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Perception of time to contact of slow- and fast-moving objects using monocular and binocular motion information

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Abstract
The role of the monocular-flow-based optical variable τ in the perception of the time to contact of approaching objects has been well-studied. There are additional contributions from binocular sources of information, such as changes in disparity over time (CDOT), but these are less understood. We conducted an experiment to determine whether an object's velocity affects which source is most effective for perceiving time to contact. We presented participants with stimuli that simulated two approaching squares. During approach the squares disappeared, and participants indicated which square would have contacted them first. Approach was specified by (a) only disparity-based information, (b) only monocular flow, or (c) all sources of information in normal viewing conditions. As expected, participants were more accurate at judging fast objects when only monocular flow was available than when only CDOT was. In contrast, participants were more accurate judging slow objects with only CDOT than with only monocular flow. For both ranges of velocity, the condition with both information sources yielded performance equivalent to the better of the single-source conditions. These results show that different sources of motion information are used to perceive time to contact and play different roles in allowing for stable perception across a variety of conditions.

Keywords Time to contact · Stereomotion · Binocular vision · Motion perception · Binocular disparity · CDOT · Optic flow

Perception of motion is critical to both everyday tasks and survival. One crucial aspect of motion perception that relates to both of these extremes is the ability of an observer to perceive the time to contact (TTC) of an approaching object. An optical variable that is based on monocular optic flow, known as τ, has often been studied in relation to this task (Lee, 1976). This variable is the ratio of the current visual angle of an object to this angle's current rate of expansion. At any given moment, an object's τ value specifies TTC with the observer if the approach velocity remains constant.

However, TTC is also perceived using many non-τ sources of information (DeLucia, Kaiser, Bush, Meyer, & Sweet, 2003). Some sources arise because, although τ is monocularly available, most human vision is binocular, yielding a redundancy of information. This redundancy exceeds just having τ information for each eye. Binocular disparity is also available, and motion is specified by changes in disparity over time (CDOT). This disparity-based motion information can be used to accurately perceive TTC (Rushton & Wann, 1999), and it can even counteract inaccuracies from other sources of information (DeLucia, 2005). Work has even shown that there are commonly encountered conditions under which the perception of TTC is better with binocular information than with τ (Gray & Regan, 2004), such as when viewing small objects (Gray & Regan, 1998; Heuer, 1993; Rushton & Wann, 1999) or rotating nonspherical objects (Gray & Regan, 2000).

Because evidence suggests that disparity is useful when perceiving approaching objects, Anderson and Bingham (2010) proposed a disparity-based τ, and further work has confirmed that humans use it to guide action in a variety of approach behaviors (Anderson & Bingham, 2011; Fath, Marks, Snapp-Childs, & Bingham, 2014). This provides further evidence that disparity-based motion perception plays a role in perception of the TTC of approaching objects. The functional role of disparity-based information in perceiving TTC and how this role compares to that of monocular TTC

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perception still need to be fleshed out, though, especially because of the extensive research on monocular-flow-based τ. If disparity-based information does play a role in TTC perception, it may differ from that played by monocular flow. The inferior temporal and spatial frequency of CDOT (Regan & Beverley, 1973; Tyler, 1971) suggests that it might not be as well-suited for the perception of fast-moving objects (Harris, Nefs, & Grafton, 2008), so perhaps CDOT is used only for slower objects. If that is the case, is CDOT the primary source of information for slower objects, or are both sources relied on?

To test disparity-based information's utility for the perception of TTC, we ran an experiment similar to that of Todd (1981). We presented participants with stimuli that specified two objects approaching from different distances at different constant velocities. These velocities and starting distances were selected to produce a range of differences in the TTCs of the two objects. During approach the objects disappeared, and participants judged which object would have contacted them first had the objects continued approaching. The displays isolated different sources of motion information, which resulted in three visual information conditions: (a) only disparity-based information was available, (b) only monocular flow was available, or (c) all sources of information were available. The experiment was run in two velocity conditions. In the slower condition the velocities of approach ranged from 26 to 32 cm/s, and in the fast condition the velocities ranged from 73 to 127 cm/s. In this way we tested what roles different sources of motion information play with respect to velocity of motion.

