Effect of expansive optic flow and lateral motion parallax on depth estimation with normal and artificially reduced acuity

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When an observer moves in space, the retinal projection of a stationary object either expands if the motion is toward the object or shifts horizontally if the motion contains a lateral component. This study examined the impact of expansive optic flow and lateral motion parallax on the accuracy of depth perception for observers with normal or artificially reduced acuity and asked whether any benefit is due to the continuous motion or to the discrete object image displacement. Stationary participants viewed a virtual room on a computer screen. They used an on-screen slider to estimate the depth of a target object relative to a reference object after seeing 2-second videos simulating five conditions: static viewing, expansive optic flow, and lateral motion parallax in either continuous motion or image displacement. Ten participants viewed the stimuli with normal acuity in Experiment 1 and 11 with three levels of artificially reduced acuity in Experiment 2. Linear regression models represented the relationship between the depth estimates of participants and the ground truth. Lateral motion parallax produced more accurate depth estimates than expansive optic flow and static viewing. Depth perception with continuous motion was more accurate than that with displacement under mild and moderate, but not severe, acuity reduction. For observers with both normal and artificially reduced acuity, lateral motion parallax was more helpful for object depth estimation than expansive optic flow, and continuous motion parallax was more helpful than object image displacement.

Introduction

To identify and locate objects in a three-dimensional (3D) environment, an observer needs to infer depth information from visual cues. In addition to binocular cues, such as stereopsis, and pictorial cues, motion-related visual cues are also available in judging object depths. When the perspective of an observer translates in a stationary environment, the projected images of the surrounding objects shift in the observer's field of view, which is the visual phenomenon of optic flow. The direction and velocity of these shifts are contingent on the depth of the objects.

For perspective translation happening on the ground plane, the projections shifts can be of two patterns. The first pattern occurs when the perspective translates forward toward an object of fixation. In this case, the object contours shift radially to the periphery of the observer's visual field, resulting in expansive optic flow (Figure 1A). The farther the object is from the observer, the slower its projection expands.

The second pattern occurs when the direction of perspective translation contains a lateral component to the line of sight. In this case, the images of the objects shift laterally to the left or right in the observer's field of view (Figure 1B). When a target object is farther away than the fixated object, its projection shifts in the same direction as the motion of the observer. When the target object is closer than the fixated object, its projection shifts in the opposite direction. The farther the target object is from the fixated object, the faster its image shifts. We term this visual phenomenon lateral motion parallax. Humans and animals can also move their perspective up and down to create vertical motion parallax (Ellard, Goodale, & Timney, 1984; Marotta, Perrot, Nicolle, & Goodale, 1995). In the current study, we focused on the perspective translation parallel to

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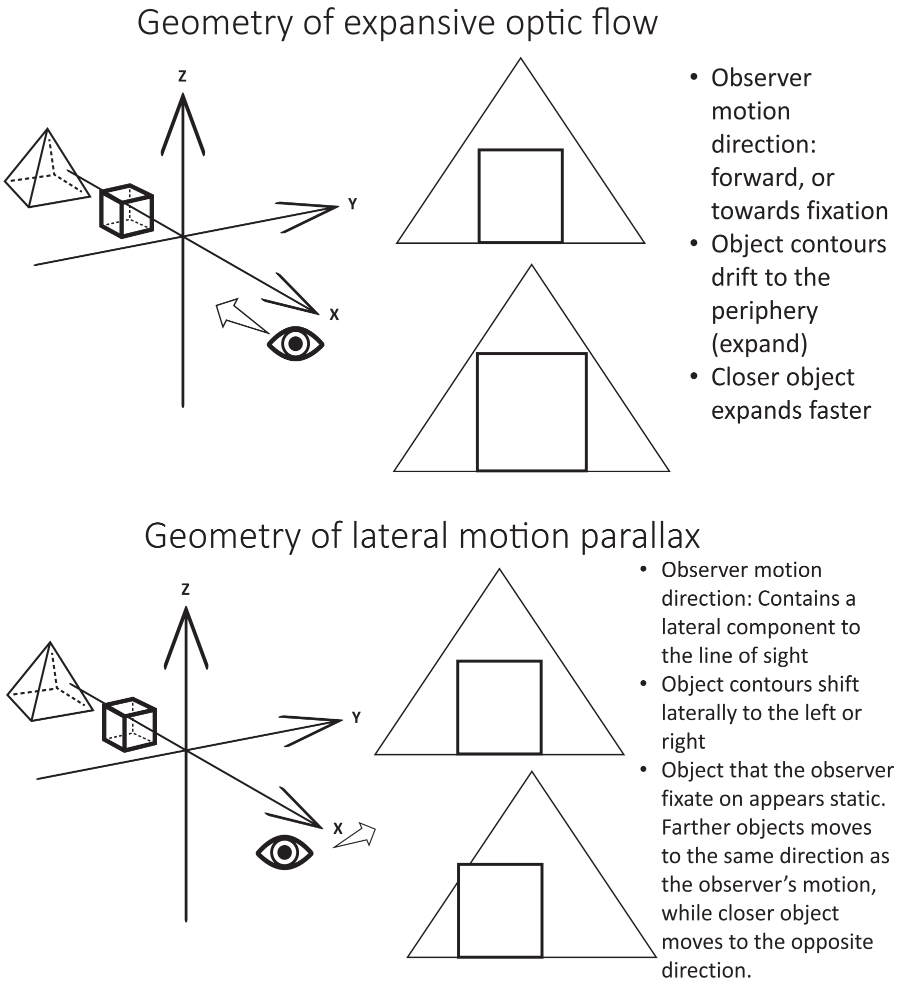

Geometry of expansive optic flow

- Observer motion direction: forward, or towards fixation
- Object contours drift to the periphery (expand)
- Closer object expands faster

Geometry of lateral motion parallax

- Observer motion direction: Contains a lateral component to the line of sight
- Object contours shift laterally to the left or right
- Object that the observer fixate on appears static. Farther objects moves to the same direction as the observer's motion, while closer object moves to the opposite direction.

Figure 1. (**A**) When the observer moves forward toward a fixated object, its image expands toward the periphery of the field of view. (**B**) When the observer moves in a direction that contains a lateral component to their line of sight, the fixated object is stationary in their visual field, while the images of the other objects move laterally to the left or right.

the ground-plane, hence examined only lateral, but not vertical, motion parallax.

