Oculomotor contribution to the change in perceived speed with viewing distance

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1. INTRODUCTION

Accurately assessing egocentric distance (i.e., the distance from an observer to objects in the visual field) has obvious survival value and is one of the most important functions performed by the visual system. Under normal binocular viewing conditions, there are numerous perceptual and physiological cues to the egocentric distance of objects of unknown size [1–3]. The perceptual cues include relative size, interposition, and perspective, and the physiological cues include ocular vergence and accommodation. The perceptual cues are generally more salient, whereas the physiological cues are generally easier to quantify. Ocular vergence and accommodation are not independent responses, but their effects can be separated experimentally, and when this is done, vergence is found to be the more reliable cue to distance [4].

It is well known that perceived size can vary with egocentric distance even when retinal image size is held constant [2,5], and subsequent research has shown that ocular vergence contributes to this change in perceived size [6–9]. If the same visual mechanisms are involved in coding both object size and the distance that an object moves [10–13], then given that speed may be defined as the change in that distance with time, it might be expected that perceived speed would also be affected by changes in ocular vergence. The dependence of perceived speed on egocentric distance has been studied almost exclusively in the context of speed constancy [10,12–15]. However, ocular vergence was not explicitly measured in those studies, nor was it assessed independently of other visual cues to egocentric distance.

In the present study, the perceived speed of two arrays of randomly distributed circular stimuli was compared when the arrays were viewed either binocularly or monocularly at different egocentric distances. In the binocular case, varying egocentric distance also varied the degree of ocular vergence. All other identifiable cues to egocentric distance were effectively minimized. Eye movements were monitored both to verify the predicted ocular vergence response and to assure that the perceived speed measurements were not affected by eye movements that could reduce retinal image motion. We have attempted to determine whether oculomotor cues alone are sufficient to affect perceived speed. If they are, they may be sufficient to provide cues to egocentric-distance scaling that could in turn affect perceived speed.

2. METHOD

A. Observers

Speed estimation data were obtained from a group of 11 observers. Six observers (numbers 2, 3, 6, 7, 8, and 9) were tested under the near-0.33-m-binocular, and near-0.33-m-monocular conditions (see below). All of these observers were not available for a subsequent experiment, designed to compare the initial binocular condition (near-0.33-m-binocular) with a second binocular condition associated with a greater near-viewing distance

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14. ABSTRACT

An array of moving circular stimuli was used to determine whether perceived speed is affected by the oculomotor responses associated with changes in viewing distance. The perceived speed of stimuli viewed at either 0.33 or 1.33 m was compared to the perceived speed of a similar stimulus viewed at a distance of 5.5 m. In addition, a control condition was run in which changes in perceived speed were compared for monocular viewing of the 0.33 m and 5.5 m stimuli. In the binocular condition, there were statistically significant decreases in perceived speed of about 11% for the 0.33 m viewing distance, and about 6.5% for the 1.33 m viewing distance. There was no significant decrease in perceived speed in the monocular condition. This latter finding, along with the similar appearance of the near and far stimuli in the monocular condition, suggests that ocular vergence (as opposed to accommodation or vergence?accommodation) was the primary determinant of the change in perceived speed with changes in binocular viewing distance. Although the change in perceived speed with fixation distance was relatively small, the data from all observers were in the direction of speed constancy. Thus, to the extent that vergence is a cue to egocentric distance, the present data suggest that egocentric distance is used to scale the perceived speed of targets moving at different distances from the observer.

15. SUBJECT TERMS
Perceived speed; Oculomotor; Viewing distance; Monocular viewing; Ocular vergence; Accommodation; Binocular viewing; Speed constancy; Moving targets

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(near-1.33-m-binocular), and so an independent group of subjects was used (numbers 1, 4, 5, 10, and 11). All observers had normal visual acuity as determined by a standard Snellen chart, and all were able to fuse random-dot stereograms (RanDot SO-002 Stereotest, Stereo Optical Co.) down to 20 arc sec. Observers 2 and 3 were two of the authors, and it was verified that their data did not differ systematically from those of the other observers.

