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ORIGINAL ARTICLE

With an Eye to Low Vision: Optic Flow Enables Perception Despite Image Blur

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ABSTRACT

Purpose. From static blurry images, it is difficult to perceive objects because high spatial frequency details are filtered out. However, in the context of events (defined as objects in motion), motion generates optic flow, which provides a depth map of 3D layout and allows good event perception. Visual motion measurement uses low spatial frequencies that remain available in blurry images, making events perceivable. Optic flow and image structure are intrinsically related in vision because optic flow takes one image to the next. Optic flow is powerful in specifying depth structures and it calibrates the degraded image structure; image structure is persistent and it preserves events perceived with ongoing motion, after it stops. Might optic flow and image structures interact and allow events to be perceived despite poor quality images? The answer to this question has implications for event perception with low vision.

Methods. Twenty blurry images depicting each of eight daily events were used as stimuli. Ten normally sighted participants perceived the stimuli and described the events in five ordered conditions: (1) when single frames were presented, (2) when all frames were presented with motion masks, (3) when all frames were presented without motion masks, (4) when single frames were presented, and (5) when single frames were presented 5 days later.

Results. With blurry static images alone, participants were unable to identify events. Events were perceptible when the blurred images were played in sequence, making motion-generated information available. Subsequently, when given the original blurry static images again, post-motion performance was vastly superior to the pre-motion performance. Furthermore, the high rate of recognition persisted after 5 days.

Conclusions. Optic flow calibrates low-quality image structure to allow accurate event perception during and after motion. This implies that low-vision observers should perform much better than allowed by weakened image structure information alone.

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Key Words: low vision, event perception, motion, optic flow, image structure

Low vision is a visual impairment characterized by a loss of visual acuity or contrast sensitivity that is uncorrectable by lens or spectacles.[1,2] Clinically, low vision usually refers to non-blind individuals with visual acuity lower than 0.3 (or 6/18), in the better eye with the best possible correction.[3] A 2012 WHO report[4] stated that 246 million people in the world had low vision. The distribution of low vision is uneven: more are found in developing countries (90%), in females, and in people age 50 and above. The leading causes of low vision in the United States are cataract (resulting in low acuity and low contrast sensitivity), glaucoma (resulting in loss of the peripheral visual field), age-related macular degeneration (resulting in loss of the central visual field), and diabetic retinopathy (resulting in low visual acuity).[5] In the current work, we study event perception with poor image resolution (due to low acuity and reduced contrast), but with an intact visual field.

Low visual acuity and poor contrast sensitivity are strongly correlated (r = 0.81, with sample size = 2520)[6] and their deterioration leads to the conscious experience of blurred visual images. Usually, in clinical practice, low vision is first diagnosed by assessing visual acuity.[7] The clinical test for visual acuity commonly utilizes still images of, for instance, a Snellen chart or a logMAR chart. Also, common low vision rehabilitation tools, such as prescription eyewear, optical devices, electronic aids, and adaptive computer software, aim to improve patients' image-based vision and the outcome measure of rehabilitation is improvement

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in acuity.[8] Although the importance of motion perception has been recognized by clinicians, it has not been included as part of low-vision evaluation due to the lack of feasible assessment techniques.[7] In this paper, we investigate how moving objects (equivalently, events) may be perceived with limited image information (as may be experienced in low vision) and subsequently how objects may continue to be perceived after motion stops.

The essential ideas are as follows. First, in a stationary visual environment, image structure information projected to the eyes from the surrounding objects is the only source of optical information available for perception. In blurry images, access to only the low spatial frequency structure in images renders the corresponding structures in the world unrecognizable. Second, visual motion measurement (that is, detection of optic flow and structure in optic flow) uses low spatial frequencies, so motion perception is generally unimpaired by loss of high spatial frequencies in images.[9] Events consist of objects in motion, and hence entail both image-based and motion-generated optical information. Because optic flow information alone can specify visual events (making image structure unnecessary),[10–12] logically, events in real time (i.e., with ongoing motion) are perceivable with blurry images. (It is therefore reasonable to expect that low-vision individuals might be able to perceive events or objects well with motion.) Finally, once the motion in the event ceases (that is, the event ends), only the low spatial frequency image structure remains, but now it has been calibrated by the preceding event. After the event has occurred and by virtue of the events being perceptible with ongoing motion, now the blurred image structure (that was previously inadequate for recognition of the surrounds) allows perception and recognition of the surrounds. Next, we shall expand and elaborate on these essential ideas.

