought to confirm that the pattern of results found in the first 3 experiments was not peculiar to the point-and-click technique. A two-alternative, forced-choice task was used, whereby observers viewed two successive 1-s RDCs depicting translational dot motion (middle panel, Figure 1). They judged whether direction of motion in the second sequence was

clockwise or counterclockwise relative to that displayed in the first sequence, guessing if necessary; error feedback was not given. The interval between motion sequences was either 0, 4, or 8 s. On each trial, the direction of motion for the first sequence was selected randomly from all directions; the direction of motion shown in the second sequence was within a range from  $\pm 12^\circ$ , of the first, with values sampled in  $4^\circ$  steps yielding a total of seven angular disparities ( $\pm 12^\circ$ ,  $\pm 8^\circ$ ,  $\pm 4^\circ$ ,  $0^\circ$ ). Each angular disparity was presented a total of 63 trials for each memory delay interval, with the order of delays and disparities varied randomly within blocks of trials.

The results for the three observers tested on this task are summarized in Figure 6, which shows psychometric functions for each of the three memory delay intervals. Performance is essentially invariant with delay interval, as indicated by the comparable slopes for the trio of curves in each panel. Estimates of accuracy on this task may be derived by

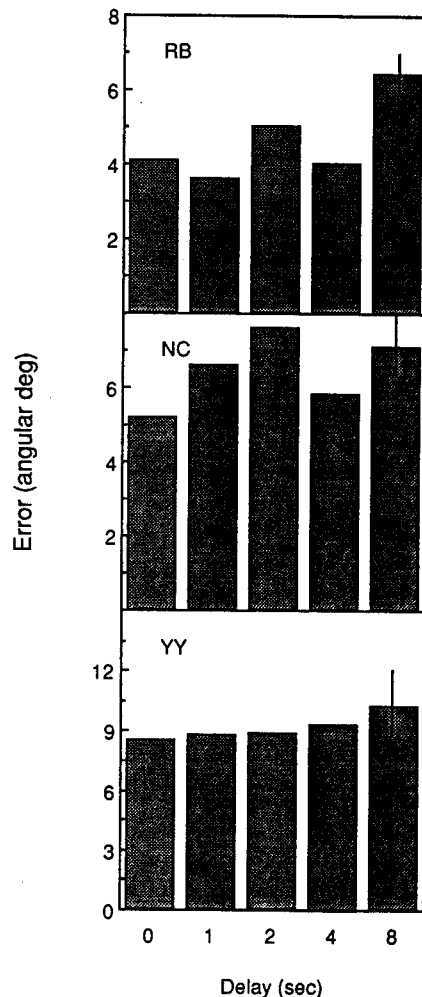


Figure 4. Average error for remembered direction of motion for three observers tested using five different memory delays. The observer visually tracked a small moving dot during the memory interval, signalling when the dot changed in size. deg = degree.

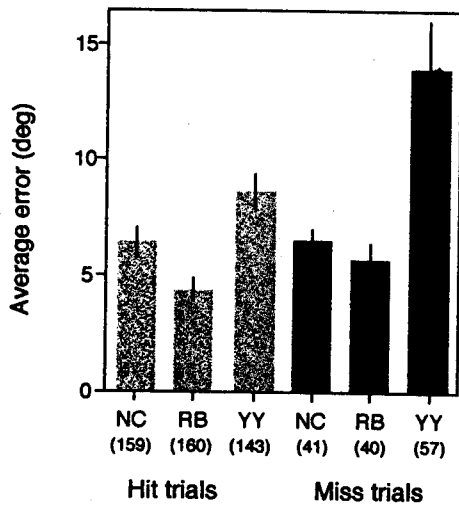


Figure 5. Average error in remembered direction of motion on trials during which the observer successfully detected a change in size of a small dot presented during the memory interval (hit trials) and on trials during which the size change went undetected within the specified 750-ms interval (miss trials). Numbers in parentheses under each observer's initials give the number of hits and misses. Vertical lines indicate  $\pm SE$ . deg = degree.

computing the values of angular deviation associated with 75% response level. For observers RB, NC, and YY, those values are  $6^\circ$ ,  $4^\circ$ , and  $8^\circ$ , respectively. Comparison of these values with the data for these observers in Experiments 1.1 and 1.3 reveals that accuracy of memory for motion was essentially the same for the two tasks, point-and-click and two-alternative forced choice, suggesting that the two different response measures tap a common memorial representation for motion direction.

#### Memory for Multiple Directions of Motion

The failure to find decay in the accuracy of memory for direction in these first experiments led us to wonder how observers would perform on tasks that presumably placed greater demands on visual memory. In particular, we wanted to devise tasks that required observers to retain direction information about multiple motion sequences. The following two experiments describe our efforts along those lines.

**Experiment 2.1: Full serial recall.** In the memory literature, a commonly used procedure—serial recall—entails exposure to a list of items to be remembered, with complete recall tested some short time later. In general, people are relatively better at remembering items appearing at the beginning and at the end of the list (e.g., Greene & Samuel, 1986). We have looked for comparable behavior when people are required to remember multiple motion sequences. To adapt the serial recall paradigm to memory for motion, a modified version of the click-and-point procedure was used. Observers successively viewed a series of 1-s RDCs, each depicting a different direction of motion (se-

lected randomly, with replacement); the number of RDCs presented on a given trial was either 3, 5, 7, or 9, and the interval between successive RDCs was 750 ms. Each successive RDC appeared within the same, centrally fixated circular aperture 3 deg in diameter. Subsequently, the observer was required to indicate the directions of motion, in the order in which they were displayed, by clicking successive positions around the circumference of a circle. This recall test was administered after an interval following

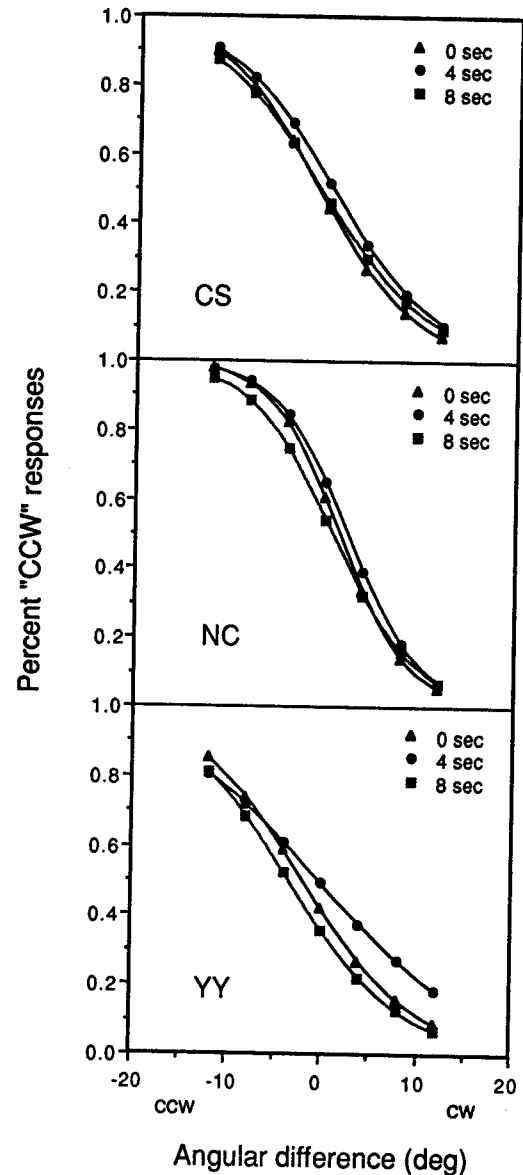


Figure 6. Percentage correct on a two-alternative, forced-choice task in which the first and second random-dot cinematogram presentations were separated by a memory interval of 0, 4, or 8 s. Results are shown individually for the three observers tested. Smooth curves were fit using logit analysis. The overlap among individual curves within a given panel is greater than the standard deviation for any curve, computed from binomial probability. cw = clockwise; ccw = counterclockwise; deg = degree.