B. Apparatus and Stimuli

A diagram of the experimental apparatus (not to scale) is shown in Fig. 1. Far (5.5 m [0.18D]) and near (either 0.33 m [3D] or 1.33 m [0.75D]) stimuli were rear-projected onto ground-glass screens (Lumiglass 350, Stewart Film Screen Corp.) by separate projectors (far, Barco Graphics, Model RCU800; near, Barco 800, with close-focus optics). The distance from the near projector to the near display screen was the same for all near-viewing conditions. The observers were surrounded by curtains and other light shields that effectively blocked all stray light.

The test stimuli were generated, and all data collection was controlled, by an SGI Indigo Elan 4000 workstation. The stimuli were 24°(H)×19°(V), random-spot arrays moving from left to right at either 6, 12, or 18 deg/sec. The arrays consisted of 60 spots. When a spot moved past the right edge of the display, it was replaced with another spot that entered at the left edge at a random position. The spots were approximately Gaussian blobs, with diameters of about 0.3° at $\pm 2\sigma$ and a luminance of about 2 fL, as measured on the far display. Each near display was luminance matched, defocused, and color filtered so as to match the far display. It was verified by two observers (two of the authors) that the near and far stimuli could not be reliably distinguished.This was done by testing each of the two observers in two sessions, one for each of the two near stimuli (0.33 or 1.33 m). The observers first viewed the far and near displays sequentially ten times with binocular vision. One eye was then covered, and the observers were translated such that the viewing eye was aligned with the fixation points on the displays. The observers again viewed the displays sequentially, this time for 20 trials presented in random order, and responded as to whether the second display was near or far. The proportion of correct responses averaged over the two observers was 0.575 and 0.50 for the 1.33 and 0.33 m near stimuli, respectively.

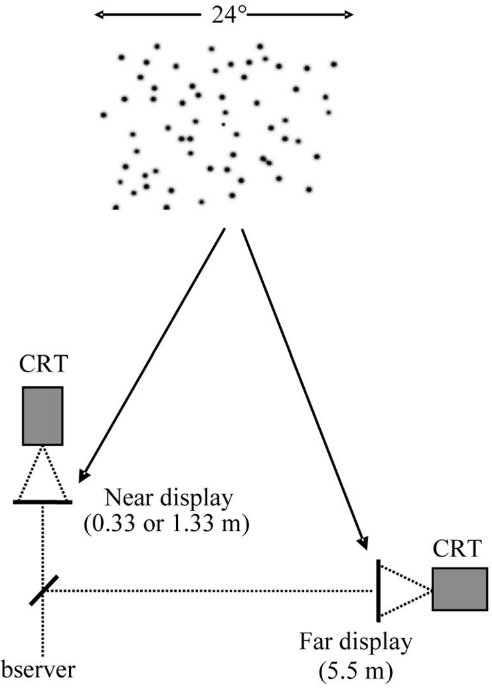

Fig. 1. Diagram (not to scale) of the display system consisting of a far (5.5 m) CRT display and a near (either 0.33 or 1.33 m) CRT display. The inset at the top shows the dimensions and approximate appearance of the random-spot stimulus array.

The low-pass filtered characteristics of the spots would be expected to minimize their effect on accommodation [16]. The general appearance of the stimulus array is shown at the top of Fig. 1. Random-spot arrays were chosen to avoid some of the problems associated with the use of individually identifiable moving objects [10]. Zohary and Sittig [15] found no difference in perceived speed between random-dot kinematograms, which they characterized as pure velocity stimuli, and stimulus arrays for which the positions of individual elements were identifiable (such as those used in the present study).

The observer viewed two stimulus arrays in each trial. One stimulus corresponded to either a monocular or binocular stimulus located at a distance of 0.33 m (referred to here as the near-0.33-m-monocular and near-0.33-m-binocular conditions, respectively), or a binocular stimulus located at 1.33 m (near-1.33-m-binocular condition). In all cases, the other stimulus viewed in each trial was located 5.5 m from the observer. To help assure that the observers could not distinguish the near and far stimuli based on their presentation order, a double-random staircase procedure was used in which one staircase was associated with the standard presented on the near display, and the other with the standard presented on the far display. For each standard speed tested (6, 12, and 18 deg/sec), one of these staircases was started above the expected threshold and the other below it. The data for the two staircases were then averaged.