Events are omnipresent in everyday experience.[10,11] We typically live in environments densely populated with objects. Those objects are frequently in motion as a result of their interaction with other objects and animals. Objects in motion constitute events. Thus, objects may be perceived based on their image structures (e.g., edges, contours, shades, and colors)[13] or in the context of events.[14,15] First, objects in the world project images to the eyes and the projected image structure in the optics is one source of information for event and/or object perception. In a given image, intensity varies across local points. Local points with similar intensity values are grouped into primitive image structures, such as edges, bars, blobs, and terminations. These primitive structures allow us to perceive some local properties of objects in the surrounds, for example orientation and position, and these local properties are integrated to yield spatial relations among objects in the surrounds.[13] For an observer to perceive an object from a static image, the observer must detect variations of intensity in the image. Thus, if the intensity change becomes hard to detect, either as a result of weakened signals (for example, in blurred images) or as a result of insensitive detectors (for example, the observer having low vision), the scene becomes difficult to perceive using image-based information alone.

Second, when objects are perceived in the context of events, on the other hand, motion generates optical information that allows an observer to perceive events. Motions of the observer and/or objects in the environment yield continuous changes in the structure of light, described as optic flow.[16] Optic flow is generated by relative motions between an observer and surrounding surfaces and objects and, thus, corresponds to and specifies the motions as well as the surfaces and objects undergoing the motions. Motion-generated optic flow, once detected, enables event perception (consequently, the perception of constituent objects).

A classic example demonstrating motion-based event perception is Johansson's Biological Motion displays.[17] In the original paradigm, lights were attached to the head and major joints of a walker whose walking was filmed in the dark. Image structure was made uninformative by this technique, which essentially reduced the images to extremely low spatial frequency structures. Given any static frame from the film, naive observers only saw bright dots on a dark background and were unable to identify anything meaningful. However, when the film was played continuously, so that the motion information became available, the event was perceived immediately.

Motion-generated information also enables effective perception of the 3D spatial structure of the environment.[18] This has been extensively investigated in studies of so-called Structure-From-Motion or SFM.[19–23] The classic SFM display consists of texture elements or points that are randomly distributed on the surface of an object, for example, a cylinder. When the object is stationary, only random texture elements or points are seen without a coherent structure or pattern (just as in the Biological Motion displays). However, when the object is rotated, the resulting optic flow specifies the 3D structure and the object is readily perceived.

Biological motion and Structure-From-Motion demonstrate that, with minimal or no image-based information, motion-generated optic flow strongly specifies objects and events, making them perceptible. With the availability of optic flow, image structure information is not necessary for perceiving events. In addition, visual detection of motion is unaffected by low image quality.[24] Motion-based information has been shown to improve the perception of 3D structure when image-based information is weak. For example, Jobling and colleagues found that the discrimination of depth differences was more sensitive and accurate using motion-based information than using only static image-based information for both normally sighted individuals simulated to be viewing with low vision and actual low-vision viewers.[2] In another study, Norman and colleagues used an SFM paradigm to investigate 3D shape discrimination with blurred vision. They made participants with normal vision wear 2-, 2.5-, and 3-diopter convex lenses and found that when the 3D objects were seen rotating in depth (i.e., with motion-generated information), the accuracy in discrimination increased at all levels of simulated blur. With detectable motion in this experiment, accuracy in shape discrimination, despite image blur equivalent to 3 diopters, was quite high ($d'_{\text{3-diopter blur}} \approx 3.05$, as compared to $d'_{\text{no blur}} \approx 3.65$).[25]

Third, optic flow and image structure both provide information about objects in visual events and the visual system uses both. Optic flow and image structure each entail unique strengths and weaknesses. Specifically, optic flow information is strong in specifying 3D spatial relations and event structure, but is transient. Image structure is weaker in its ability to specify 3D spatial relations and poor at specifying event structure, but is persistent. In natural vision, the system makes use of both sources of information to achieve effective perception because each is strong where the other is weak. Once the two are combined, optic flow carries one structured image into the next structured image. Optic flow and image structure are intrinsically related and largely symmetric. They often specify the same things. In part, the relation could be cast as a calibration of image-based information about 3D structure by the more powerful optic flow information. More than this, optic flow can specify the changes in 3D spatial structure that, in turn, relate sequential images. Furthermore, due to its stability and persistence, image structure preserves information about 3D layout once it has been specified by the fleeting optic flow, for as long as the images remain.[26] In this way, image structure becomes an embodied memory system for situated, active observers. The 3D structures perceived using optic flow are preserved externally in image structures that remain available for ''retrieval'' when needed.