offset of the last RDC of the sequence; memory intervals tested were 0, 10, and 30 s, with no explicit distracting task during the memory interval. Four observers were tested on this task, with 50 observations devoted to each of the 12 conditions (4 different numbers of RDCs  $\times$  3 Memory Intervals).

Results are presented in Figure 7. The data were submitted to a randomized block, partially hierarchical ANOVA, the dependent variable being error and the independent variables being delay, number of items and serial position; in this particular design, the Serial Position factor was nested within the Number of Items factor. Analyses revealed significant main effects for number of items ( $F(3, 9) = 16.2, p < .01$ ) and for serial position ( $F(20, 60) = 8.55, p < .01$ ); the effect of delay was nonsignificant ( $F(2, 6) = 2.8$ ) as was the interaction between delay and the number of items ( $F(6, 18) = .56$ ). The interaction between delay and serial position just reached significance ( $F(40, 120) = 1.5, p < .05$ ). We conclude, therefore, that accuracy of memory for direction deteriorates with increasing numbers of directions to remember. In addition, accuracy depends on where in the initial presentation sequence the to-be-remembered event occurred, a classic serial position

effect of the sort commonly found in word recall. The pattern of results in Figure 7, especially for sequences consisting of 7 or 9 successive RDCs, is suggestive of a strong primacy effect (i.e., relatively small errors for remembered direction of motion of RDCs appearing early in the serial order) and, perhaps, a weak recency effect (i.e., smaller errors for the last RDC in the sequence, compared with errors for those directions presented in the middle of the sequence). Again, however, we find that memory accuracy for a given set size of motion sequences does not deteriorate with time, at least up to 30s.

Accuracy was generally poorer on this task involving multiple animation sequences—comparing the average accuracy for 0-s delay in this experiment (a value in the neighborhood of 10°) with that for the 0-s condition from Experiment 1.1 (average error around 5°). This general impairment in memory for motion is certainly not surprising, for the original task never required remembering more than one direction of motion at a time. Evidently, a more potent, limiting factor in memory for motion is the number of items that must be held in memory, not the interval over which that information must be retained. This conclusion is subjected to more testing in the next experiment.

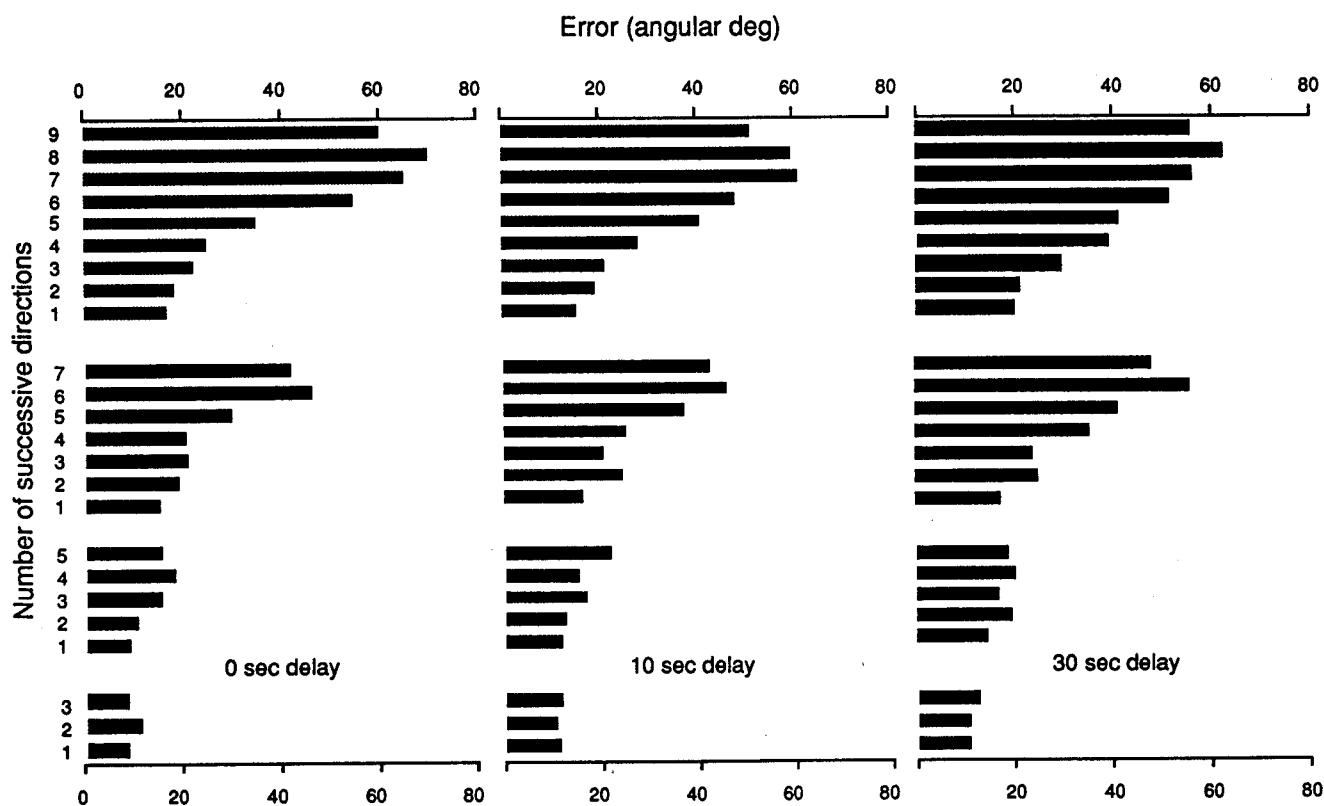


Figure 7. Average absolute error in remembered direction of motion as the function of the number of random-dot cinematogram (RDC) sequences seen (3, 5, 7, or 9) and the interval between the offset of the last RDC and the test period (0, 10, or 30 s). Results averaged across four observers are shown. Particularly when required to remember seven or nine directions of motion, observers evidence relatively better performance (i.e., lower error) for the first and last sequences in the serial order of presentations. deg = degree.