For people with low vision, many types of depth cues are inaccessible. For example, many people with visual impairments have asymmetric vision loss in their two eyes (McKibbin, Farragher, & Shickle, 2018), limiting the value of stereopsis (Tong et al., 2021). Some pictorial depth cues, such as texture gradients, usually require seeing fine details in the environment and can be difficult to use for people with low acuity. In the visual system, motion signals are processed along with low-spatial frequency information, which carries the coarse contours in an image, in the magnocellular pathway (Kaplan, Lee, & Shapley, 1990; Shapley, 1990), meaning that perceiving motion does not necessarily rely on seeing fine details in the environment. Therefore, motion-related depth cues may be helpful for people with low acuity. The current study is motivated by the potential values of motion-related cues for depth estimation, especially in people with reduced acuity.

Most psychophysical studies on depth perception through motion have used lateral motion parallax as stimuli and few have included expansive optic flow in the scope of research. Some studies have investigated how expansive optic flow reveals time-to-contact estimation (Daneshi, Azarnoush, Towhidkhah, Bernardin, & Faubert, 2020; Lee & Reddish, 1981; Tresilian, 1991; Tresilian, 1995). Some studies examined the value of expansive optic flow for low vision observers in identifying architectural features. For instance, Bochsler, Legge, Gage, and Kallie (2013) found expansive optic flow improved the identification accuracy, whereas Liu, Carpenter, Legge, and Kersten (2019) did not. One of the goals of this study was to compare the impact of expansive optic flow and lateral motion parallax on depth perception with reduced acuity. Many studies have validated the effect of optic flow and motion parallax on depth perception with theoretical inference (Longuet-Higgins & Prazdny, 1980; Simpson, 1993) and psychophysical methods (Jobling, Mansfield, Legge, & Menge, 1997; Rogers

& Graham, 1979). Many of the previous studies have used highly simplified visual stimuli to isolate motion parallax cues, such as two virtual surfaces covered with random dots to present lateral motion parallax (Rogers & Graham, 1979; Rogers & Graham, 1982; Yoonessi & Baker, 2011). Some other studies used physical objects as stimuli while occluding the boundary between the object and the ground plane to limit access to pictorial depth cues, such as the angle of declination and the angular size of the object (Durgin, Proffitt, Olson, & Reinke, 1995; Gillam, Palmisano, & Govan, 2011; Jobling et al., 1997; McKee & Taylor, 2010). In the current study, we wanted to examine the effect of motion-related depth cues in a more ecologically valid context. We constructed a virtual 3D indoor scene and had the participants estimate the depth of a target object in this environment, while providing richer pictorial depth cues in the stimuli.

When observing optic flow or motion parallax, the depth of objects can be revealed by the two sources of information, the discrete displacement and the continuous motion of the object image. We considered whether the discrete displacement of object image associated with observer motion provides the same information about object depth as the continuous motion. We compared a continuous presentation of motion parallax or optic flow with a separate presentation of the first and last images of the motion sequence.

The current study investigated whether two kinds of motion-related depth cues, expansive optic flow and lateral motion parallax, enhance depth perception for observers with normal or reduced acuity, and whether there is a difference between the continuous motion and discrete displacement of the object image. In scenarios such as driving, moving in a wheelchair, and gaming in virtual reality, observers have access to the visual information in motion parallax and optic flow without experiencing bodily motion. The current study focused on the visual aspect of motion parallax and optic flow. We constructed 3D models of a virtual indoor scene and rendered static view and simulated expansive optic flow and lateral motion parallax. The participants sat stationarily, looked at the scene under the three viewing conditions, and estimated the depth of an object in the scene. Experiment 1 tested participants with normal vision and Experiment 2 tested normally sighted participants with artificial acuity reduction.

Experiment 1: Test with normal acuity

A preliminary experiment with 11 participants was conducted before Experiment 1 during the coronavirus disease 2019 pandemic lockdown. The preliminary experiment was a remote version of Experiment 1 conducted over Zoom, using the same paradigm. The preliminary experiment was used to guide the design of Experiment 1. The Methods and Results section of Experiment 1 focuses on the formal in-person experiment.

Methods

Subjects

In Experiment 1, ten students at the University of Minnesota participated. They had a mean age of 23.5 ± 3.6 years and three were male (see details in Appendix 3, Supplementary Table S5). All participants had self-reported normal vision. All participants participated after giving informed consent. The experiment protocol was approved by the University of Minnesota Institutional Review Board.

Apparatus

The participants looked at a NEC E243WMi-BK 16:9, 24-inch monitor from a viewing distance of 60 cm. The monitor extended 45° horizontally and 27° vertically in the participant's field of view.

Stimuli

The stimuli were images rendered from a 3D model of a virtual room built with the Blender software 2.9 (Community, 2018). The room was 33 feet wide (from west to east), 52 feet long (from south to north), and 13 feet high (from floor to ceiling), with gray walls, brown flooring, and no windows. An area light was placed at the center of the room so that no noticeable shadows were cast. In the room were two objects, a red hexagon sign hanging from the ceiling, which was the reference object, and a gray column sitting on the ground, which was the target object. The hexagon sign was located at the center of the room in every trial, whereas the column was in one of eight possible positions along the south-to-north midline of the room. The hexagon sign was 2 feet tall, 2 feet wide, and 0.6 feet thick. Details of the location and dimensions of the column (target object) are explained in the Design section.

The virtual camera in the scene was placed by the south wall and at the midpoint between the east and west wall, 5.5 feet from the ground. The height of the camera simulated the perspective of a standing pedestrian. The camera either stayed in place or moved in two possible directions within each trial.

Design

Three independent variables were manipulated: motion type (expansive optic flow and lateral motion parallax), presentation type (continuous motion, object image displacement, and static viewing), and depth separation between the reference and the target object.