The present test stimuli were anisotropic in that the test spots moved in one direction only. It might be argued that this anisotropy could provide extraneous visual cues related to, for example, differences in disparity or directional variations in speed perception. We, therefore, obtained control data from four (numbers 2, 3, 8, and 9) of the six observers tested under the near-0.33-m-monocular condition, using test stimuli in which the spots moved at 6 deg/sec in a radial direction away from the fixation point. In addition, each test spot had a limited lifetime of about 0.5 s, and upon disappearing was replaced by another spot at a random location in the array. The testing procedures were similar to those of the main experiment. No significant difference was found between these data and those obtained with the laterally moving stimuli [pairwise $t(3)=0.89$, $p=0.44$].

C. Ocular-Vergence Monitoring

In order to ensure that vergence was consistent with the viewing distance under test, and that fixation was maintained while the moving spot arrays were viewed, eye movements were monitored using an El-Mar Series 2000 eye measurement system. Eye movement responses of the left eye were recorded at 60 Hz via the serial port on a standard PC, and they were analyzed using our own software. Eye movements as small as 0.5° could be reliably measured with this system. The vergence responses of all 13 observers were monitored constantly throughout each testing session to assure that they were appropriate for the stimulus distance under test.

D. Procedure

Following 8–10 min of dark adaptation, the observer first viewed a fixation point presented on either the far or near display. The observer was allowed 2 s to verge and thereby fuse the image of the fixation point. The standard moving spot stimulus was then presented for 3 s on the same display as the fixation point. The standard was then extinguished, a fixation point was presented on the other display, and the observer was again allowed 2 s to fuse the fixation point. The variable stimulus was then viewed for 3 s, and the observer responded as to whether it appeared to move faster or slower than the standard. The variable speed on successive trials was increased or decreased by a factor of 0.07 depending on the observers' previous response. In order to minimize the use of local motion cues, observers were instructed to judge the speed of the random-spot array as a whole, as opposed to attending to individual spots. When this was done, the visual impression was that of a globally moving sheet of spots.

In each experimental session, each of three standard speeds was tested at one of the two viewing distances. Standard speed was randomized within each session. Testing was completed at one vergence level before the other was tested, and the order in which the vergence levels were tested was varied among observers. For each vergence level, data were collected from each observer in three to four sessions (one session/day) over the course of 4–6 days. A point of subjective equality (PSE) was used to define a speed match (i.e., the speed to which the variable stimulus was set) and was estimated as the mean of the six reversal points of each of the two staircases (standard near and standard far) associated with each condition tested in each experimental session. The results of 3 to 4 sessions were then averaged to obtain a speed match for each observer. A Weber fraction was then calculated as (speed of near stimulus–speed of far stimulus)/speed of standard, where, as described earlier, the standard stimulus could be in either the near or far position. These Weber fractions were used as the dependent variable in the analyses of variance (ANOVAs) (SPSS, v.8.0), with viewing condition and speed of the standard as the factors of interest.

3. RESULTS

A. Ocular Vergence

Typical vergence responses (in this case from Observer 7) are shown in Fig. 2. The upper trace shows an eye movement sequence as the observer changed binocular fixation several times between the far (5.5 m) and the near-0.33-m fixation points. The lower trace shows analogous data for fixation changes between the far and the near-1.33-m stimulus locations.

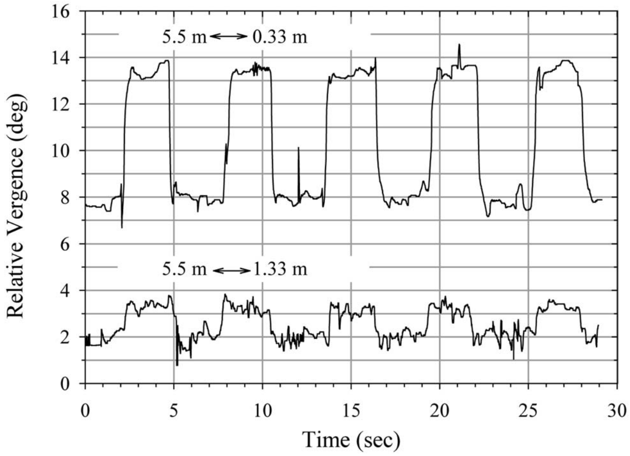

Fig. 2. Typical vergence responses obtained as one observer successively verged to the far (5.5 m) and near test stimuli. The upper and lower traces correspond to near distances of 0.33 and 1.33 m, respectively.