Experiment 1

Methods

Participants Twelve adults (ten female and two male, 20–36 years of age) were recruited to participate in this study. The participants had normal or corrected-to-normal vision, with stereoacuity of at least 80 arcsec crossed disparity as measured by the Stereo Fly Test (Stereo Optical Company, Inc.). All participants gave their informed consent prior to participation. All procedures were approved by and conform to the standards of the Indiana University Institutional Review Board and are in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Procedure The procedure was similar to that used by Todd (1981), but now it consisted of stimuli that specified motion with disparity-based information only, flow-based information only, or both. The displays were viewed at a distance of 76 cm from a Dell UltraSharp LCD monitor with a resolution of 1,920 × 1,080 and a refresh rate of 60 Hz. Participants were placed at this viewing distance and told to maintain that location, without head movements being mechanically restricted beyond the use of a chinrest. Stimulus presentation, data recording, and all data analysis was handled by a custom Matlab toolbox, incorporating the Psychophysics Toolbox (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997). The entire session lasted about 1 h.

In the present study, the slowest speeds tested were much slower than those used by Todd (1981), so we similarly scaled down the virtual distances that the objects were viewed from, especially due to concern about the salience of the very small changes in disparity that would result from the slowest object speeds in the present study if they were viewed from the great distances used by Todd. A wide range of object velocities were required in order to test our hypothesis, so fewer frames were used in the fast condition across all display types, to keep distances covered similarly. The displays consisted of 30 frames per second, so in the fast condition six frames were presented within a 200-ms interval, and in the slow condition 21 frames were presented within a 700-ms interval. As in Todd (1981), the displays depicted two approaching squares. One square was located on the left side of the screen, and the other was on the right. Both squares appeared at the same time at different depths, and each square approached at a different constant velocity. Both squares disappeared during approach at the same moment. Participants were instructed to use the left or right arrow key on a keyboard to select the square that would have contacted them first had both squares continued to approach at their respective constant velocities.

Trials were performed in three display conditions, with each condition providing different visual information. In one condition, approach of the objects was specified only by disparity (disparity-only). The disparity-only stimuli were red and blue dynamic random-dot stereograms viewed with anaglyph glasses. These stereograms measured 15 × 15 cm and were set against a dark, desaturated background. The magnitude of the lateral offset of each matching pair of red and blue dots that specified disparity was determined on the basis of the corresponding object's location relative to the participant, given the participant's interpupillary distance (IPD), which was measured before the session. The background plane of these displays defined a background 20 cm behind the screen. For each frame, a new random array of points was created, the correct on-screen locations of the target objects were determined, given their velocities, and then the disparity of all points within these regions was manipulated to specify the correct depth of the objects. This difference in disparity between points in the target regions and points in the background plane was all that specified the presence of the targets. When viewed monocularly or without the anaglyph glasses, the display appeared to be an array of random dots at screen depth (Fig. 1).

In a second condition (flow-only), only flow-based information was available. Random dots were drawn in the display window, as in the disparity-only condition, with three differences. First, the dots were not rerandomized each frame, so there was coherent motion across frames. Second, the display

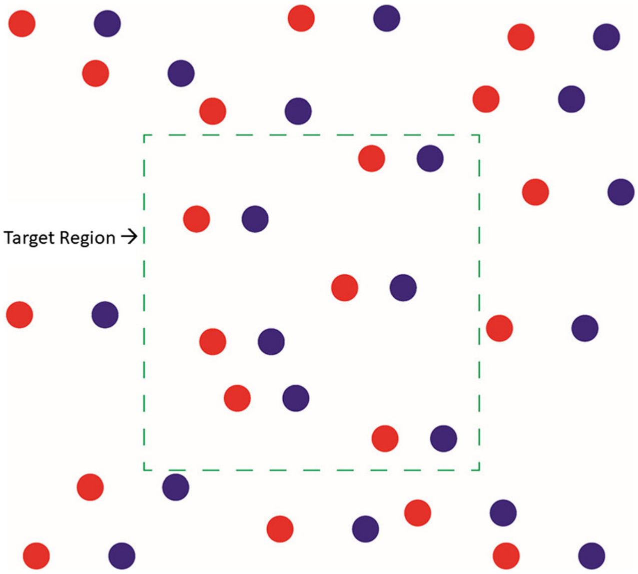

Fig. 1 For both the disparity-only and combined conditions, binocular disparity was specified by manipulating the lateral offset of matching pairs of red and blue dots viewed through anaglyph glasses. Points in the regions determined to be target locations had different disparities than those in the background plane, and in the disparity-only condition this disparity was all that specified the presence of the targets. Note that in the actual display, the dots were at a much higher density than in this simplified figure, so the edges of the target region were well-specified by these dots alone