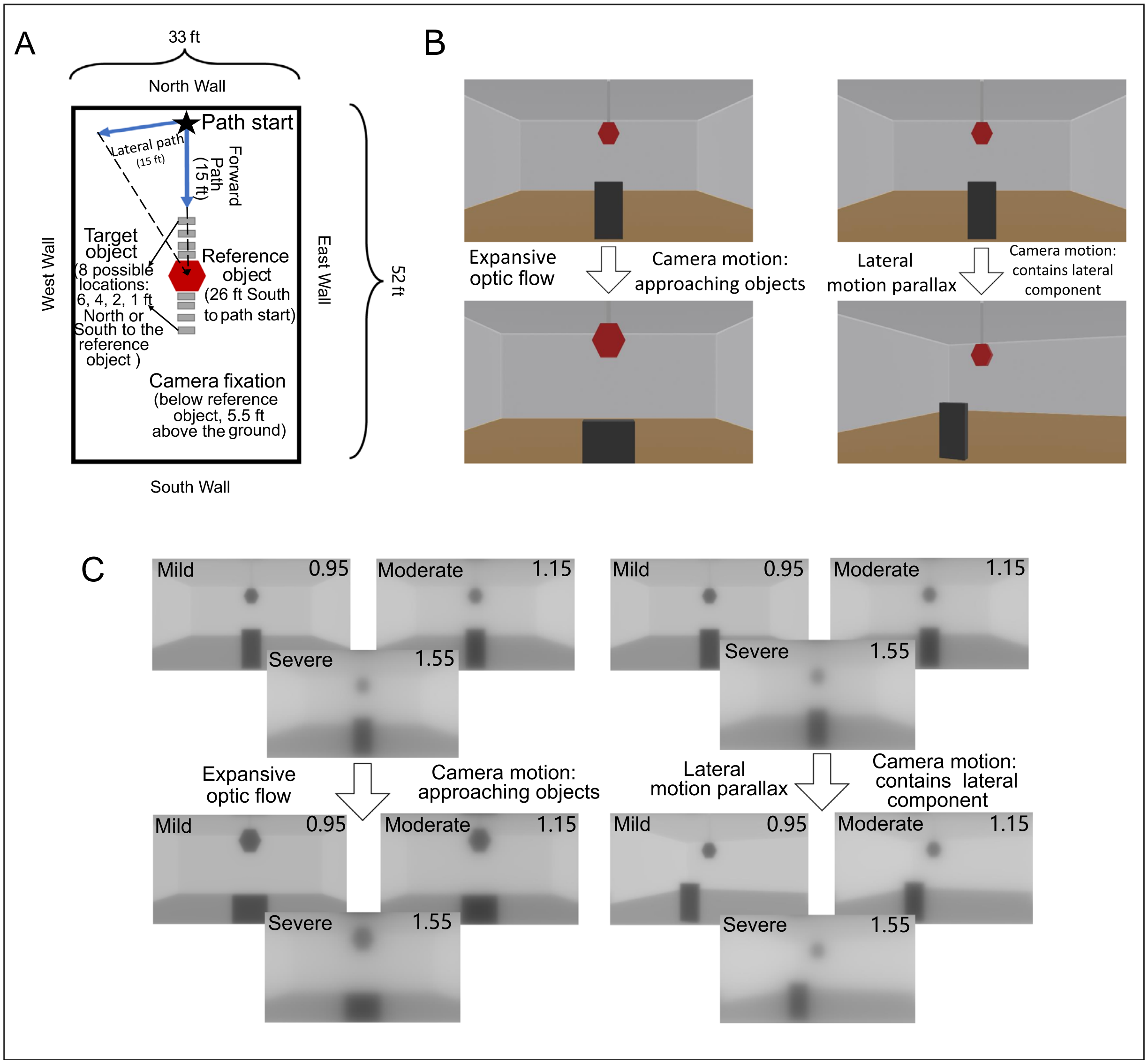

Figure 2. (**A**) Bird's-eye view diagram showing the layout of the virtual scene presented in the stimuli. Signs for location and objects are enlarged disproportionately for ease of viewing. (**B**) Starting and ending frame of an expansive optic flow and lateral motion parallax sequence in the test with normal acuity. (**C**) Starting and ending frames of expansive optic flow and lateral motion parallax with simulated mild, moderate, and severe acuity reduction. The number on the top right of each image is in units of logarithm of the minimum angle of resolution.

The virtual scene was presented in five viewing conditions: expansive continuous motion, lateral continuous motion, expansive displacement, lateral displacement, and static viewing. To simulate expansive optic flow, the virtual camera in the model pointed and moved north. For lateral motion parallax, the camera moved 80° clockwise from the north and rotated to retain the reference object on the midline of the image frame. In both cases, the camera moved 15 feet in 2 seconds. In the continuous motion condition, the stimuli were videos showing 60 consecutive frames of images sampled at 30 frames per second along the motion of the virtual camera. In the displacement condition, the stimuli showed only the first and last frame of the motion sequence (Figure 2). The two frames were each presented for 0.5 seconds, separated by a 1-second-long white screen. In the static viewing condition, only the first image of the motion sequence was shown on the screen for 2 seconds. With a static view, the depth of the target object was mainly conveyed by the relative size (how large the front size of the target object appears on the image) and angle of declination (how far the bottom edge of the target object appears below the floor–wall boundary). The front side of the target object was shown completely in the image frame at all locations in the static viewing condition.

The target object had eight possible locations, 6, 4, 2, or 1 foot (feet) in front or behind the reference object. In the following text and figures, the negative sign in front of the perceived or ground-truth depth separation means the target object is to the south of, or closer to the viewer than, the reference object.

The target object had three combinations of dimensions so that the participants could not rely solely on the angular size to estimate the depth of the target object. The three combinations of dimensions were: 1.6 feet wide × 4.98 feet tall × 0.6 feet thick; 2 feet wide × 4 feet tall × 0.6 feet thick; and 3.6 feet wide × 3.67 feet tall by 0.6 feet thick.

Each trial was repeated twice. All participants went through five viewing conditions of three target object dimensions at eight ground-truth depths with two repetitions, making a total of 240 trials. All the trials were randomized for each participant.

Procedure

Participants sat stationarily, looked at computer-rendered stimuli in five viewing conditions, and then moved a slider on the screen to report their estimate of the depth difference between the reference and the target objects. Participants viewed the stimuli on a flat screen, so that their left and right eyes received the same input and any disparity information would be unhelpful in judging target depth. The experiment was built with the software PsychoPy v2020.2.9 (Peirce et al., 2019). Each stimulus lasted for 2 seconds. After the stimulus video finished playing, the stimulus disappeared. A slider with labels ranging from –26 feet to 26 feet appeared at the bottom of the screen. Negative values meant that the target object was to the south of, or closer to the viewer than, the reference object. The participants reported their estimation of the depth separation between the target and reference objects by moving the slider. The slider was limited to integer values. The participants were familiarized with the scale in the virtual room through 2 reference images and 12 practice trials. The practice trials covered all viewing conditions and provided correct answer feedback.