In this optic flow-image structure synergy, the role of image structure information is not so much for the perceiving of events per se. Events are intrinsically spatial-temporal and, thus, event-specifying information is also necessarily spatial-temporal. Optic flow provides powerful but transient information that specifies events. Image structure serves to hold what has been specified by the transient optic flow, so that the perception of the event persists. High-quality image structure may not be required for this purpose. Because visual motion measurement uses low spatial frequency images structure, the question is whether those same low spatial frequency images would serve to provide the persistence that image structure normally does.

Does the combination of optic flow and static image structures yield more effective perception of daily events when high spatial frequencies are lost in blurry images? This is the question investigated in the current study. We predicted that adding motion to blurry images, which depict complex everyday events involving multiple objects, would enable the perceiving of such events. Although it should be difficult to perceive the events from static blurry images, observing the image sequence should allow motion information to make it easy for the observer to perceive the events. Furthermore, after the motion ceases, because by hypothesis the blurry images have been calibrated, observers should continue to be able to recognize the events from the same static blurred images, which previously had failed to allow the events to be recognized.

To study how events are perceived with limited image information and motion, we videotaped eight daily events, treated them to become highly blurry, and extracted static frames from the processed videos. Observers with normal vision viewed the blurry images in five conditions and attempted to identify the events. In the first condition, observers viewed static blurry images of events. In the second condition, observers viewed all the blurry images from every event in sequence, but without motion. In the third condition, observers viewed all blurry images in sequence with detectable motion. The fourth and fifth conditions were identical to the first condition, except that the blurry images were viewed either immediately after having seen the moving sequences (fourth condition) or a week later (fifth condition). With this design, we tested whether having seen the motions would improve event perception with static blurry images and if so whether the perceived events would be retained. Results from this study should enrich the understanding of how low-vision individuals might perceive events, recognize objects, and interact with their surroundings.

METHODS

Participants

Sixteen participants volunteered to participate in this experiment: 10 were in the experimental group (seven males and three females, ages between 19 and 55) and six were in the control group (four males and two females, ages between 20 and 43). All participants reported having normal or corrected to normal vision (acuity above 20/20). All participants signed informed consent in accordance with the procedures approved by the Indiana University institutional review board.

Materials

Eight everyday events were recorded with a Canon digital camera. The events were a man shooting a basketball, a woman bowling, a woman washing dishes at a kitchen sink, a dog running in a backyard, a woman pouring tea from a thermal flask into a cup on a table, a man and woman dancing tango, two teams playing soccer on a field in a stadium, and a man walking toward the camera and waving his hand.

All videos (with image quality of 720 × 480 pixels) were then processed with Adobe Premier Pro CS5. The final videos were silent, black and white with reduced contrast and high blur. Gaussian blur with a 15-pixel radius in the horizontal and vertical directions were applied to the videos. The cut-off frequency of the Gaussian blur filter was 0.02 cycles/pixel. We selected 20 still frames from each processed video clip as test stimuli in the experiment (see Fig. 1 for example frames). The frames were assembled in a java applet (display size: 18 cm × 12 cm; or approximately 17.2 degrees × 11.5 degrees visual angle with viewing distance of 60 cm). Given the resolution of the images (720 pixels × 480 pixels), the display size (18 cm × 12 cm), and the viewing distance at 60 cm, the frequency cutoff of 0.02 cycles per pixel converted to 0.84 cycles per degree visual angle in the final stimulus set. The java applet allowed the frames to be displayed one at a time (in conditions 1, 4, and 5), in sequence with white frames (serving as motion masks) in between (in condition 2) and without white frames in between (in condition 3). The stimuli were displayed on a 20″ iMac with refresh rate of 60 Hz. Immediately underneath each display, there was a text box for participants to type descriptions of the video images.