**Experiment 2.2: Partial report.** Results from the previous experiment indicate that memory for motion becomes increasingly poorer as observers are required to register and recall more and more discrete events. It is conceivable, however, that this degradation in performance arises, at least in part, from response interference at the time of recall, not from memory deterioration during the blank interval. *Response interference* is an impairment in performance occasioned by the demand to reproduce multiple, successive click-and-point responses. To address the question of memory deterioration per se, uncomplicated by response requirements, we tested observers on a task involving simultaneous exposure to multiple motion sequences followed by a single response designed to probe short-term memory for those sequences. Specifically, we used a version of the partial report technique, developed by Sperling (1960) and modified by Treisman et al. (1975), which is illustrated schematically in the bottom panel of Figure 1. On each trial, the observer triggered the simultaneous 1-s presentation of multiple RDCs arranged in an evenly spaced configuration around the circumference of an imaginary circle centered on a fixation point. Each RDC (300 black dots against a white background) appeared within a 3° circular area. The direction of coherent motion portrayed in each RDC was determined independently, with no restriction on direction; dot speed was always approximately 4°/s. During the blank, memory interval (i.e., the period between offset of the RDC and onset of the cue signalling the memory test), only the fixation mark was visible. Following the blank interval, a 3° diameter, black-outline circle appeared at one of the locations in which a RDC had been displayed; the width of the line defining the circle's circumference was 3 arc min. Using the mouse, the observer moved a small spot to a position on the circumference of this circle corresponding to the remembered direction of motion for that RDC. In a given block of trials, the number of RDCs presented on a given trial was either 3, 5, or 7, the particular number varying randomly from trial to trial. The interval elapsing between offset of the array of RDCs and the cue was either 0, 10, or 30 s, and this too varied randomly from trial to trial. A total of 50 trials was devoted to each of the nine conditions (3 Memory Delays × 3 Display Sizes); three observers were tested.

Results from this experiment are summarized in Figure 8. Memory accuracy varied with number of motion directions initially presented but was minimally affected by the interval between the presentation of these multiple RDCs and the administration of the recall test. ANOVA revealed a significant effect of display size [ $F(2, 18) = 30.2, p < .005$ ] but a nonsignificant effect of memory interval [ $F(2, 18) = 2.87, p = .083$ ] and a nonsignificant interaction between delay and interval [ $F(4, 18) = 0.23, p = .91$ ].

The magnitudes of the errors made by observers corresponds very closely to those found in Experiment 2.1 (comparing the data for 3, 5, and 7 displays in Figure 8 with the corresponding histograms in Figure 7). So again, we have evidence that memory for motion is distinctly limited in channel capacity (as implied by the increase in error magnitude with number of displays to remember) but is rela-

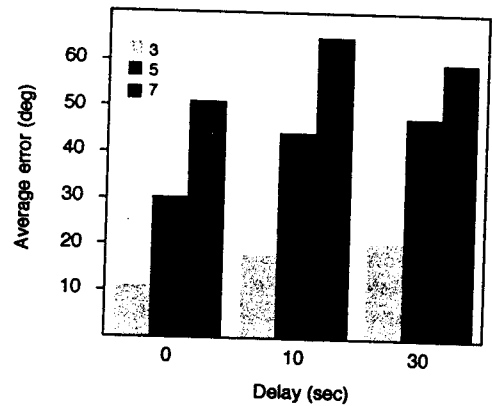


Figure 8. Average error in remembered direction of motion on a task in which the observer initially saw either 3, 5, or 7 random-dot cinematograms simultaneously and was then cued to remember one of the directions, the cue appearing 0, 10, or 30 s after the stimulus presentation. Results for the three observers tested are shown as averages; the pattern of results was the same for all observers. deg = degree.

tively immune to degradation over time (at least within the intervals studied in these experiments).

Treisman et al. (1975) found evidence for a rapidly decaying iconic representation of visual motion. In their study, observers viewed six rotational motion sequences simultaneously presented very briefly (100 ms); each of the six sequences consisted of a single dot that appeared to move either clockwise or counterclockwise. Observers were cued to report the direction of rotation of one of the six motion sequences, with the cue occurring either at the onset of the brief motion sequences, at the offset of the motion sequences, or 1 s following the offset of the sequences. Percent-correct performance deteriorated significantly under the two delayed cue conditions, pointing to the existence of a rapidly decaying iconic memory for motion. How do we reconcile those results with our partial report findings that the accuracy of memory for motion remains unchanged for at least 30 s? We used considerably longer exposure durations (1 s vs. 100 ms), and the cue signalling recall never occurred while the display itself was still present. The hallmark of iconic memory is the very rapid decay of the iconic representation, as implied by the decrease in report performance with cue delay. This hallmark characteristic is not present in our partial report results. We believe, therefore, that the sequence of events in our partial report task place the task outside the realm of iconic memory. In the parlance of stage models of memory, our observers, unlike Treisman et al.'s, were relying on short-term memory.

### Memory for Degree of Motion Coherence: Experiment 3

In the first 2 series of experiments, observers were always required to remember the direction(s) of motion. Now, it could be argued that observers accomplished this task by



visually selecting the single dot at the exact center of a display and tracking it to the point at which it crosses the circumference of the virtual circle defined by the array of dots; this crossing point position then becomes the information remembered. Or, perhaps observers noted the direction of global flow and then simply translated that direction into some spatial analog, such as a position on the face of an imaginary clock. The authors participated in one or more of these experiments, and none of us explicitly adopted either of these tactics, but this does not rule out the possibility. These considerations motivated us to design a memory for motion task in which such strategies would be fruitless. Accordingly, in this final experiment, we assessed the observers' ability to remember the degree of coherence of motion.

Generally speaking, coherence refers to the extent to which individual elements conform to a global property of an object or event; it is a measure of the degree of disorganization among stochastic elements. In the case of motion in these RDCs, coherence refers to the degree to which individual dots move in a given direction. The RDCs used in the previous experiments were completely coherent, that is, all dots moved in the same direction. The opposite extreme would be an RDC composed of dots each of which was free to move in any direction from frame to frame of the animation sequence—such an RDC would portray no net flow of motion and would look like the random snow seen on a detuned television. One effective way to vary the coherence of motion in RDC displays is to vary the bandwidth of directions within which individual dots can move (Hiris & Blake, 1995; Williams & Sekuler, 1984). When this directional bandwidth is narrow (e.g.,  $30^\circ$ ), the resulting animation sequence appears highly coherent, with dots having a strong directional flow in the direction of the mean of the bandwidth. Expanding the bandwidth admits more and more different directions into the animation, thus reducing the perceived coherence. In other work, we have shown that the perception of coherence may be adequately quantified as the amount of information entropy in the stimulus (Gilden et al. 1995).

For our present purposes, RDCs varying in coherence provide a useful tool for probing memory for motion. When required to remember the degree of motion coherence, rather than the direction of motion portrayed by the sequence, observers cannot recode the event in terms of some spatial analog, such as the position on an imaginary circle. Moreover, we were able to design the task so that an observer could not simply look at the extreme directions present in a given display and base the judgment on those extreme values; the task, as designed, forced the observer to maintain a mental representation of global coherence that could be compared to a subsequently seen RDC that was more or less coherent than the first one. Does the ability to judge relative coherence deteriorate when an interval of time elapses between exposure to the first RDC and the second?