Data analysis

The dependent variable was the slider setting position of the participants at the end of each trial, and the independent variable was the ground-truth depth separation between the target and the reference object. A linear regression model was fitted for each viewing condition, following the Equation:

$$y = ax + b \quad (1)$$

where y is the dependent variable, participants' slider setting, and x is the ground-truth depth separation. Coefficient a was termed the slope and coefficient b was the intercept of the model. The slope indicated the scale bias in participants' depth perception, and the intercept represented the offset bias. A slope smaller than 1 meant that the participant had a compressive scale bias in depth perception. The closer the slope was to 0, the more compressive the scale bias. The intercept, or offset bias, represented a perceived offset in the overall depth of the target. If the intercept (coefficient b) was greater than 0, it meant that the observer estimated the target object to be farther away than its true depth by b feet, which was a positive offset bias. The closer the slope was to 1 and the intercept was to 0, the more accurate the depth perception.

The adjusted R^2 values reflected how much the participants' depth estimation varied around the regression line. The larger the R^2, the less the residual variation, hence a higher consistency in the participants' response and higher depth perception accuracy.

The regression slope, the regression intercept, and the adjusted R^2 were taken as the indicators of depth perception accuracy for each viewing condition. We used R package v.4.3.0 (R Core Team, 2018) to conduct data analysis. The glm function was used to fit linear regression models and the lstrends function of the lsmeans package was used to compare regression slopes of different viewing conditions (Lenth, 2016). Fisher's r-to-z transform was used to compare the correlation coefficients of different linear regression models.

Results

Baseline performance

The static viewing condition, in which participants only had access to pictorial depth cues, was considered the baseline condition. Table 1 lists the fitted slopes and intercepts and their 95% confidence intervals. Data were

	Viewing condition	Slope (CI 2.5%, 97.5%)	Intercept (CI 2.5%, 97.5%)	Adjusted R^2
1	Static	0.39 (0.33, 0.45)	−0.25 (−0.48, −0.02)	0.25
2	Expansive continuous	0.57 (0.51, 0.62)	−0.36 (−0.58, −0.14)	0.44
3	Lateral continuous	1.02 (0.97, 1.07)	−0.08 (−0.26, 0.1)	0.79
4	Expansive displacement	0.44 (0.38, 0.5)	−0.85 (−1.09, −0.6)	0.27
5	Lateral displacement	0.68 (0.62, 0.73)	−0.13 (−0.35, 0.09)	0.52

Table 1. Regression coefficients and 95% confidence intervals for static viewing, expansive continuous motion, lateral continuous motion, expansive displacement, and lateral displacement trials. *Note*: The regression model had the depth estimates of the participants as the dependent variable and ground-truth depth as the independent variable.

accumulated from all participants. The average slope, or the coefficient a in Equation 1, in the static viewing condition was 0.39. The slope of the static viewing regression model was significantly less than 1, showing a compressive scale bias in depth estimation. The intercept, or coefficient b in Equation 1, was slightly less than 0 in both tests. The adjusted R^2 was 0.31 and 0.25, showing substantial variability in the participants' estimates.

Effect of motion-related cues

To compare the two types of motion-related cues (expansive optic flow and lateral motion parallax) with static viewing, we looked at the linear regression model fitted with continuous expansive optic flow and lateral motion parallax (see lines 2 and 3 in Table 1). The models fitted with continuous motion trials and the baseline are visualized in Figure 3.

The regression slope of the trials with lateral motion parallax, 1.02, was significantly steeper than that with expansive optic flow, 0.57, $t = 11.5$, $p < 0.001$. Expansive optic flow also yielded a steeper slope than static viewing $t = 3.04$, $p = 0.007$.

These results show that participants had more accurate depth estimation with lateral motion parallax than with static viewing, and the effect of expansive optic flow was smaller.

Effect of continuous motion

Lines 1, 4, and 5 in Table 1 denote the coefficients and confidence intervals of the regression lines fitted for static viewing, expansive displacement, and lateral displacement trials, also shown in Figure 4.

For the expansive optic flow, neither continuous motion nor displacement was significantly different from static viewing. For lateral motion parallax, displacement had a significantly steeper slope than static viewing, $t = 6.8$, $p < 0.001$. Continuous lateral motion parallax yielded an even steeper slope and a closer-to-0 intercept compared with lateral displacement, $t = 8.3$, $p < 0.001$. The 95%

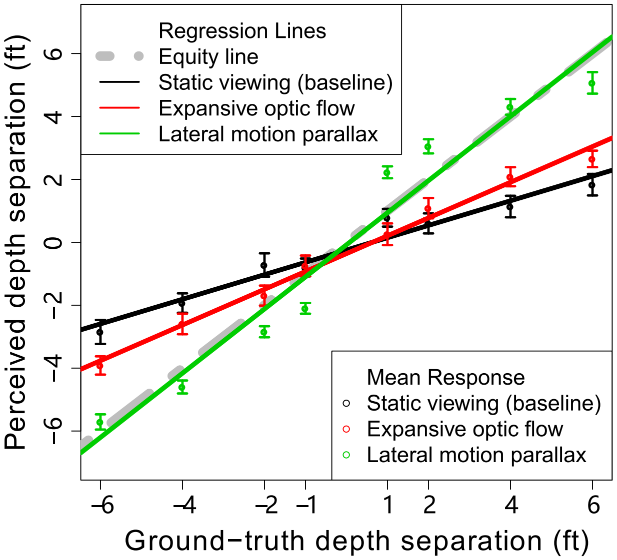

Figure 3. Scatter plots and regression lines of depth estimates as a function of ground-truth depth. Error bars show standard errors. The three lines represent static viewing, expansive continuous motion, and lateral continuous motion. The negative sign means the target was to the south of, or closer to the observer than, the reference object.