B. Speed Matches

The data of Fig. 3 show the decrease in the perceived speed of the near stimulus relative to the far stimulus as a function of standard-stimulus speed for each of the six observers tested at the 0.33 m viewing distance. In general, a higher near-stimulus speed was required to match the speed of the far stimulus and, thus, the near stimulus appeared to move slower than the far stimulus when their retinal speeds (i.e., in deg/sec) were the same. In the case of binocular viewing (near-0.33-m binocular), the decrease in perceived speed increased with the speed of the standard. There was no indication that the perceived speed varied with the speed of the standard for the monocular viewing condition (near-0.33-m-monocular).

The data of Fig. 4 are analogous to those of Fig. 3 but for the farther near-viewing distance (i.e., near-1.33-m binocular). Again, perceived speed generally increases with the speed of the standard stimulus, although the increase is less than that found for the near-0.33-m-binocular condition.

The mean data of Figs. 3 and 4 have been replotted in Fig. 5 for the purpose of comparing them to predictions derived from an assumption of either no constancy (retinal-velocity matching) or full constancy (physical-velocity matching). The plotted data points were on average 3.2%, 11.2%, and 2.3% of the full-constancy prediction for the near-0.33-m-monocular, near-0.33-m-binocular, and near-1.33-m-binocular conditions, respectively.

Shown in Fig. 6 are the data of Figs. 3 and 4 converted to Weber fractions by dividing them by the standard speed. Separate ANOVAs were used to analyze the Weber fraction data because different combinations of observers were used to test the viewing conditions of interest, namely, near-0.33-m-binocular versus near-0.33-m-monocular and near-0.33-m-binocular versus near-1.33-m binocular.

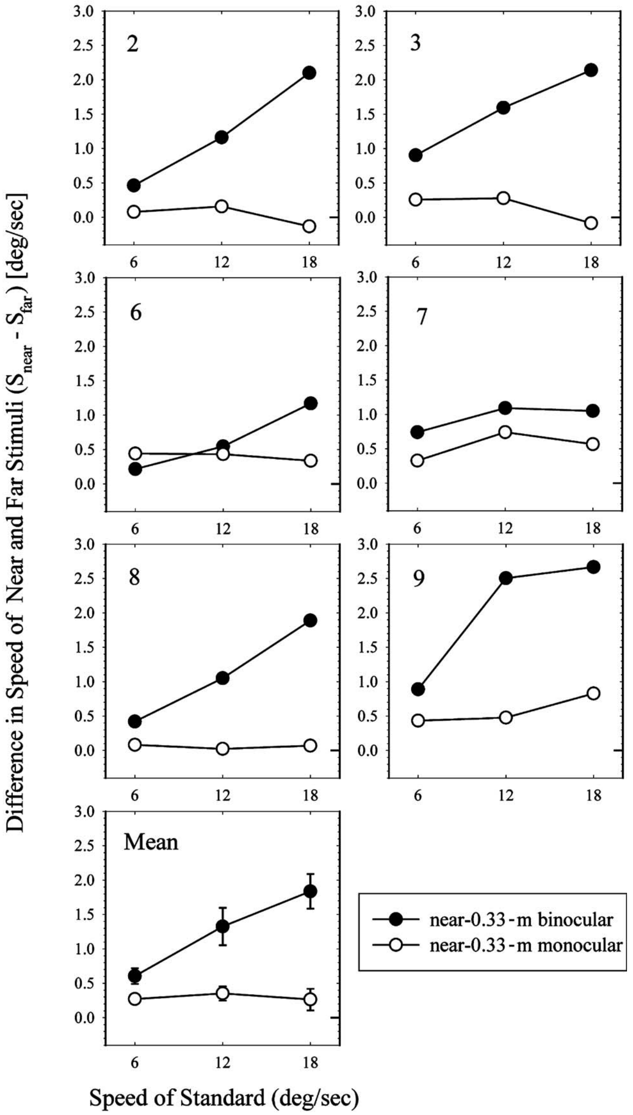

Fig. 3. Speed of the 0.33 m near stimulus that matched that of the far (5.5 m) stimulus for both the monocular (-○-) and binocular (-●-) viewing conditions. The greater matched speed for the near stimulus indicates that the near stimulus was perceived to move more slowly than the far stimulus. Data are shown for each of the six observers tested. The error bars for the mean data represent ±1 s.e.m. (standard error of the mean).