Procedures

Participants in the experimental group completed five conditions in this experiment. The first four conditions were tested in a single session and the last condition, the retest, was done 5 days later. In all conditions, participants were seated in front of a computer screen and told that they would see some blurred images and animations depicting common everyday events. Their task was to study each display and write a description of it in the text box below the display.

FIGURE 1.

Examples of static images extracted from the processed videos of familiar events. Altogether, there were eight events (shooting basketball, bowling, doing dishes, dog running in the backyard, pouring a drink, two teams playing soccer, two people dancing tango, and a man approaching and waving); 20 static frames were extracted from each video and used in the experiment. Illustrated in this figure were frames of the events of bowling (top) and a man approaching and waving (bottom).

In the first condition, 3 out of 20 static frames from each of the eight events were randomly selected to present to participants, one at a time (a total of 24 trials). While a frame was displayed on the monitor, participants typed a brief description of the event depicted in the frame. The low-pass filtering limited image information so that it would be rather hard, if not totally impossible, to recognize the events from the static pictures alone. See Fig. 1 for an example.

Next, in the second condition, the 20 frames from each video were played in the order they appeared in the natural events, with a white screen inserted after each frame. The duration of each frame was 500 ms and that of the white screen was 2000 ms. With four times the ISI, the stimuli appeared somewhat like a flipbook, with complete image information, but lack continuous motion due to the motion masking effect of the white screen in between image frames. Participants had to identify the events in the flipbooks, that is, with all image-based information, but no motion-generated information.

In the third condition, the 20 blurred frames taken from each video were played in sequence without the white screens, providing both image structure and motion-based information. That is, they were played as normal (although highly blurred) videos. Again, participants identified and described the events.

Fourth, after the blurred images had been viewed in the context of motion, participants were provided with 24 static blurred images (three randomly selected frames from eight processed videos) again to identify the events. The stimuli and procedure were identical to those in the first condition.

Finally, 5 days later, participants performed a test of retention. First, they listed all the events that had previously identified as best they could recall. Then the remainder of the test was exactly the same as in conditions 1 and 4, where participants saw 24 blurred images from eight events and described the events.

(A video illustration of one event is available at http://links.lww.com/OPX/A137. The full experiment [with instructions] can be downloaded from the webpage of the Perception Action Laboratory at Indiana University: http://www.indiana.edu/~palab/Resources/Demos/SLAEblur4_RunExp.zip. Or, for more information, visit: http://www.indiana.edu/~palab/research.php and click to expand "Perception and Embodied Memory".)

Participants in the control group received the same instructions and described events based on static blurry images (i.e., did condition 1) twice, with a short break in between. Performance in the first and second tests was contrasted to determine if merely seeing the static images twice would improve event perception.

Data Processing

There were 24 trials (three of each event and eight events altogether) in conditions 1, 4, and 5, and eight trials (for the eight events) in conditions 2 and 3. In total, each of the 10 participants in the experimental group completed 88 trials. Three trials were excluded due to participants' error (they accidentally skipped trials during the experiment), making the total number of trials in the experimental group 877. The six participants in the control group completed 48 trials each.

The data were event descriptions written by the participants. While participants were typing their responses, in conditions 1, 4, and 5, the static images were continuously displayed on the monitor. In conditions 2 and 3, ordered frames were played in loops. The descriptions of the events were coded as correct or incorrect by two raters (see the coding scheme in the Appendix, available at http://links.lww.com/OPX/A138). The raters first watched the experimental stimuli as well as the unprocessed event videos (i.e., the original videos with color and normal image quality) and then coded participants' responses based on their own judgments. The only guideline we offered to the raters was that a trial would be correct if the response captured the essence of the events. (For example, one of the events was a woman sitting at a table, pouring tea from a thermal flask into a cup and drinking from the cup. A correct response would have to cover the meaning of pouring liquid and drinking. Details like "a woman" [versus "a person"] or "a thermal flask" [versus "a water bottle"] were not required.) We did not provide the raters with lists of key words to match or other explicit rules for coding. The two raters coded independently and their coding was the same in 839 out of 877 trials, making the inter-rater reliability rate 96% (assessed using the "joint probability of agreement" method[27]). In the 38 trials where the raters coded differently, we randomly picked one rater's coding as the final judgment. We did not simply exclude these 38 trials because 10 such trials occurred in conditions 2 or 3, where there was only one response per participant per event. Because the main comparison was of performances in different conditions, which were tested within subjects, we retained those trials to maintain a balanced design for analysis.