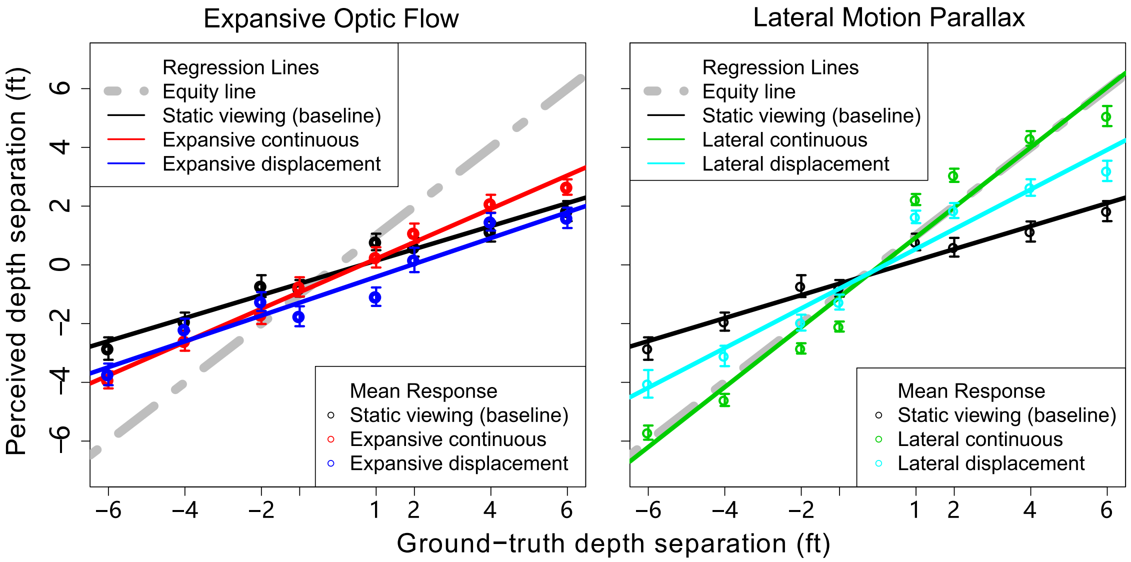

Figure 4. Scatter plots and regression lines of depth estimates as a function of ground-truth depth. Error bars show standard error. The negative sign means the target was to the south of, or closer to the observer than, the reference object.

confidence interval of regression slope yielded by the continuous lateral motion included 1.0. A Fisher's r-to-z comparison indicated that the Pearson correlation of the regression model fitted with continuous lateral motion trials, $r = 0.89$, was higher than that of the model fitted with lateral displacement trials, $r = 0.71$, $z = 4.89$, $p < 0.001$, meaning depth perception was more consistent in continuous motion trials than in displacement trials.

Answering our research questions, the results show that lateral motion parallax increased depth perception accuracy compared with static viewing. Expansive optic flow yielded more accurate depth estimation than static viewing. Continuous motion was more effective in enhancing depth perception than object image displacement.

Experiment 2: Test with artificially reduced acuity

In Experiment 2, we examined how artificially reduced acuity affects depth perception from expansive optic flow and lateral motion parallax. The apparatus, procedure, and data analysis methods of Experiment 2 were the same as those of Experiment 1.

Methods

Participants

Eleven students were recruited from the campus of the University of Minnesota. There were six male and five female participants with a mean age of 19.5 ± 1.4 years and ranging from 18 to 22 years (see details in Appendix 3, Supplementary Table S6). All participants had self-reported normal or corrected-to-normal vision. All participants started the experiment after giving informed consent. The experiment protocol was approved by the University of Minnesota Institutional Review Board.

Stimuli

The virtual scene used in Experiment 2 was the same as in Experiment 1 apart from the color information (Figure 2A). Examples of the stimuli are presented in Figure 2C. In Experiment 2, the target object only had two possible dimensions, one being 2 feet wide, 4 feet tall, and 0.6 feet thick, the other being 3.66 feet wide, 3.66 feet tall, and 0.6 feet thick. This strategy was used to limit the total number of trials each participant needed to complete.

Design

There were four independent variables in this study: the motion type (expansive optic flow and lateral motion parallax), the presentation type (continuous motion, object image displacement, and static viewing), the acuity reduction level (mild, moderate, and severe), and the location of the target object. The virtual scene was presented in five viewing conditions: expansive continuous motion, lateral continuous motion, expansive displacement, lateral displacement, and static viewing. These five viewing conditions were designed the same way as in Experiment 1.

The location of the target object (gray column) had eight levels. It could be placed at 6, 4, 2, or 1 foot (feet) to the south or north of the reference object. In the following text and figures, the negative sign in the perceived or ground-truth separation means the south direction, or that the target object was closer than the reference object.

The acuity reduction had three levels. A digital filter was used to simulate three levels of acuity (Xiong et al., 2020). The filter takes the acuity and contrast sensitivity values to generate an estimate of the minimum luminance contrast detectable at each spatial frequency band. The filter then attenuates the amplitude of the Fourier transform of the input image at each spatial frequency to simulate acuity reduction. In this experiment, the filter simulated three levels of acuity reduction and was calibrated with an Early Treatment Diabetic Retinopathy logarithm of the minimum angle of resolution (logMAR) acuity chart. The mild acuity loss level equals 0.95 logMAR (20/178 Snellen), the moderate level equals 1.15 logMAR (20/282 Snellen), and the severe level equals 1.55 logMAR (20/709 Snellen). The corresponding contrast sensitivity of the three levels was set to be 1.0, 0.75, and 0.5 Pelli–Robson to simulate realistic vision impairment conditions. There is a wide variation in ability to see colors among people with low vision. Therefore, we focused on motion information carried by luminance contrast and presented the images in gray-scale.

The pictorial depth cues (relative size and angle of declination) were mainly contained in low-spatial frequency information of the image. Therefore, under acuity reduction, participants could still use these pictorial cues to estimate the depth of target object in the static viewing condition. No participants reported difficulties in completing the task during the experiment. Informal inspection by the experimenter confirmed that these features were visible in the blurred images.

Three acuity reduction levels, five viewing conditions, eight depth separations, and two target object dimensions combined to give a total of 240 conditions. Each condition was tested twice on each participant. The whole experiment contained 480 randomized trials.

	Acuity reduction level	Viewing condition	Slope (CI 2.5%, 97.5%)	Intercept (CI 2.5%, 97.5%)	Adjusted R^2
1	Mild	Static	0.31 (0.24, 0.39)	−0.72 (−1.01, −0.43)	0.15
2		Expansive continuous	0.39 (0.34, 0.45)	−0.96 (−1.16, −0.75)	0.36
3		Lateral continuous	0.78 (0.73, 0.83)	−0.24 (−0.43, −0.05)	0.73
4	Moderate	Static	0.36 (0.28, 0.43)	−0.87 (−1.14, −0.59)	0.21
5		Expansive continuous	0.34 (0.28, 0.4)	−1.12 (−1.34, −0.9)	0.27
6		Lateral continuous	0.82 (0.77, 0.86)	−0.41 (−0.59, −0.22)	0.76
7	Severe	Static	0.26 (0.19, 0.34)	−1.63 (−1.91, −1.36)	0.12
8		Expansive continuous	0.24 (0.18, 0.3)	−1.09 (−1.32, −0.86)	0.15
9		Lateral continuous	0.7 (0.64, 0.76)	−1.04 (−1.28, −0.81)	0.59

Table 2. Regression coefficients and 95% confidence intervals of static viewing, expansive continuous optic flow, and lateral continuous motion parallax trials in mild, moderate, and severe blur. *Note*: The regression model had perceived depth as the dependent variable and ground-truth depth as the independent variable.