C. Weber Fractions for the Near-0.33-m-Binocular versus Near-0.33-m-Monocular Conditions

As shown in Fig. 6, Weber fractions varied between about 0.10 and 0.11 for the near-0.33-m-binocular viewing condition and between about 0.015 and 0.045 for the near-0.33-m-monocular viewing condition. A within-subjects ANOVA (using the Greenhouse–Geisser correction) was performed for the two viewing conditions and the three standard speeds (6, 12, and 18 deg/s). The main effect of viewing condition was significant [$F(1,5)=18.1$, $p<0.01$], but that of standard speed was not [$F(1,7)=2.0$, $p>0.05$]. The interaction between viewing condition and standard speed was not significant [$F(2,10)=1.9$, $p>0.05$].

We also tested each of the mean Weber fractions for the three standard speeds used under the near-0.33-m-monocular and near-0.33-m-binocular viewing conditions in order to determine whether any of them were significantly different from zero. For the near-0.33-m-monocular condition, the mean Weber fraction was significantly different from zero for the 6 and 12 deg/sec stimuli ($t=4.1$, $p<0.01$ and $t=3.22$, $p<0.05$, respectively), but not for the 18 deg/sec stimulus ($t=1.67$, $p>0.10$). For the near-0.33-m-binocular condition, the mean Weber fraction was significantly different from zero for the 6, 12, and 18 deg/sec stimuli (all t's>4.7, all p's<0.01).

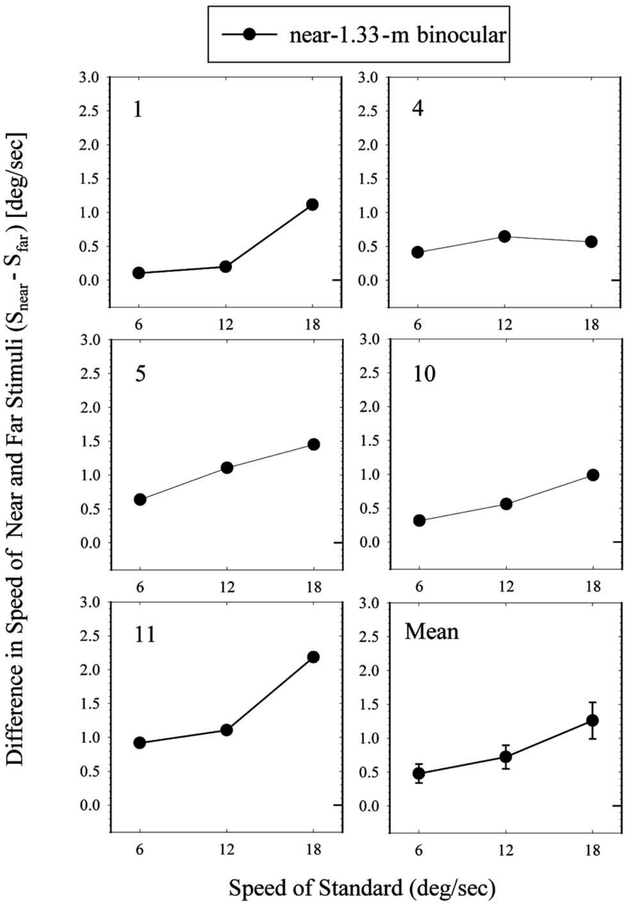

Fig. 4. The speed of the 1.33 m near stimulus that matched that of the far (5.5 m) stimulus for the binocular viewing condition. The greater matched speed for the near stimulus indicates that the near stimulus was perceived to move more slowly than the far stimulus. Data are shown for each of the five observers tested. The error bars for the mean data represent ±1 s.e.m. (standard error of the mean).