We used a two-alternative, forced-choice procedure to measure how accurately observers could remember the degree of coherence in an RDC; in terms of trial structure, but

not display type, the procedure resembled the one illustrated in the bottom panel of Figure 1. On each trial, the observer viewed a 1-s RDC of a given degree of coherence followed by another 1-s RDC the coherence of which was greater than, equal to, or less than that of the first. The observer judged which sequence (the first or the second) was more coherent, guessing if necessary. Coherence was manipulated by varying the bandwidth of directions of motion comprising the RDC; directions were drawn from a rectangular distribution the range of which defined the bandwidth and the mean specified the net direction of flow. To complicate the task further, the mean direction of the RDCs was varied randomly from the first exposure to the second. Thus, for example, the first RDC of a trial might depict a  $70^\circ$  bandwidth of motion centered about "upward," whereas the second RDC might depict a  $60^\circ$  bandwidth of motion flowing generally "down and to the right"—the task called for judging the coherence of the first compared with the second, in which case the more coherent of the two sequences in this example would be the second. We actually created three families of coherence stimuli, with one family of RDCs centered around a bandwidth of  $70^\circ$ , another centered around one of  $90^\circ$ , and a third centered around one of  $110^\circ$  (keeping in mind that *degree* in this context refers to the angular bandwidth of possible directions in the RDCs). For each family of RDCs, we created seven values of coherence that spanned the central value. So, for example, the  $70^\circ$  family consisted of RDCs having a bandwidth of 40, 50, 60, 70, 80, 90, or  $100^\circ$  deg. The actual members of each family (i.e., RDCs presented on a given trial) were regenerated before each trial so that no two RDCs were ever exactly alike. From the observer's perspective, it was unpredictable from which family of RDCs the members would be drawn for a given trial, so the observer could not simply look at the first RDC, judge its coherence, and compare that immediately with an internalized standard.<sup>3</sup> Thus, on some trials, the bandwidth of the first RDC (e.g.,  $100^\circ$ ) would be more coherent than that of the second RDC (e.g.,  $110^\circ$  bandwidth); whereas on other trials, it would be less coherent than the second RDC (e.g.,  $70^\circ$  bandwidth). This forced the observer to remember actually the degree of coherence and compare it with that associated with the second RDC. It is also important to stress that these animation sequences were random-path motion, meaning that a given dot's direction of motion changed from frame to frame of the sequence (as contrasted with fixed-path motion in which a dot would always travel in the same direction throughout the duration of the sequence); this random-path property prevented observers from simply picking out and remembering a couple

<sup>3</sup> McKee and Welch (1989) have shown that observers can establish an implicit standard accurately, on the basis of successive presentations of motion bracketing this standard and then use this standard as a basis for velocity discrimination. The conditions of our experiment render this strategy impossible, thereby allowing us to measure the accuracy for memory of the specific RDC portrayed in the first interval.

of dots moving at the two extreme directions of motion. Because no single dot ever moved in the extreme for more than a pair of frames, it was impossible to judge direction from just a couple of dots. Instead, the judgment required the formation of a global impression of coherence.

Results for the two observers tested on this task are shown in Figure 9. The data have been broken into performance using the three families of RDCs, meaning that on each trial one of the three standard bandwidths (70, 90, or 110°) was presented as the first or the second RDC. However, one must keep in mind that, from the observer's standpoint, trials across all three panels of the graph were intermixed randomly. The best-fit logit curves show that performance on this task was essentially the same regardless of whether the second RDC was presented immediately after the first or 8 s after the first (the overlap between pairs of curves in each panel is well within the standard deviations computed using the standard formula for binomial distributions). Observers were able to remember the degree of coherence portrayed in the first sequence and compare that to the coherence of the second without loss of accuracy. Incidentally, the Weber fraction derived from these data (i.e., the

minimum discriminable difference in coherence) averaged 0.16, in very close agreement with the values (0.13–0.15) found by Hiris and Blake (1995) using a different procedure not involving memory.

Because there is no spatial analog for degree of motion coherence, we conclude that observers were not deploying some strategy involving the translation of motion information into position information. Of course, one could argue that observers were implicitly performing magnitude estimation, assigning a single number to each of the two RDCs seen on each trial and selecting the lower of the two. Introspection reveals the deployment of no such strategy; rather, one has the sense of visualizing coherence during the 8-s interval and directly comparing that mental visualization with the second RDC sequence. Of course, a more definitive statement about the nature of the information retained and subsequently used during recall will require additional procedures to isolate and test potential mental representations. At the least, the present results indicate that information about coherence is being stored with great fidelity for short periods of time, making the question of the nature of that stored representation of interest and importance.

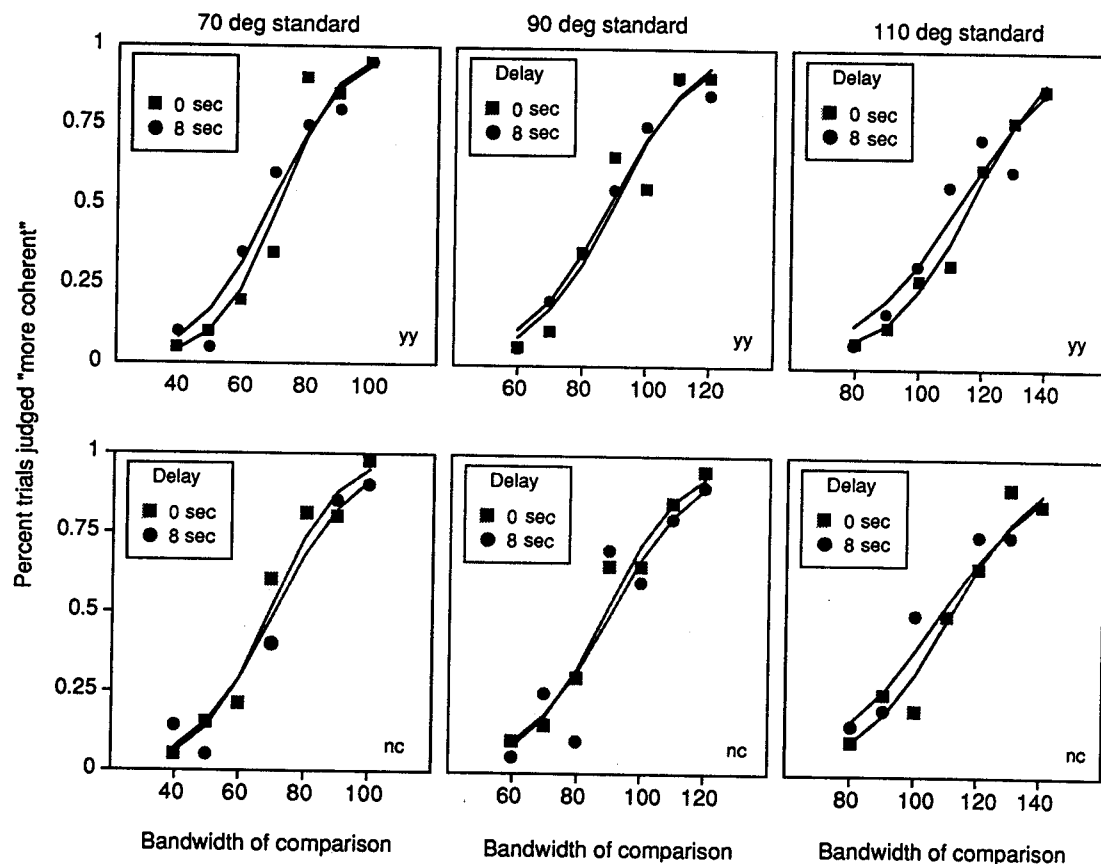


Figure 9. Percentage of trials during which the standard random-dot cinematogram (RDC) (which was either 70, 90, or 110° in bandwidth) was judged to be more coherent than a comparison RDC (the bandwidth of which varied randomly from trial to trial). Results are for two observers tested, with each data point consisting of 60 observations. Smooth curves were fit using logit analysis. deg = degree.