Results

Depth estimates for static viewing

The first, fourth, and seventh lines of Table 2 denote the slopes, intercepts, and adjusted R^2 values of the static viewing condition in the three acuity reduction levels. We considered the static viewing conditions to be the baseline.

To verify that the participants could distinguish the target object and the reference object, we checked the percentage of trials where the participants correctly judged the depth order of the two objects. Based on binomial test results, the correct judgment rate was 59%, 64%, and 56% in the mild, moderate, and severe acuity reduction levels, which were all significantly above the chance level: mild condition, $p < 0.01$; moderate condition, $p < 0.01$; and severe condition. $p = 0.02$.

Under all three levels of acuity reduction, the slope of the linear regression lines (coefficient a in Equation 1) in the baseline condition all fell within the range of 0.26 to 0.36, showing no significant difference. This result reflected a substantially compressive scale bias. Severe reduction yielded a significantly lower than 0 intercept (coefficient b in Equation 1) than the other two reduction levels. This meant that the observers estimated the target object to be closer than it was under severe acuity reduction (1.55 logMAR), but not under mild and moderate reduction (0.95 and 1.15 logMAR). These results showed that the baseline depth estimates in the three simulated acuity loss conditions had low accuracy, with a compressive scale bias, a negative offset bias, and substantial variability around the regression line.

Figure 5 visualizes the linear regression models fitted from static viewing trials under the three acuity levels.

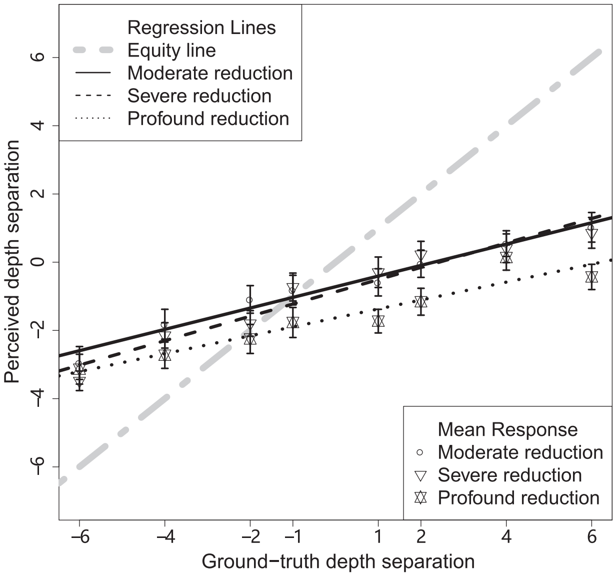

Figure 5. Scatter plots and regression lines of participants' perceived depth plotted against ground-truth depth. Error bars show standard errors. The negative sign means the target was to the south of, or closer to, the observer than the reference object. The three lines represent static viewing regression models under mild, moderate, and severe acuity reduction.

Effects of motion-related cues

Lines 2, 3, 5, 6, 8, and 9 of Table 2 denote the regression coefficients and confidence intervals for continuous expansive optic flow and lateral motion parallax trials in the three acuity levels. Figure 6 visualizes these regression models.

For all three acuity levels, expansive optic flow did not make the regression slopes significantly steeper than that yielded by static viewing. Lateral motion parallax yielded significantly steeper slopes than static viewing under all three levels of acuity reduction: mild, $t = 10.3$, $p < 0.001$; moderate, $t = 10.1$, $p < 0.001$; and severe, $t = 9.8$, $p < 0.001$. The value of the slopes ranged from 0.70 to 0.82.

These results show that lateral motion parallax yielded more accurate depth estimates than static viewing. Expansive optic flow also made the offset bias

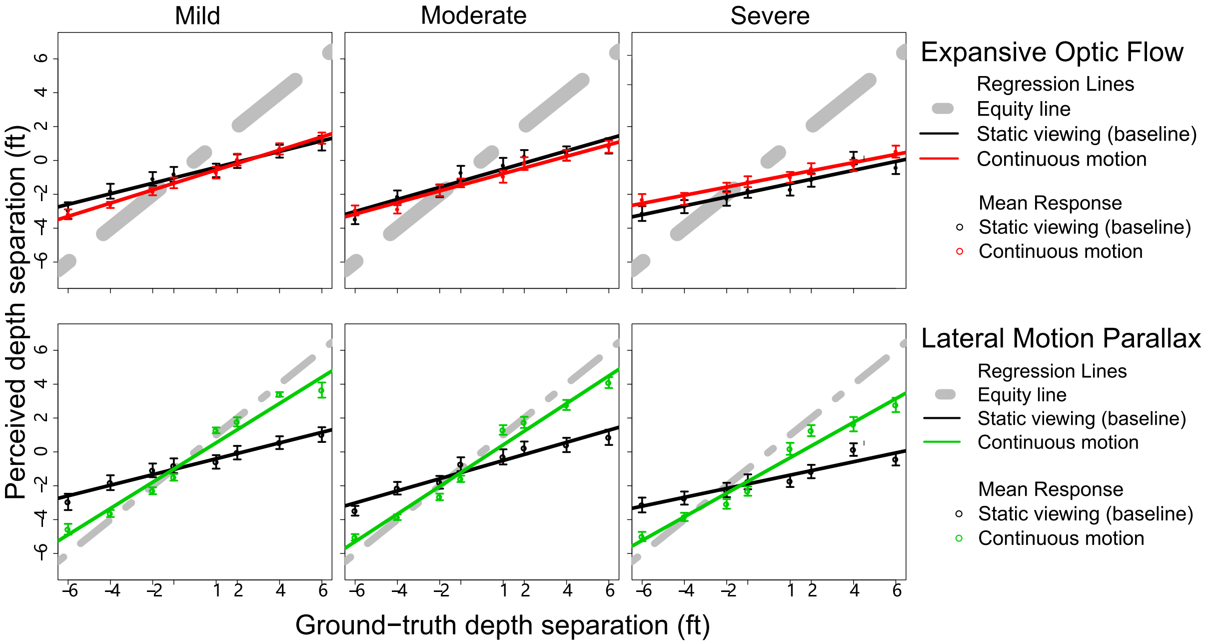

Figure 6. Scatter plots and regression lines of depth estimations as a function of ground-truth depth. Error bars show standard errors. The negative sign means the target was to the south of, or closer to the observer than, the reference object. The top row shows static viewing and continuous expansive optic flow, and the bottom row shows static viewing and continuous lateral motion parallax. The left, middle, and right columns show trials under mild, moderate, and severe acuity reductions.