was viewed monocularly with the dominant eye, which was identified with the Miles test (Miles, 1930). This eliminated all binocular cues. Thus, only one set of dots was drawn; that is, no second set of matching dots was offset from the first. Finally, the dots were drawn only at the on-screen locations depicting the squares; that is, there were no background dots. In the third condition (combined), the dots also did not rerandomize, so there was coherent motion across frames, as in the flow-only condition. However, a corresponding set of offset dots was used to add disparity to the stimuli, which were viewed binocularly with anaglyph glasses. As in the disparity-only condition, the dots that were not in the part of the screen occupied by the squares specified a background plane 20 cm behind the screen.

Each trial was a mathematically accurate simulation of a pair of approaching square objects. The squares had a side length of 4 cm in all trials. Each square started at one of three starting distances—15, 17, or 19 cm behind the screen—which resulted in starting visual angles of 2.52, 2.46, or 2.41 deg. The difference in TTC between the two squares on any given trial was 50, 100, 200, 300, 400, or 500 ms. These TTC differences were chosen to be similar to those used by Todd (1981), but the maximum values were larger because we anticipated that under some conditions the disparity-only display might be more difficult for some participants than the displays used by Todd had been. In the slow condition, the square that would first have contacted the point of observation had a TTC of 3 s, so the square that would have contacted last had a TTC of 3.05, 3.10, 3.20, 3.30, 3.40, or 3.50 s. In the fast condition, the square that would have first contacted the point of observation had a TTC of 0.75 s, so the square that would have contacted last had a TTC of 0.80, 0.85, 0.95, 1.05, 1.15, or 1.25 s. Trials were blocked by visual information condition, and the order of presentation of the visual information conditions was counterbalanced across participants. In each block, two trials were performed for each of the six TTC differences from each of the nine left/right starting distance pairs ({15, 17, 19} × {15, 17, 19}). In one of these two trials, the left object would have contacted the point of observation first, and in the other the right object would have contacted first. This resulted in a total of 108 trials per visual information condition, presented in a randomized order. For a given trial, once these parameters were determined, the velocities required to produce the selected TTC from the selected starting distances in that block's number of frames were computed in order to execute the virtual approach. These parameters were chosen so that the square that started the trial closest to the observer was not necessarily the one with the smaller TTC, and neither was the square that ended the trial closest to the observer. In the slow condition, this resulted in simulated velocities of the approaching squares ranging from 26 to 32 cm/s, and in the fast condition these velocities ranged from 73 to 127 cm/s. For both speed conditions, the average final target visual angle was 3.15 deg. Given the initial distances that corresponded to these velocities, the initial expansion rates ranged from 0.73° to 3.36°/s, and the terminal expansion rates ranged from 1.11° to 5.69°/s. The resulting disparities ranged from 0.42 crossed disparity to 0.41 uncrossed disparity.

Participants were allowed to repeat any trial by pressing the space bar. They could repeat a trial as many times as they liked before providing a response. This was allowed because we recognized that we were asking participants to make fine discriminations of TTC (as little as 50 ms) from very short presentations (as brief as 200 ms) of impoverished stimuli, and errors could result on a given trial from perturbing the visual system in this way, not because the participants were generally unable to use the information available in the stimulus. We wanted to eliminate such errors so we could be confident that if we observed chance performance from a certain set of conditions, it was really because the human visual system is not sufficiently sensitive to the information presented by this set of conditions. Once a response was given, immediate feedback was provided by displaying a white star to the correct side of the display window. Text-based feedback (e.g., "left/right" or "correct/incorrect") was not used because it might have been disruptive to look at the text and then back at the random-dot display before every trial. Our feedback method allowed participants to focus on the display throughout and to detect the feedback in their periphery. The next trial began after feedback had been displayed for 1 s.