## Discussion

A fundamental purpose of vision is the guidance of action and, in many instances, those actions are carried out some time after the occurrence of a visual event. Indeed, it may be argued that the perception of an event itself is a process that inherently involves memory (Johansson, 1979). Surely, then, the neural machinery for registration and analysis of visual information, including motion, has evolved to embody this characteristic. Given this perspective, a complete understanding of visual function should include an understanding of the fidelity with which visual information is maintained for subsequent use. This question of the fidelity of memory for motion was the motive for this study.

Our results point to several general conclusions. First, upon viewing one episode of coherent motion in a given direction, observers are quite good at remembering that direction of motion. Evidently, storage and retrieval of visual information about individual events involve a high-fidelity representation of that information, albeit one that can be biased by cognitive factors (e.g., Freyd, 1987). Just how accurate is memory for motion, as measured in our experiments? In fact, observers on our tasks involving a single direction of motion are only slightly worse at remembering that direction than people are when asked to discriminate differences in direction of motion between simultaneously viewed animation sequences (e.g., Watamaniuk, Sekuler, & Williams, 1989). This leads us to wonder whether the memorial representation of coherent motion direction might be actively maintained within the same neural network believed to register motion upon its presentation (e.g., Salzman & Newsome, 1994). Of course, our findings apply to relatively brief retention intervals, the longest tested being 30 s; we have not inquired about the fidelity of memory for motion over hours or days. Moreover, our observers always knew that recall was to be measured following each sequence of RDCs. It would be informative to test memory for motion under conditions in which people perform tasks requiring full processing of a motion sequence without being aware that memory for that motion sequence will be subsequently tested.

In marked contrast with the accuracy of memory for a given direction of motion, observers experienced difficulty accurately remembering multiple directions of motion. Indeed, performance under these conditions deteriorates monotonically with the number of separate directions initially presented, whether presented simultaneously or successively. This relation implies a very limited channel capacity for the memorial representation of direction of motion. Again, we are intrigued to think about this limited channel capacity in terms of the representation of coherent motion within a network of direction-selective neurons, the particular direction being registered as a pattern of activity within those neurons. It is not unreasonable to imagine that the requirement to hold multiple patterns of activity within this network would degrade those neural representations.

*Cognitive Bias in Memory for Motion*

Is the recollected direction of motion of an RDC altered in any systematic way that might imply the involvement of nonsensory, cognitive processes? For instance, do people's reports of remembered direction tend to gravitate toward cardinal directions? This question is motivated, in part, by the substantial body of evidence pointing to systematic biases in the mental representation of objects and events. For instance, a person's memory for a static picture depicting an object in motion (e.g., a single frame from a sequence depicting a person jumping) tends to be distorted in a direction consistent with the implied motion (Freyd, 1983). In a similar vein, two-frame apparent motion sequences depicting natural movements are judged to be more compelling when the frames are shown in their correct temporal order, even though the spatial and temporal intervals are exactly the same when the sequence is played backward (Freyd, 1983) or when the elements in the sequence move in uncharacteristic directions (Yu, 1995). People, in other words, seem to form mental representations that are augmented (i.e., biased) by dynamical information. These and related phenomena, grouped under the rubric of dynamic mental representations, were reviewed by Freyd (1987) and by Hubbard (1995).

Another body of work implicating biases in cognitive processes comes from Huttenlocher, Hedges, and Duncan (1991), who studied short-term memory for spatial location. In their task, a single, small dot appears briefly somewhere within a circular area and, following a short memory interval, observers are required to reproduce the dot's position to the best of their memory; over a block of trials, dot position varies quasi-randomly. On this task (which does not involve motion), observers evidence a clear tendency to place the dot at a remembered position that is biased *away* from the horizontal and vertical axes. In effect, observers (mis)place the dot more toward the center of an imaginary quadrant in which the dot actually appeared.

More directly related to our work on memory for motion are studies by Freyd and colleagues (reviewed in Freyd, 1987). Those studies show that people's memory for the final location of a moving object is biased (i.e., reliably mislocated) in a direction consistent with the continued motion of the object. In effect, people behave as if the cognitive representation of the event had momentum and, for this reason, the phenomenon was termed *representational momentum* (Freyd & Finke, 1984). These errors in memory for position are found even when several seconds elapse between the termination of the actual motion sequence and interrogation of the person's memory for location. It should be noted that these memory errors are systematic and do not simply arise from random variability.

The three findings listed above are just a few examples of the ubiquitous, formative power that cognitive processes have on the mental representation of objects and events. It is natural, therefore, to ask whether memory for motion is altered in any systematic way that might imply the involvement of nonvisual, cognitive processes? Are the errors made by our observers distributed randomly over all directions of

motion or do errors cluster in some manner implicating biases in remembered direction of motion? The histograms shown in Figure 2 summarize absolute error averaged over all directions and, in that format, those data do not speak to the question of bias. To address this question, we have

replotted each observer's data from Experiment 1.1 in a more revealing format.

Figure 10 plots the individual error values (i.e., the difference between actual direction and adjusted direction) as the function of actual direction of motion; data were pooled