	Blur level	Viewing condition	Slope (CI 2.5%, 97.5%)	Intercept (CI 2.5%, 97.5%)	Adjusted R^2
1	Mild	Static	0.31 (0.24, 0.39)	−0.72 (−1.01, −0.43)	0.15
2		Expansive Displacement	0.31 (0.25, 0.37)	−0.92 (−1.15, −0.7)	0.23
3		Lateral Displacement	0.62 (0.57, 0.67)	−0.37 (−0.56, −0.19)	0.64
4	Moderate	Static	0.36 (0.28, 0.43)	−0.87 (−1.14, −0.59)	0.21
5		Expansive Displacement	0.29 (0.23, 0.35)	−0.93 (−1.15, −0.71)	0.22
6		Lateral Displacement	0.65 (0.59, 0.7)	−0.54 (−0.75, −0.33)	0.61
7	Severe	Static	0.26 (0.19, 0.34)	−1.63 (−1.91, −1.36)	0.12
8		Expansive Displacement	0.29 (0.23, 0.35)	−1.04 (−1.28, −0.8)	0.19
9		Lateral Displacement	0.63 (0.56, 0.7)	−1.45 (−1.71, −1.18)	0.47

Table 3. Regression coefficients and 95% confidence intervals for static viewing, expansive displacement, and lateral displacement trials in mild, moderate, and severe blur. *Note*: The regression model had participants' perceived depth as the dependent variable and ground-truth depth as the independent variable.

closer to 0 compared with static viewing under severe acuity reduction, but overall, its improvement to depth estimation accuracy was less pronounced than that of lateral motion parallax.

Effect of continuous motion

Lines 2, 3, 5, 6, 8, and 9 of Table 3 denote the regression coefficients and their confidence intervals for the expansive and lateral displacement conditions under three levels of acuity reduction. Figure 7 visualizes the regression models.

The regression slope in expansive displacement trials did not differ from that in static viewing trials under all levels of acuity reduction. Expansive displacement trials had an intercept significantly closer to 0 compared with static viewing trials under severe blur. This result meant that expansive displacement only had a small effect on depth perception accuracy, which was similar to the effect of continuous expansive optic flow.

Under all three acuity reductions, the regression slope of lateral displacement trials was significantly steeper than that of static viewing trials: mild, $t = 7.23$, $p < 0.001$; moderate, $t = 6.7$, $p < 0.001$; and

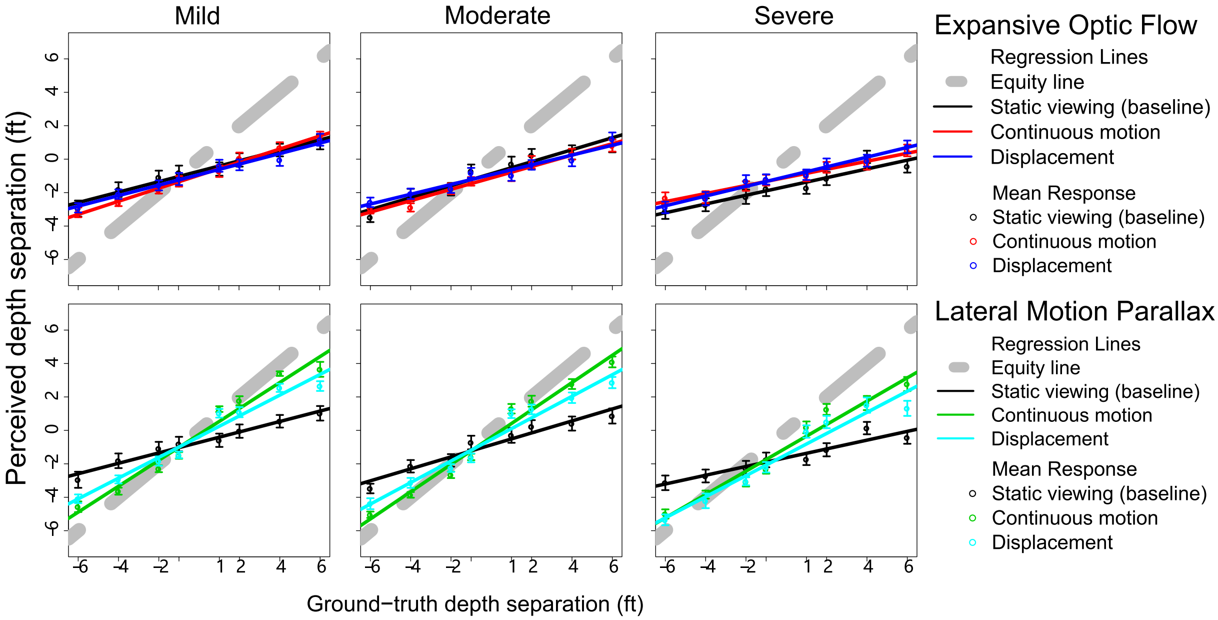

Figure 7. Scatter plots and regression lines of depth estimates as a function of ground-truth depth. Error bars show the standard error. The negative sign means the target was to the south of, or closer to, the observer than the reference object. The top row shows static viewing, expansive displacement, and expansive continuous motion, while the bottom row shows static viewing, lateral displacement, and lateral continuous motion. The left, middle, and right columns show trials under mild, moderate, and severe acuity reduction respectively.

severe, $t = 7.8$, $p < 0.001$. Under mild and moderate acuity reduction, the regression slope in the lateral displacement condition was still lower than that in the lateral continuous motion condition: mild, $t = 3.6$, $p = .002$; and moderate, $t = 4.0$, $p < 0.001$. However, that difference became insignificant under severe acuity reduction.

In summary, continuous lateral motion parallax yielded more accurate depth perception than lateral displacement only with mild and moderate acuity reduction, but not with severe reduction.

Discussion

The results addressed the research questions of this study. First, both lateral motion parallax and expansive optic flow helped increase depth perception accuracy for observers with normal or artificially reduced acuity, while lateral motion parallax yielded more accurate depth estimates than expansive optic flow. The object image displacement also increased depth perception accuracy compared with static viewing under all levels of acuity reduction. Continuous motion had an advantage over displacement under mild and moderate reduction, but not under severe acuity reduction.