RESULTS

In this experiment, we tested if motion could calibrate blurred images to allow subsequent accurate perception of events despite limited image information. Our results showed that this was indeed true. In the experimental group, proportions of events correctly perceived varied across conditions, with post–motion-calibrated conditions (namely, conditions 4 and 5) having significantly higher rate of correct perception than the pre-motion condition (condition 1). This was not simply due to having observed the blurry images repeatedly: participants in the control group, who observed the single frames of blurry images twice, did not show any improvement in event identification (proportions of events correctly perceived: $\text{mean}_{\text{First Time}} = 0.139$, $\text{SD}_{\text{First Time}} = 0.34$; $\text{mean}_{\text{Second Time}} = 0.146$, $\text{SD}_{\text{Second Time}} = 0.35$; the difference was not significant, $F[1, 5] = 0.033$, $p = 0.86$).

In the experimental group, to show that motion-generated information aided perceiving events with limited image details, we performed a repeated-measures ANOVA, comparing proportions of trials correctly perceived (out of the total number of trials) across different conditions and events. The factors of "condition" and "events" were both significant ($F[4, 36] = 73.76$, $p < 0.001$; and $F[7, 63] = 6.00$, $p < 0.001$, respectively). As shown in Fig. 2, rates of correct identification in pre-motion conditions (conditions 1 and 2) were much lower than in the motion and post-motion conditions (conditions 3, 4, and 5). Also, the significant main effect of event suggested that some events used in the experiment were harder to perceive than others. However, there

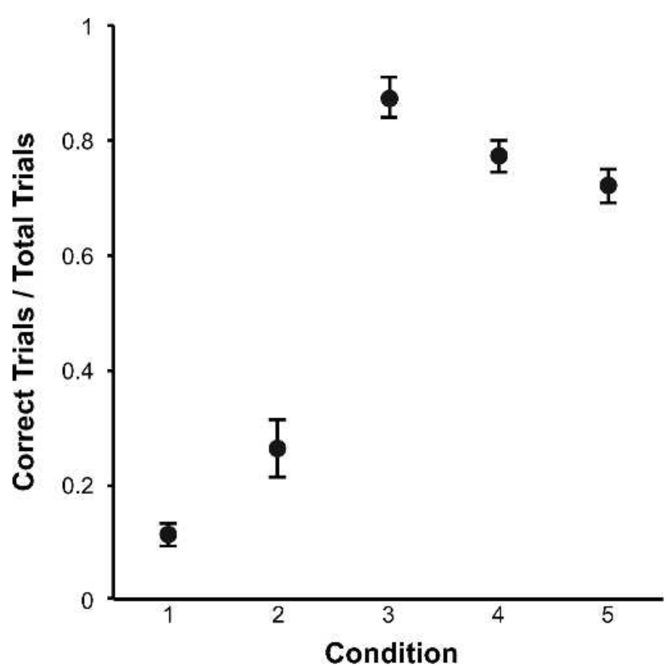

FIGURE 2.
Proportion of correctly perceived trials in the five conditions. Error bars = +/− 1 SE.

was no significant interaction between condition and event ($F[28, 252] = 1.09$, $p = 0.35$), so events did not affect performance in the five conditions differentially (Fig. 3). Hence, in the subsequent analysis, we focused on the effect of condition.

In condition 1, events were perceived correctly in 26 out of 238 trials. Because this experiment required free response, chance performance would be zero, that is, not identifying any event correctly with random guessing. Although performance in condition 1 was significantly better than chance ($t[9] = 3.72$, $p = 0.0024$, one-tailed), the rate of correct identification was extremely low (10.92%). For purposes of guiding action and/or recognition, at this level of accuracy, the perceptual system would be nonfunctional if required to operate only with such low spatial frequency image information.

In condition 2, where sequences of images were available, performance improved as compared to that in condition 1: in 21 out of 80 trials, participants identified the events correctly. This improvement was significant ($F[1, 9] = 5.19$, $p < 0.05$) but the rate was still quite low (26% correct) even with the full range of (blurred) image information, but no motion information.