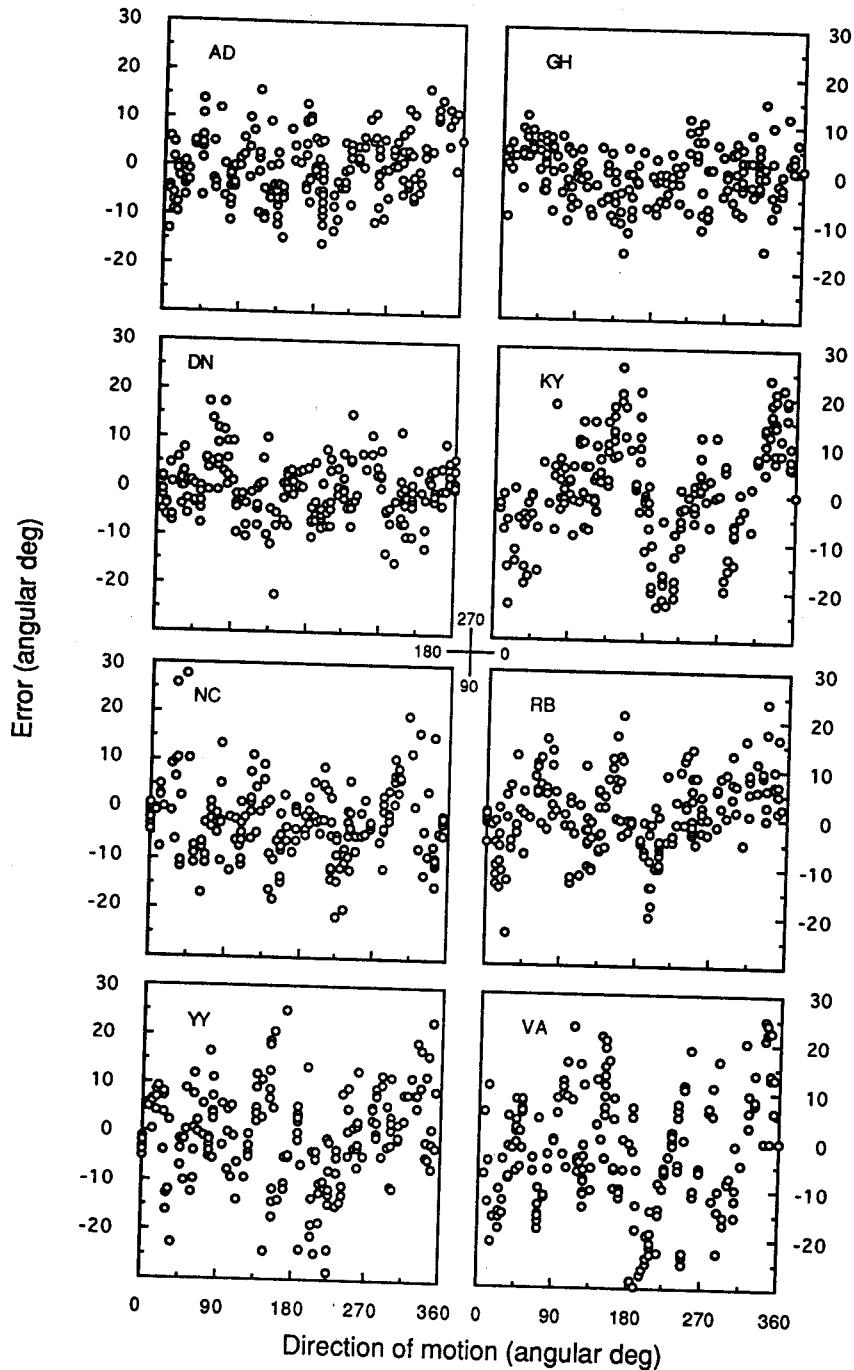


Figure 10. Scatter plots for each of the eight observers tested in Experiment 1.1. Each plot shows the signed error in remembered direction of motion (ordinate) as the function of actual direction (abscissa). Each symbol represents the results from a single trial. The inset in the middle of the figure specifies the actual directions associated with given values along the abscissa of each of these plots and of those in Figures 12 and 13. deg = degree.

over the five delay values, because delay had no significant effect on error. It should be stressed that these individual data points reflect both the magnitude and direction (i.e., sign) of error and not absolute error as in Figure 2. To each of these data sets, we applied the Wald-Wolfowitz runs test, a nonparametric test for serial patterns in sequential data.<sup>4</sup> For all observers, the resulting  $z$  values were statistically significant ( $p < .05$  in all cases), indicating that errors in remembered direction of motion are not unsystematically related to direction.

In an effort to understand the source(s) of bias implicated in the structure of these data, we have considered three possible patterns of errors in remembered motion, each associated with an a priori reasonable source of cognitive bias. One pattern of errors would implicate gravitational bias, i.e., a tendency for remembered motion to be attracted in the downward direction. In work on representational momentum, there is evidence for this kind of bias in that memory for a horizontally moving object is displaced downward. In our data, a gravitational bias would be evidenced by error values clustering above zero for directions from 90 to 270 (i.e., downward clockwise to upward) and below zero for directions ranging beyond 270 back to 90 (i.e., upward clockwise to downward); this pattern of errors is shown schematically in the upper panel of Figure 11. Alternatively, errors in remembered direction of motion could be attracted to cardinal directions (i.e., up, down, left, and right), which would yield the pattern of errors shown in the middle panel of Figure 11. Yet, another possibility is that errors in remembered direction of motion might be repulsed away from cardinal directions, i.e., the outcome discovered by Huttenlocher et al. (1991) in the case of remembered position for static stimuli. In the manner of Huttenlocher et al., repulsion away from cardinal directions would yield the pattern of results schematized in the bottom panel of Figure 11 (Huttenlocher et al. found that dots exactly on the vertical and horizontal axes were localized with great accuracy; it was dot positions on either side of these axes that were biased away from the cardinal axes and toward the diagonals).

Visual inspection of the scatter plots in Figure 10 reveals no single, obvious pattern of errors across observers. For most observers, there are clear peaks and troughs in the plots of error magnitude, implying systematic bias toward given directions. The locations of these peaks and troughs, however, are not identical across observers and, for this reason, it is potentially misleading to pool data across observers. Instead, the following analyses are applied to the results of each individual observer.

Certainly none of the data sets in Figure 10 conforms to the pattern associated with gravitational bias (upper panel, Figure 11); however, it may be unreasonable to expect gravitational bias to affect all directions of motion. To create a more generous test of this gravitational hypothesis, we have replotted (in Figure 12) just those error values associated with directions within  $\pm 45^\circ$  of straight downward and have plotted best-fit lines to those data. The gravitational hypothesis predicts that errors should cluster along a diagonal with the positive slope centered around 90

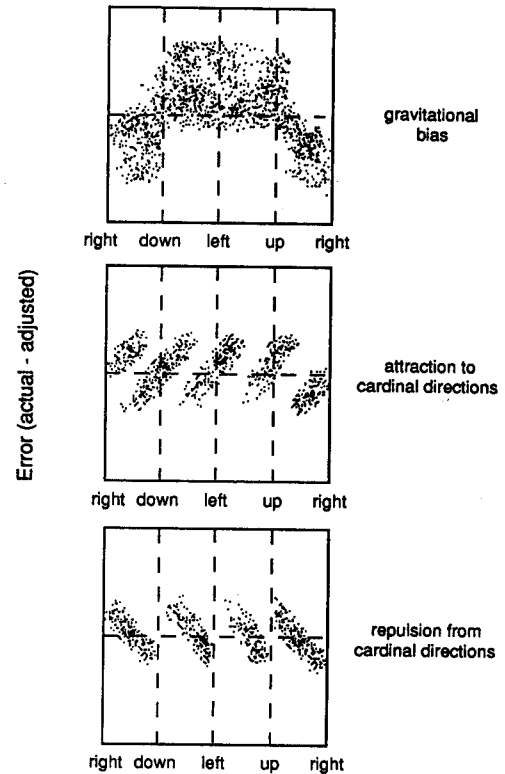


Figure 11. Three hypothetical patterns of errors on the visual memory for motion task. The upper panel schematizes the outcome on the basis of gravitational bias, the middle panel the predicted pattern of results on the basis of attraction to cardinal directions (up, down, left, and right), and the bottom panel the predicted pattern of results on the basis of repulsion away from cardinal directions.

deg. There is, however, no consistent trend for errors to vary in this manner; for only two of eight observers (NC and KY) were the slopes of the regression lines in the predicted direction. We have also looked at the range of motion directions centered  $\pm 45^\circ$  around leftward ( $180^\circ$  in our format) to see whether remembered directions in this neighborhood are attracted downward by gravity. As may be seen in Figure 13, no such trend was found and, indeed, the most pronounced systematic biases with leftward motion (observers VA and KY) implied repulsion away from those directions (reminiscent of Huttenlocher et al.'s results). Comparable analyses for a gravitational effect for directions centered around "upward" and around "rightward" were inconclusive.