Comparing the results of Experiments 1 and 2, acuity reduction had only a small influence on the relationship between motion parallax and depth perception. As acuity reduction becomes more severe, depth perception accuracy with a static view becomes slightly worse, allowing the enhancement of expansive optic flow on depth perception accuracy to emerge. Severe acuity reduction also limited the benefit of continuous motion, making the difference between continuous motion and displacement disappear.

Compressive scale bias in depth perception

For participants with both normal acuity and artificially reduced acuity, a compressive scale bias and a negative offset bias were consistently shown in the static viewing condition. The regression slope (coefficient a in Equation 1, representing the scale bias) was roughly the same in all three blur levels and fell in the same range of value as the regression slope found in the baseline condition with normal-acuity observers. For more severe acuity reduction, offset bias (coefficient b in Equation 1) becomes more negative, which leaves room for the effect of expansive optic flow to show. However, in general, the change in acuity levels did not have a substantial effect on depth perception accuracy in the static viewing condition. This result was consistent with the findings of Tarampi, Creem-Regehr, and Thompson (2010), where participants with normal acuity and participants wearing blur goggles showed the same scale bias in a depth matching task. The reason behind this finding might be that the two pictorial cues in the stimuli—the relative size and the angle of declination—only involve low spatial frequency features in the image, which are the wall–floor boundary and the object contour. These features may be accessible to observers with normal or reduced acuity. This result is consistent with the findings of Rand, Tarampi, Creem-Regehr, and Thompson (2011) and Rand, Tarampi, Creem-Regehr, and Thompson (2012), who found that the angle of declination is a robust depth cue for observers with reduced acuity.

Advantage of lateral motion parallax over expansive optic flow

At all acuity levels, lateral motion parallax yielded higher accuracy of depth estimation than expansive optic flow. One possible explanation of this finding is the different image information contained in the two types of motion-related cues. With expansive optic flow, an observer can use the different rates of expansion of the images of two objects to infer the depth separation between them, whereas with lateral motion parallax, they can use the different rates of lateral shift. In the current scene layout, with the same increment of depth separation, relative lateral shift increased more than expansion (see Appendix I, Table S1, and Supplementary Figure S1). This meant that lateral motion parallax was more effective in converting geometrical information into image information compared with expansive optic flow. However, even in the trials where the magnitudes of the relative expansion and the relative lateral shift were matched, lateral motion parallax still had a lower depth perception error than expansive optic flow (Appendix I). This result indicates that the difference in the magnitude of the relative expansion and lateral shift does not fully explain the difference between lateral motion parallax and expansive optic flow.

Another difference between expansive optic flow and lateral motion parallax was the image shift of wall–floor–ceiling boundaries in the room background. The boundaries shifted a greater number of pixels laterally in lateral motion parallax than they expanded radially in the expansive optic flow. Compared with expansion, the lateral shift of the boundaries might give the observers more information on the spatial layout of the room and the heading direction of the motion, and hence help them to make better depth estimations. In a supplementary study, 10 participants were tested via Zoom doing the depth separation estimation task with original stimuli with the room background and an alternative version with a solid gray background. Without the presence of wall-floor boundaries, participants still made more accurate depth estimations with lateral motion parallax than with expansive optic flow (Appendix II). This finding shows that the image shift of wall–floor boundaries in the background does not explain the difference between motion-related cue types.

Another possible reason behind this difference could be the Gestalt grouping of objects. In expansive optic flow, the contours of both the target and the reference object shifted toward the periphery, resulting in a common fate of the contours of the two objects. Based on Gestalt theory, the common fate of moving features makes observers more likely to group the features together (Wagemans et al., 2012). There have been several studies concluding that Gestalt grouping, including grouping by common fate, can influence depth perception (Palmer & Brooks, 2008; Rashal & Wagemans, 2022; Yonas, Craton, & Thompson, 1987). The common fate of object image shifts in expansive optic flow might make the observer less sensitive to the depth separation between these two objects. In contrast, the contours of the target and reference objects do not have a common fate in lateral motion parallax. This strategy might help the participants to estimate the depth separation more accurately.

Liu et al. (2019) and Bochsler et al. (2013) both studied the effect of expansive optic flow on the identification of architectural features. Whereas Bochsler et al. found that forward observer motion, which induced expansive optic flow did increase identification accuracy, Liu et al. found that expansive optic flow did not have a significant effect. This apparent discrepancy might be because Liu et al. presented a virtual indoor space on a computer screen and had participants identify architectural features on the screen, whereas Bochsler et al. had the participants stand still or walk forward in a physical space while looking at the architectural structures. Extraretinal information, namely, the knowledge of one's eye height and moving speed, might be an important factor in whether expansive optic flow can be used for depth perception.

Advantage of continuous motion over image displacement

With normal acuity and mildly or moderately reduced acuity, both lateral displacement and lateral continuous motion increased depth perception accuracy compared with static viewing. This result was consistent with Pan and Bingham (2013), who investigated event identification under visual blur. The authors found that a continuous presentation of an event yielded a higher identification rate than a discrete presentation. The results suggest that the high temporal frequency motion signals do provide extra benefit for depth perception compared with the temporally separated presentation of object image displacement. However, when the acuity reduction was severe, continuous motion did not have a significant advantage over contour displacement. It is possible that the velocity of image shift in some continuous motion trials fell below the perception threshold of observers under severe acuity reduction (Shanidze & Verghese, 2019; Snowden & Kavanagh, 2006), making the advantage of continuous motion weaker.

The current study only tested normally sighted participants with normal or artificially reduced acuity. The cue integration strategy of the normally sighted participants might be different from that of low vision observers. More research is needed to verify the relationship between motion continuity and depth perception in low vision observers, especially those with severe acuity loss.

Conclusions

In estimating the depth between two objects in virtual space, motion-related cues help to increase the accuracy of depth perception in human observers with both normal and artificially reduced acuity. Lateral motion parallax is more effective in improving depth perception from static viewing than expansive optic flow. Future studies are needed to explain the advantage of lateral motion parallax over expansive optic flow. Displacement of object contours in the field of view, without continuous motion, can enhance object depth perception under artificial acuity reduction. Seeing the continuous motion can further increase the enhancement under normal or mildly and moderately reduced acuity, but not under severe reduction.

Keywords: depth perception, motion parallax, low vision, spatial vision

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