When both static image information and motion information were available in condition 3, events were easily perceived and the rate of correct identification was 87.5% (or in 70 out of 80 trials among all participants). Comparing performance in condition 2 and in condition 3, everything else being equal, the added motion information yielded a significant and robust improvement in event perception ($F[1, 9] = 75.00$, $p < 0.001$).

Once the images had been calibrated by motion, the events represented in the blurred images were readily perceptible. In the post-motion condition 4, with the same images as used in condition 1, the rate of identification was 77% (or 185 out of 240 trials). Although performance in condition 4 was worse than in condition 3 ($F[1, 9] = 7.04$, $p < 0.05$), possibly as an effect of removing motion information and reducing image information (from 20 frames to 1 frame), it was still significantly better than performance in condition 1 ($F[1, 9] = 89.30$, $p < 0.001$). Given that the only difference between conditions 1 and 4 was whether the judgments were performed before or after the availability of motion-based information, the significant contrast in performance suggested that the effect of motion was preserved in the blurred image structures.

Finally, we tested the same participants 5 days later. We asked the 10 participants to write down the events that they could remember having seen in the previous testing session and the recall rate was 52 out of 80 events. Then, we presented the blurred images from the same set of stimuli as used in conditions 1 and 4 one frame at a time. The rate of correct identification in this condition was 72% (or 172 out of 239 trials). Performance in this retention test was significantly better than that in condition 1 ($F[1, 9] = 106.22$, $p < 0.001$). More importantly, performance did not drop from condition 4, which happened immediately after motion calibration, to condition 5, which was done 5 days later ($F[1, 9] = 1.25$, $p = 0.29$). The high rate of identification in this condition was not dependent on whether participants had remembered the events that they had perceived 5 days ago: the rate of event identification during retest was 48% among events that participants failed to recall. This was significantly higher than the rate of identification in condition 1 (i.e., 11%; $t[33] = 3.92$, $p < 0.001$) when participants first saw the blurred images. Alternatively, the rate of identification in this retention test was more closely related to performance in condition 3, where blurred images were presented in continuous sequence. Specifically, if participants did not perceive the events correctly in condition 3, with motion, their rate of event identification in the retest was 10%, equally low as that in condition 1. If participants correctly identified the events in condition 3, their rate of identification in the retest was 80%. This, together with the equal performance between conditions 4 and 5, showed that motion-generated information (which allowed viewers to perceive the events with limited image information) was crucial for perceiving events and it was preserved in the image structures and not held in memory. If what had been perceived with motion was kept in memory, it would decay with time and yield a deterioration of performance in condition 5. Such is the nature of human memory. The lack of decay over a period of 5 days suggested that events perceived were held externally in the image structures. Thus, upon re-presenting the images, events could be identified with the same accuracy as they had been immediately after motion calibration.

DISCUSSION

We studied how optical flow information might allow events in everyday life to be perceptible despite low quality of image-based information. Our results showed that motion-generated optic flow information compensates for the lack of image details and enables effective event perception. Specifically, we created highly blurred static images and tested the ability to use them to perceive a number of everyday events. From performance in the experimental group, we found that with image information that contains low spatial frequencies alone (i.e., static blurry images), perception was poor. The rate of correct identification was below 30% in conditions 1 and 2. When these frames were played in sequence so as to allow continuous motion to be detectable (condition 3), the events they depicted were readily perceived with the rate of correct identification increased significantly to 87.5%. Moreover, the perceived events were preserved in the limited image structures as shown by the higher rate of identification in condition 4 than in condition 1, where the same static images yielded 77% correct identification as compared to 11%. Such preservation endured over long time delays, with the rate of identification after 5 days being 72% in condition 5, with no statistical difference compared to condition 4, which had immediately followed the motion phase. Additionally, participants in the control group performed condition 1 twice without being exposed to the motion condition, and they showed no improvement in event identification. This result indicates that the improvement exhibited by the experimental group between condition 1 and conditions 4 and 5 was not merely a result of repeated viewing of the static images.