D. Weber Fractions for the Near-0.33-m-Binocular versus Near-1.33-m-Binocular Conditions

Weber fractions for the near-1.33-m-binocular condition varied between about 0.06 and 0.08 across the three standard speeds and thus were intermediate to those obtained for the two 0.33 m conditions. The Weber fractions obtained for the near-0.33 m-binocular and near-1.33-m binocular conditions were analyzed by a 2×3 ANOVA for mixed designs, with the two viewing conditions as the between-subjects factor and the three standard speeds (6, 12, and 18 deg/sec) as the within-subjects factor. This

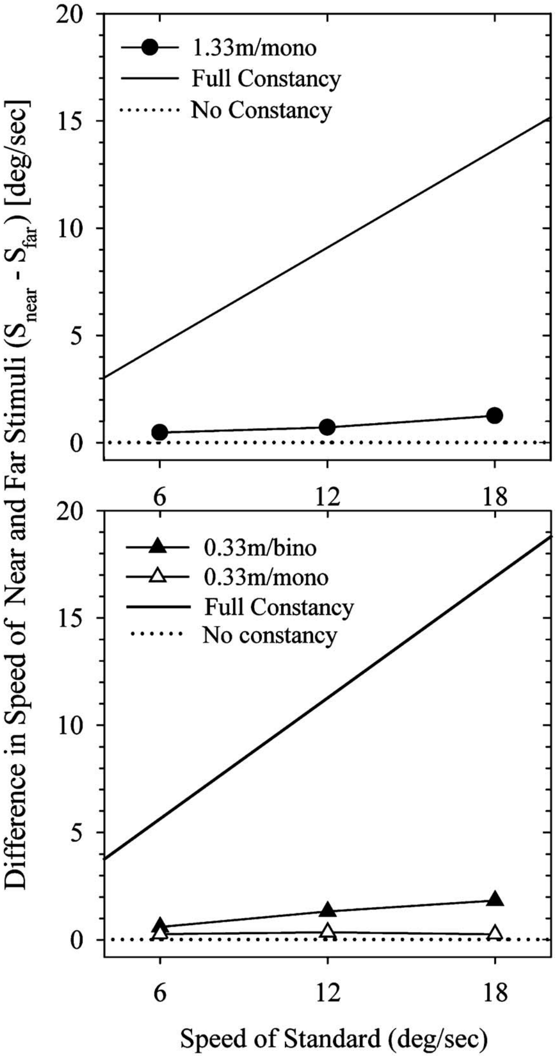

Fig. 5. Comparison of the mean data of Figs. 3 and 4 with the predictions derived from assuming either no constancy (retinal-velocity matching) or full constancy (physical-velocity matching): (top) 1.33 m viewing distance; (bottom) 0.33 m viewing distance.

analysis (using the Greenhouse–Geisser correction for the within-subjects factor) revealed that neither the main effect of viewing condition [$F(1,9)=2.1$, $p=0.18$] nor of standard speed [$F(2,18)=0.14$, $p=0.87$], nor the interaction between these variables [$F(2,16)=1.1$, $p=0.37$], was significant.

4. DISCUSSION

A. Oculomotor Response and Perceived Speed

The data of Fig. 6 show that increasing the vergence response results in a decrease in perceived speed. Further, a comparison of the monocular and binocular data allows the contribution of selected components of the oculomotor response to be evaluated. This conclusion cannot be drawn from previous studies of speed perception because either vergence was not isolated from other egocentric distance cues [12,17–19], or vergence level was either not explicitly varied [10,20–24] or not varied over a sufficiently large range [14,15,25,26]. However, in the present study, no significant effect of egocentric distance on perceived speed was obtained for the monocular condition, under which the only identifiable cue was accommodation. Thus, we conclude that vergence is the primary oculomotor cue responsible for the change in perceived speed with egocentric distance. The data of Fig. 6 show that the effect of vergence on perceived speed is relatively small, as is consistent with the results of analogous studies on the effect of vergence on perceived size, distance, and stereoscopic depth [6,27,28].

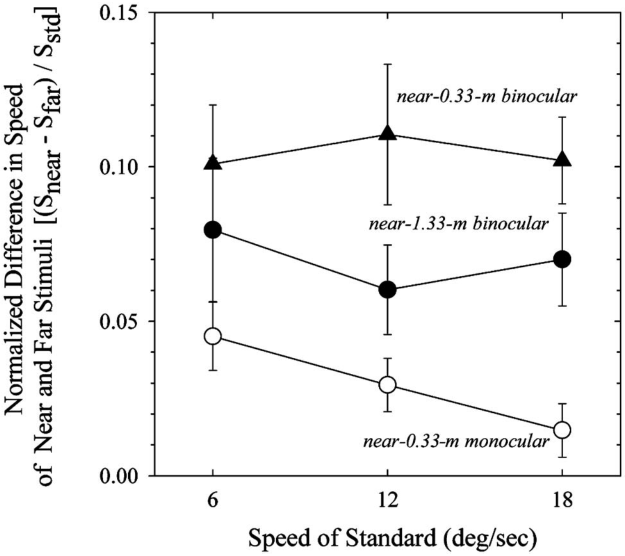

Fig. 6. Proportional increase in the perceived speed of the near stimulus, which was obtained by scaling the mean speed increases shown in Figs. 3 and 4 by the speed of the standard stimulus. The error bars represent ±1 s.e.m. (standard error of the mean).