Nor is there consistent evidence across observers for attraction to or repulsion away from cardinal directions. For a given observer, error values might show bias to be con-

<sup>4</sup> The direction of motion presented on each individual trial was selected at random from a uniform distribution, thus there is not an equal number of observations for each direction nor is the dimension sampled regularly. Consequently, a nonparametric test was deemed to be more appropriate for testing sequential dependence.

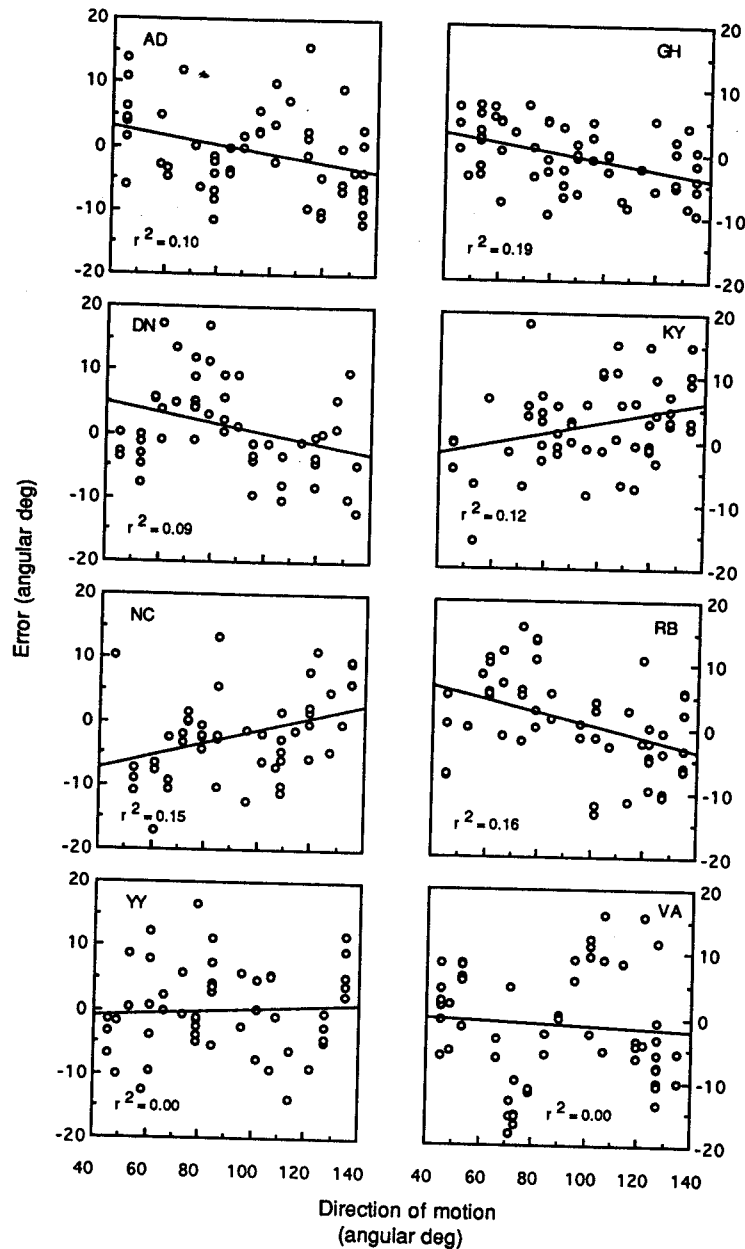


Figure 12. Distribution of errors for each observer as the function of direction for motion directions within  $\pm 45^\circ$  of downward (i.e.,  $90^\circ$ ). These data are a subset of those from Figure 10. Straight lines specify best-fit regression lines, with the associated  $r^2$  values given in each panel. deg = degree.

sistent with repulsion in one quadrant of motion but bias favoring attraction in another quadrant. In the absence of other specific models of bias,<sup>5</sup> we are left with the conclusion that memory for motion does include some cognitive component leading to systematic misrepresentation of direction. This cognitive bias appears to be idiosyncratic, however, and does not conform to patterns of bias described for other tasks involving motion or remembered location.

Before turning to other considerations, it is worth clarifying the relationship of our results with those dealing with

representational momentum (Freyd & Finke, 1984). As mentioned above, people systematically misjudge the final position of a previously moving object, as if they were

<sup>5</sup> Interested readers may access a tab-delimited file containing the error data summarized in Figure 10 by navigating to <http://www.vanderbilt.edu/AnS/psychology/cogsci/blake/blake.html> on the World Wide Web. Alternatively, Randolph Blake will provide the data file on receipt of a self-addressed, stamped mailer and an unformatted floppy disk.