The implications of these results are two-fold. First, visual functioning need not be limited solely by the quality of image-based information. Motion-generated information is also of key importance and such information is relatively unaffected by significant degradation in the quality of image structure. Motion measurement relies on low spatial frequencies and, thus, remains relatively effective despite losses in visual acuity. Second, a role of image-based

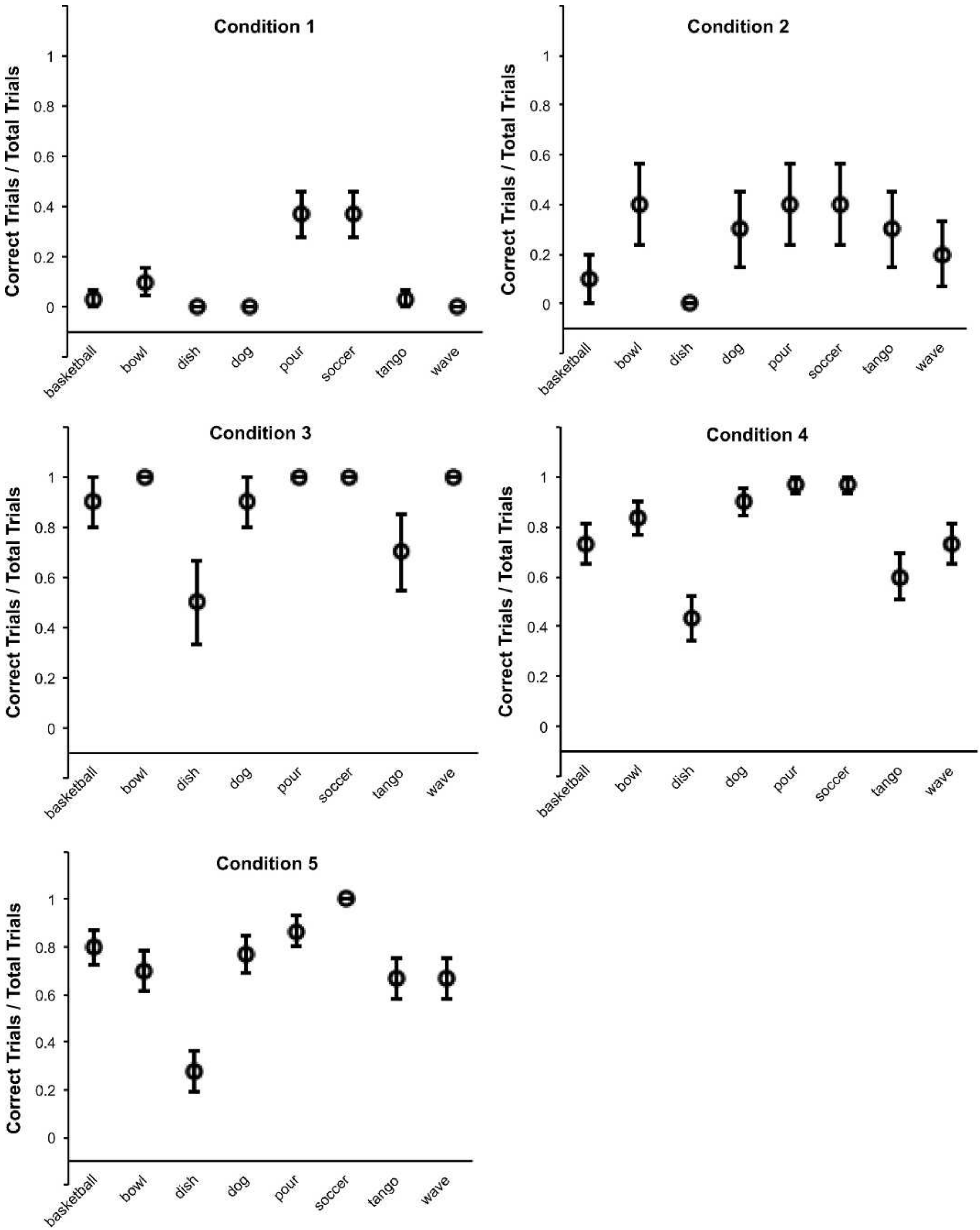

FIGURE 3.

Proportion of correct perception in each condition, by events. Performance was affected by condition and events, but not their interaction. Error bars = +/− 1 SE.

information, given its persistent nature, is to serve as a stable external reference that effectively stores perceived events. To fulfill this role, high image quality is not required.

Traditionally, it is expected that good visual acuity is required to perceive and identify events from images. The idea is that the eyes need to be able to discriminate high spatial frequency changes of intensity in visual stimuli to detect features such as edges and boundaries.[13] Thus, in practice, optometrists prescribe eyeglasses for patients to reach a certain level of acuity. To obtain a driver's license in the US, an individual's corrected vision is checked using static images. This is certainly relevant, but it is not the whole story.