Results

Figure 2 shows the proportions of correct responses in the fast condition for each TTC difference in each visual information condition. Participants performed comparably in the flow-only and combined conditions, but significantly worse in the disparity-only condition. We performed a three-way repeated measures analysis of variance (ANOVA) with speed (slow and fast), TTC difference (50, 100, 200, 300, 400, and 500 ms), and visual information condition (disparity-only, flow-only, and combined) as factors. We found main effects of speed [$F(1, 11) = 19.09$, $p < .05$], TTC difference [$F(5, 55) = 172.66$, $p < .05$], and visual information condition [$F(2, 22) = 7.12$, $p < .05$], as well as a Speed × TTC Difference interaction [$F(5, 55) = 5.02$, $p < .05$] and a Speed × Visual Information Condition interaction [$F(2, 22) = 28.46$, $p < .05$]. Post hoc tests demonstrated that in the fast condition, participants performed worse with disparity-only stimuli than with either flow-only or combined stimuli, but performance with the flow-only and combined stimuli did not differ, as can be seen in the Fig. 2. Similarly, in the slow condition, participants performed worse with flow-only stimuli than with disparity-only or combined stimuli, but performance with the disparity-only and combined stimuli did not differ (see Fig. 3).

Table 1 shows the average numbers of repetitions per trial across participants for each Visual Information Condition × Speed pair. Participants could repeat any trial as many times as they liked before responding. Thus, if a participant had, say, 16 total repetitions for a given Visual Information Condition × Speed pair, they could have repeated 16 different trials once apiece, one trial 16 different times, or anything in between. We performed a three-way repeated measures ANOVA with speed (slow and fast), TTC difference (50, 100, 200, 300, 400, and 500 ms), and visual information condition (disparity-only, flow-only, and combined) as factors. There were main effects of speed [$F(1, 11) = 8.97$, $p < .05$] and TTC difference [$F(5, 55) = 11.93$, $p < .05$], but no main effect of visual information condition and no interaction. We also observed a Speed × TTC Difference interaction [$F(5, 55) = 5.73$, $p < .05$] and a Speed × TTC Difference × Visual Information Condition interaction [$F(10, 110) = 6.00$, $p < .05$].

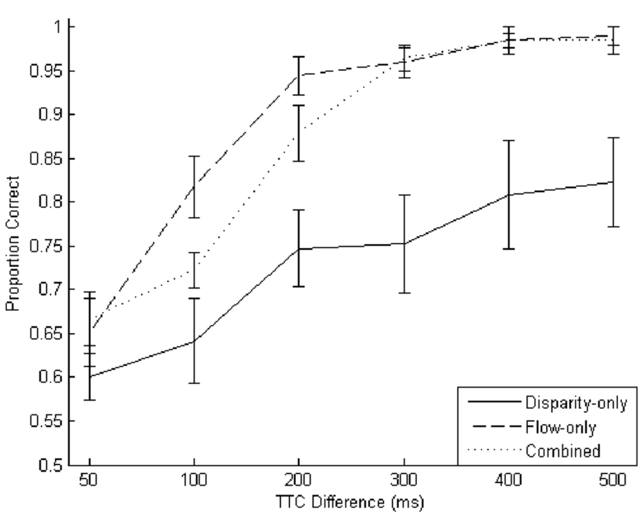

Fig. 2 Proportions correct in the fast condition across 12 participants, as a function of time-to-contact (TTC) differences for the three visual information conditions. These TTC differences were relative to a baseline of 0.75 s. Error bars represent standard errors

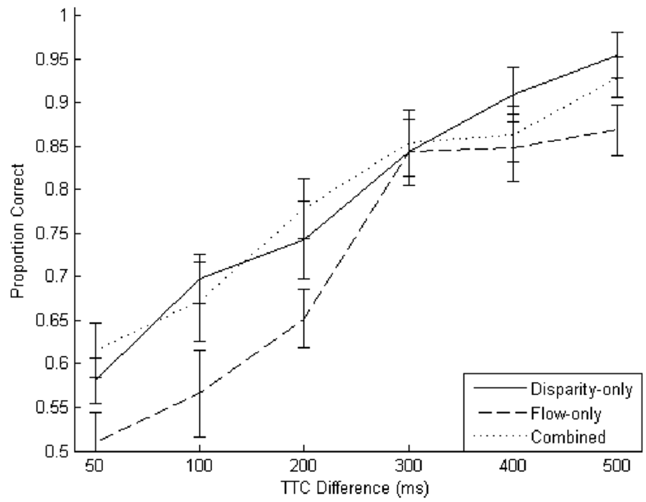

Fig. 3 Proportions correct in the slow condition across 12 participants, as a function of time-to-contact (TTC) differences for the three visual information conditions. These TTC differences were relative to a baseline of 3.0 s. Error bars represent standard errors