Although they were not explicitly discussed in the context of oculomotor responses, the results of several previous studies are qualitatively consistent with the present data. For instance, Rock *et al.* [12], in their Experiment 1, used single targets moving over a fixed extent but viewed binocularly from different distances. For near- and far-target viewing distances of 18 and 72 in. (1 in. = 2.54 cm), respectively, a near-target speed of 3 in./sec was matched by a far-target speed of 4.2 in./sec. Although this result does not indicate full speed constancy (in their case, 3 in./sec), it is much closer to speed constancy than are the present data. This difference may be attributed to the fact that the size of their binocularly viewed stimuli was not adequately scaled with viewing distance. Perceived size is an important cue to target distance, and in the present study, where size was scaled with distance, such scaling may have mediated the lesser speed constancy effect. Epstein [14], in his Experiment 4, also used single circular targets but moved them within illuminated frames. The size and distance of the targets and frames were varied such that their angular sizes did not change. He found that the angular speeds of the nearer, variable stimuli were set slightly higher than those of the farther, standard stimuli. The perceived speed differences, which ranged from about 5% to 11%, are consistent with the effect of ocular vergence on perceived speed found in the present study, despite the fact that the shortest viewing distance studied by Epstein was 1 m, and thus the total vergence change was less than in the present study.

B. Role of Egocentric Distance in Speed Perception

It has been concluded from several studies that relative perceived speed is dependent upon perceived distance [12,14,17,18,20], whereas the results of other studies have suggested that it is not [10,13,15]. These seemingly conflicting data can be reconciled by positing that while egocentric distance cues are used to scale retinal speed, the effects of relational cues may be more salient and may override the effects of distance scaling. This possibility may also have theoretical implications for assessing the complexity of speed-discrimination mechanisms (e.g., see [29,30]).

Zohary and Sittig [15], in their Experiments 2a and 3a, asked observers to compare the speed of random-dot kinematograms viewed at distances of 1 and 2 m and found that observers tended to match the retinal speed of the stimuli, and they concluded that there was no speed constancy. However, a visual inspection of their Figs. 4 and 8 shows, in each case, a deviation from retinal speed matching in the direction of constancy for at least three of their five observers. These deviations, which are in the same direction as those of the present study, suggest that Zohary and Sittig did not eliminate egocentric distance cues in their study [26]. The present data relating egocentric distance to perceived speed are consistent across observers, in that all observers perceived a decrease in target speed as egocentric distance was increased (see Figs. 3 and 4).

C. Speed Constancy

The importance of accurately assessing egocentric distance derives also from the role of distance scaling in mediating certain perceptual constancies (e.g., see [31]). These constancies are essential to the most fundamental function of the visual system, namely, forming an accurate percept of the visual environment from the limited information available in the retinal image. One example is size constancy. When an observer moves closer to an object, its retinal size will increase. In order for a veridical perception of physical size to occur, the increase in retinal size must be scaled by a shorter egocentric distance [11]. Another example is stereoscopic depth constancy. When an observer moves closer to a set of objects, the binocular disparity among them will increase. In order for a veridical perception of relative depth among the objects to be obtained, the increase in the disparities among the objects must again be scaled by a shorter egocentric distance (e.g., see [23,29]).

Now consider speed constancy. When an observer changes egocentric distance relative to a moving object, its retinal speed will vary. In order for a veridical perception of physical speed to occur, the change in retinal speed must be scaled by the change in egocentric distance. The present data indicate that ocular vergence can contribute to this scaling operation [32]. Specifically, measured constancy (see Fig. 5) was between about 2% and 12% of full constancy. These values are an indication of the relative effect on speed constancy of ocular vergence as compared with other potential egocentric distance cues such as relative size, interposition, and perspective.

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