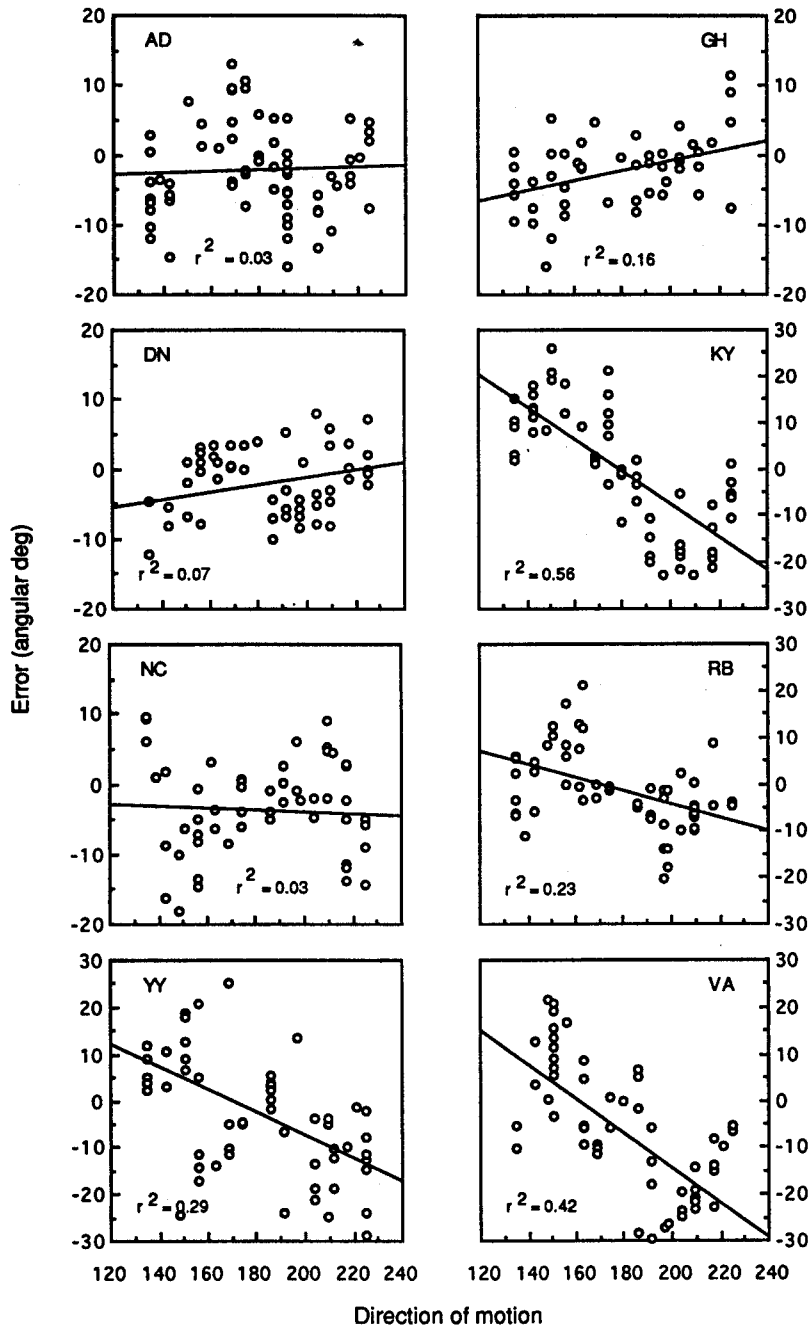


Figure 13. Distribution of errors for each observer as the function of direction for motion directions within  $\pm 45^\circ$  of leftward (i.e.,  $180^\circ$ ). deg = degree.

remembering a dynamic event. In most of those studies (reviewed by Freyd, 1987), people were making judgments of a single location along a path of motion; that location seems to be displaced in the direction implied by the path of motion, and this distortion is evident within the first second following termination of the actual event (Freyd & Johnson, 1987). Observers in our experiments were making a somewhat different judgment: They were reporting the remem-

bered direction of a path of motion itself, and the accuracy of this judgment did not deteriorate during memory intervals to 30 s. This raises the interesting possibility (suggested by a reviewer of an earlier version of this article) that memory for location along a path of motion may be more labile than memory for the path of motion itself. In future work, it could be informative to modify our task so that people are required to remember both the path of motion

and the final location of a given element in the motion sequence. Would errors on these two judgments be dissociated?

### *Comparison With Other Types of Perceptual Memory*

Our results indicate that memory for the direction and the degree of coherence of motion is almost as accurate as the ability to discriminate immediate differences in direction and coherence. How does this level of performance compare with memory for other aspects of vision and for other modalities? Quantitative comparisons with other studies are not straightforward, because the indices of memory accuracy vary widely among studies. It does seem clear, however, that visual memory for motion is *not* unique in terms of its high fidelity. People can remember the spatial frequency of a grating with essentially no loss in accuracy for durations as long as 2 days (Magnussen & Dyrnes, 1994). Likewise, velocity discrimination thresholds for drifting gratings are unchanged even when the standard and reference gratings are separated in time by as much as 30 sec (Magnussen & Greenlee, 1992). Perhaps the most remarkable case of visual memory is the female artist exhibiting eidetic imagery who could fuse the two half-images of a random-dot stereogram even when the two were presented separately to each eye on different days (Stromeyer & Psotka, 1970). Not all aspects of vision, however, are immune to memory decay. Both vernier acuity (Fahle & Harris, 1992) and texture discrimination (Harvey, 1986) are impaired when successively presented targets are separated in time by several seconds. As discussed earlier, iconic memory for rotational motion decays rapidly within a second following offset of stimulation (Treisman et al., 1975). It may be noteworthy that in these tasks yielding memory decay, the test targets were presented very briefly (vernier acuity: 100 ms; texture discrimination: 125 ms; rotational motion: 100 ms), compared with the typically longer exposure durations used in the studies of memory for spatial frequency and for velocity.

Turning to other sensory modalities, auditory memory, like visual memory, has been parsed into distinct stages, including a very brief, short-term auditory storage (sometimes called *echoic* memory) and a longer auditory memory lasting several seconds (Cowan, 1987). Short-term auditory memory appears to decay rapidly, but long-term auditory memory operates with very high efficiency (the evidence for these distinctions was reviewed by Crowder, 1993). In demonstration of the fidelity of long-term memory, Deutsch (1970) found that listeners could judge with perfect accuracy whether or not one briefly heard tone was the same as another heard 5 sec earlier (the use of tones makes it unlikely that verbal coding was used). Listeners are also good, although not perfectly accurate, at remembering tone loudness (Lu, Williamson, & Kaufman, 1992). Of course, the most compelling cases of high-fidelity auditory memory are those of individuals with perfect pitch. Auditory memory, like memory for motion, deteriorates significantly

when listeners are required to remember multiple sounds, including unfamiliar voices (e.g., Legge, Grosman, & Pieper, 1984).

The literature on odor memory was reviewed thoroughly by Schab (1991), and several generalizations emerge. Although people are notoriously poor at identifying odors (i.e., recalling the correct name of an odorant), they are quite good at remembering whether or not an odor was among those experienced previously. One of the more dramatic examples of long-term odor memory was provided by Lawless and Cain (1975), who found very little decay in odor recognition for memory retention intervals to 28 days. There are conditions, however, that disturb odor memory, including presentation of other odorants during the memory interval (Walk & Johns, 1984) and, it is speculated, initial exposures that are brief in duration (Jones-Gotman & Zatorre, 1993).

So, viewed within the context of these other findings, it is perhaps not so striking that memory for motion is accurate for retention intervals up to 30 s. The ubiquity of high-fidelity memory for sensory events may point to a common principle, namely that memory for perceptual events is embodied in the same neural processes engaged at the time of registration of those events (e.g., Crowder, 1993). This speculation brings us to the final point of our article.

### *Concluding Observation*

As a final note, we believe the procedure developed for this work could be imported into physiological laboratories where motion perception is being studied in awake, behaving primates. One can envision the monitoring of the temporal sequence of neural activity from direction-selective cells following cessation of stimulation of those cells by their preferred directions of motion. Would this activity depend on whether the animal needed to remember the exposed direction of motion for the performance of a subsequent task? This possibility is not far fetched, for neurophysiological experiments have shown that neural responses recorded from cells in alert, behaving monkeys may be modulated by task demands, including attention (e.g., Maunsell, Sclar, Nealey, & DePriest, 1991) and expectation (Pellizzer, Sargent, & Georgopoulos, 1995). We hope that the work described in this article sets the stage for an examination of the neural concomitants of remembered visual motion.

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