Discussion

We confirmed that disparity-based information is used in the perception of TTC. Previous work had suggested that disparity-based information should not be as useful as flow-based information when viewing faster moving objects (Regan & Beverley, 1973; Tyler, 1971). This was supported

Table 1 Average repetitions across participants for each Visual Information Condition × Speed pair

	50 ms	100 ms	200 ms	300 ms	400 ms	500 ms
Slow						
Flow-only	0.32	0.28	0.30	0.22	0.20	0.16
Disparity-only	0.30	0.26	0.23	0.15	0.08	0.13
Combined	0.36	0.25	0.23	0.18	0.15	0.18
Fast						
Flow-only	0.24	0.15	0.09	0.04	0.01	0.01
Disparity-only	0.21	0.19	0.16	0.14	0.13	0.14
Combined	0.19	0.18	0.06	0.05	0.02	0.02

Each trial could be repeated more than once, and entries indicate the average number of repetitions per trial for each Visual Information Condition × Speed pair by our results. Interestingly, we also found that performance was better when viewing slower objects with disparity-based than with flow-based information. It is worth noting that performance with disparity-only stimuli in the fast condition and with flow-only stimuli in the slow condition was still above chance, even in the more difficult trials (i.e., those with smaller TTC differences). Thus, the least reliable source of motion information in any given condition was still informative. Overall, performance was better with the fast stimuli.

Performance with all sources of information available was not superior to performance with only the single most reliable source. It is worth noting that the combined condition was the only binocularly viewed condition with flow-based information available, and thus was the only condition that yielded interocular velocity differences (IOVD). Given the utility of IOVD in the speed discrimination of motion in depth (Harris & Watamaniuk, 1995), it might be expected to play a large role in the perception of TTC. The lack of improvement when IOVD was available in the combined condition does not rule this out, but it suggests that IOVD plays little or no role in the performance of this task. However, there is evidence that suggests that a small but significant population exists who are disproportionately sensitive to IOVD as compared to CDOT, with or without underlying pathology (Nefs, O'Hare, & Harris, 2010). Such persons might rely on IOVD when perceiving TTC, even if others do not.

The main effect of speed and the interactions in the analysis of trial repetitions seem to occur because participants frequently reached very reliable performance (above 95% correct) in the fast condition, but rarely in the slow condition. That is, trial repetition was not necessary when performance was high, which should be expected. This pattern of participants reaching very reliable performance in the fast, but not the slow, condition also explains the Speed × TTC Difference interaction in the analysis of TTC judgments.

Experiment 2

However, even though the finding that flow-based information alone was superior to disparity-based information alone in the fast condition was expected, there was still a potential confound that should be explored. The movement duration for the fast stimuli was very brief (200 ms), much shorter than for those used by Todd (1981), so it might have been difficult for participants to fuse the stereogram stimuli and track the objects' motion within that time. Thus, we ran a second experiment in which half of the trials were from the same fast condition that we had used in the previous experiment, and the other half were from a new fast condition in which the objects had the same velocities but were moving at these velocities for twice the duration.

The effect, if any, of increased duration on the performance with disparity-only stimuli was the primary interest, since this would tell us whether the reduced performance with disparity-only stimuli in the fast condition of Experiment 1 was a product of the high speeds or the short duration. However, we ran all three of the visual information conditions from Experiment 1, to also check whether the increased stimulus duration would affect performance in any other visual information conditions.

Method

Participants Ten adults (eight female and two male, 22–37 years of age) were recruited to participate in this study. The participants had normal or corrected-to-normal vision, with stereoacuity of at least 80 arcsec crossed disparity, as measured by the Stereo Fly Test (Stereo Optical Company, Inc.). All participants gave their informed consent prior to participation. All procedures were approved by and conformed to the standards of the Indiana University Institutional Review Board and were in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Procedure The apparatus and procedure were identical to those in Experiment 1, with the exception that the slow condition was replaced by a condition with the same velocities as the fast condition but twice the stimulus duration (long). The original fast condition that we replicated here will be referred to as the *short condition*. The displays in the long condition consisted of 12 frames presented within a 400-ms interval. The background plane was specified at 48 cm behind the screen. Each square started at one of three starting distances: 30, 37.5, or 45 cm behind the screen. The square that would have contacted the participant first had an initial TTC of 1 s, so the square that would have contacted last had an initial TTC of 1.05, 1.10, 1.20, 1.30, 1.40, or 1.50 s. As in Experiment 1, trials were blocked by visual information condition, and the order of presentation of the visual information conditions was counterbalanced across participants.