In everyday life, events constitute a significant portion of perceptual experience.[28] Event perception is not well enabled by static images because motion generates optic flow information that is not available in static images. On the other hand, optic flow provides immediate and powerful information about events, including the 3D structure, relative speeds, and directions of motion of objects in events.[23,29,30] As shown by the results of this experiment, when static image information is extremely poor and insufficient for perception, adding motion generated information allowed the successful identification of events.

The effectiveness of motion-generated optical information for object recognition and identification of locations in 3D spaces has been studied extensively.[26,31–33] For instance, using an approach that was similar to that used in the current work, Wallach, O'Connell, and Neisser studied perception of three-dimensional forms and obtained results that were also similar to the current work.[34] In that study, shadows of 3D wire figures (a helix and a parallelogram) were projected on a screen. The shadows were ambiguous and appeared to be either 2D objects or 2D representations of 3D objects. The task was to identify the dimensionalities of the objects. To some, but not all, participants, the authors showed the wire figures rotating continuously so as to reveal their 3D structure. Those participants who saw the rotation subsequently identified the original flat image (the shadow) as a 2D representation of a 3D wire figure and those who had not seen the rotation still reported the original flat image as ambiguous, either 2D or 3D. A week later, when the participants viewed the flat images of the wire figures again, their perception of the dimensionality remained the same. Wallach, O'Connell, and Neisser explained that it was the experience that some participants had watching the wire figures rotate that made them continue to see the shadows as 3D. We note that this experience was specifically the detection of optic flow information made available by rotation in depth. When a wire figure rotated, optic flow was generated with differential speed across the figure: higher speed at near points and lower speed at farther points, relative to the axis of rotation.[21] This calibrated the image structure of the wire figure (i.e., the shadow) providing information about the relative depths of the line segments and/or vertices. Furthermore, the perceived 3D figures were preserved in the otherwise ambiguous 2D forms, allowing participants who had perceived the spatial structure to continue to perceive it.

In naturally occurring events, two sources of information, image structure and optic flow, interact to yield effective perception. Image structure is relatively weak in specifying spatial relations in events. However, image structure is stable: it is always available as long as the objects are visible. Optic flow is strong in specifying spatial relations in events, but it is transient. Optic flow information yields good event perception, but the information is gone once the event ends. Image structure and optic flow each entail strengths and weaknesses, but when combined, they complement each other to yield effective performance. We found that the combination yielded both good perception of events (and the constituent objects) as well as good subsequent recognition performance. Once the blurred image structure was calibrated by motion in condition 3, it allowed the events to be recognized subsequently, both immediately afterwards in condition 4 and 5 days later in condition 5. Thus, reduced image structure may not specify events directly, but it can serve nevertheless to allow events and objects to be recognized.

This finding has important implications for understanding of the daily functioning of observers with low vision. In low vision, the detection of high spatial frequencies in images is poor. As a result, low-vision observers often are unable to recognize their surroundings based on image-based information alone when everything is stationary. However, because the detection of optic flow does not require the sensitivity to high spatial frequencies (in other words, high image resolution is not required for the detection of motion and motion-generated information[24]), the same observers might be able to perceive events in their surroundings using optic flow that is generated either by their own motions or by the motions of objects in surrounding events. This might explain why individuals with relatively low visual acuity (<1.0 or <20/200) could successfully perform, in unfamiliar environments, daily tasks that entail recognition of common objects and then guide their actions relative to them,[6] for instance, walking into an unfamiliar kitchen, recognizing the kettle on the stove and the water faucet in the sink, and grabbing the kettle and filling it with water at the sink before putting it on for tea. When the motions stop, the blurry images may continue to inform low vision observers about the surrounding objects and their layout. For low-vision observers, static image information is not the only (or perhaps even the primary) source of information about the surroundings. Instead, it provides a stable remnant of previously available optical flow, and its availability allows individuals to continue to perceive and act upon objects and events originally perceived using optic flow.

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APPENDIX

A video illustration (.flv) of one event is available at http://links.lww.com/OPX/A137. The appendix is available online at http://links.lww.com/OPX/A138.

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