Results

Figure 4 shows performance in all conditions. Our primary interest was whether the stimulus duration would affect performance with the disparity-only stimuli. To test this, we performed a two-way repeated measures ANOVA with TTC difference (50, 100, 200, 300, 400, and 500 ms) and duration (short and long) as factors. There was a main effect of TTC difference [$F(5, 45) = 3.15$, $p < .05$], but no effect of duration and no interaction. Similarly, we performed two-way repeated measures ANOVAs on the data from the two other visual information conditions, with TTC difference (50, 100, 200, 300, 400, and 500 ms) and

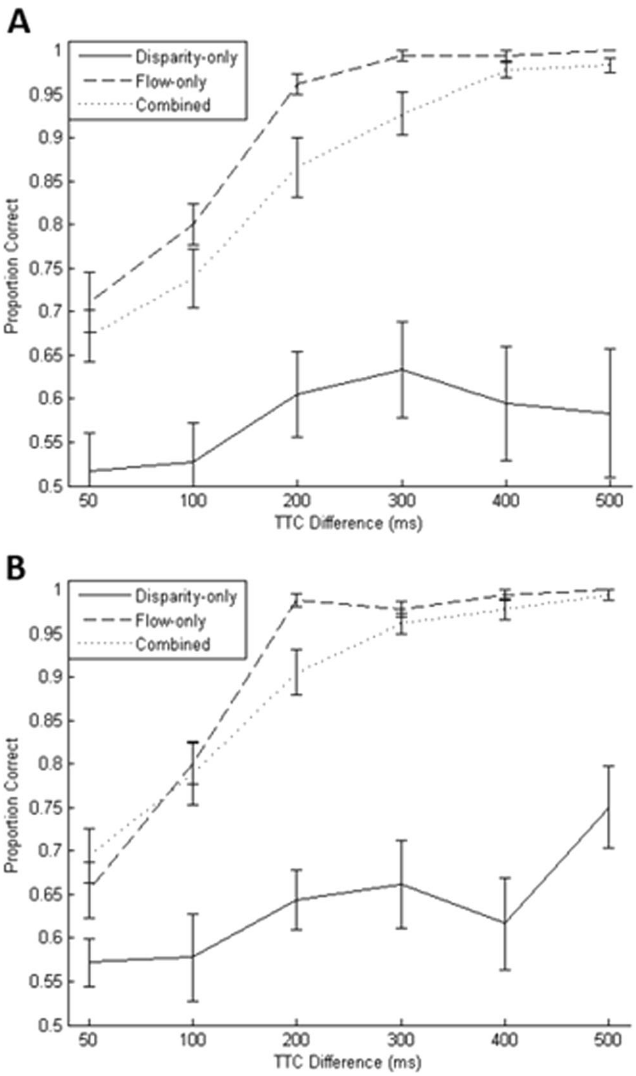

Fig. 4 Proportions correct in the short condition (**A**) and the long condition (**B**) as a function of time-to-contact (TTC) differences for the three visual information conditions. These TTC differences were relative to a baseline of 1.0 s. Error bars represent standard errors

duration (short and long) as factors. In the flow-only condition, we found a main effect of TTC difference [$F(5, 45) = 118.31$, $p < .001$], but no effect of duration and no interaction. In the combined condition, we again found a main effect of TTC difference [$F(5, 45) = 96.72$, $p < .001$], but no effect of duration and no interaction.

Discussion

Experiment 2 yielded no evidence for an increase in performance with a doubling of duration when viewing the disparity-only stimuli. Thus, the finding from Experiment 1 that performance was poor in the fast condition with disparity-only stimuli was supported, and this result was not an artifact of the short stimulus duration.

Conclusion

Stability of the perception of TTC across a variety of conditions is functionally advantageous. This stability is achieved by relying on different sources of motion information, depending on their utility given the current circumstances. In the context of the speed of motion, we found that flow-based information is used primarily for the perception of fast motion of approaching objects, and disparity-based information for slower motion. Research on the control of approach behaviors has shown that monocular information about TTC is used to control approach during tasks such as braking (Warren, 1998) that often involve faster motion, and stereo information about TTC is used to control approach during tasks such as reaching (Anderson & Bingham, 2010; Watt & Bradshaw, 2003) that typically involve slower motion. The results of this study are consistent with these prior findings.

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