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Visual Information for Judging Temporal Range

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ABSTRACT

Work in our laboratory suggests that pilots can extract temporal range information (i.e., the time to pass a given waypoint) directly from out-the-window motion information. This extraction does not require the use of velocity or distance, but rather operates solely on a 2-D motion cue. In this paper, we present the mathematical derivation of this information, psychophysical evidence of human observers' sensitivity, and possible advantages and limitations of basing vehicle control on this parameter.

INTRODUCTION

Helicopter control and navigation require the pilot to orchestrate a complex set of control inputs in response to visual information gleaned from the external scene and cockpit instruments. We suggest that a temporal scaling of the external environment, i.e., gauging the time to reach a chosen way-point at current vehicle speed, is a highly useful metric for the pilot. And, in fact, there is sufficient information in the optical flow to support such temporal metrics.

In this paper, we delineate the visual information that specifies temporal range, describe laboratory research demonstrating people's sensitivity to this information, discuss how this information can be used in vehicular control, and consider specific situations in which this information leads to errors in perceived range.

TEMPORAL RANGE INFORMATION

In the mid-1950s, astrophysicist and novelist Fred Hoyle allowed one of the more clever characters in his book, The Black Cloud, to develop a proof showing that the time to impact of an approaching body can be calculated from the size of the object's image and its rate of expansion. Specifically, the time to contact (TTC) is approximated as:

$$TTC \cong \phi_t / \delta\phi/\delta_t \qquad (1)$$

where ϕ_t is the angle subtended by the object at time t and $\delta\phi/\delta_t$ is that angle's temporal derivative (i.e., expansion rate). This equation is an approximation in that it assumes the Law of Small Angles (i.e., $\tan \phi = \phi$). The derivation of this equation can be found in Ref. 1.

This elegant observation that TTC can be derived without knowing either target distance or velocity was "rediscovered" by perceptual psychologists, most notably David Lee (Ref. 1), who recognized its significance for perception and control, and derived general formulations for such visual-temporal (or tau) variables. The one most relevant for our discussion describes a moving observer and a target not directly on the observer's motion track, i.e., the passage situation. In this case, an analogous approximation can be made for when the target will pass the observer (i.e., intersect the eye-plane perpendicular to the track vector, as shown in Figure 1):

$$TTP \cong \theta_t / \delta\theta/\delta_t \qquad (2)$$

where TTP is time to passage, θ_t is the angle between the observer's track vector and the proximal edge of the target, and $\delta\theta/\delta_t$ is that angle's temporal derivative. As before, this equation requires the tangent approximation.

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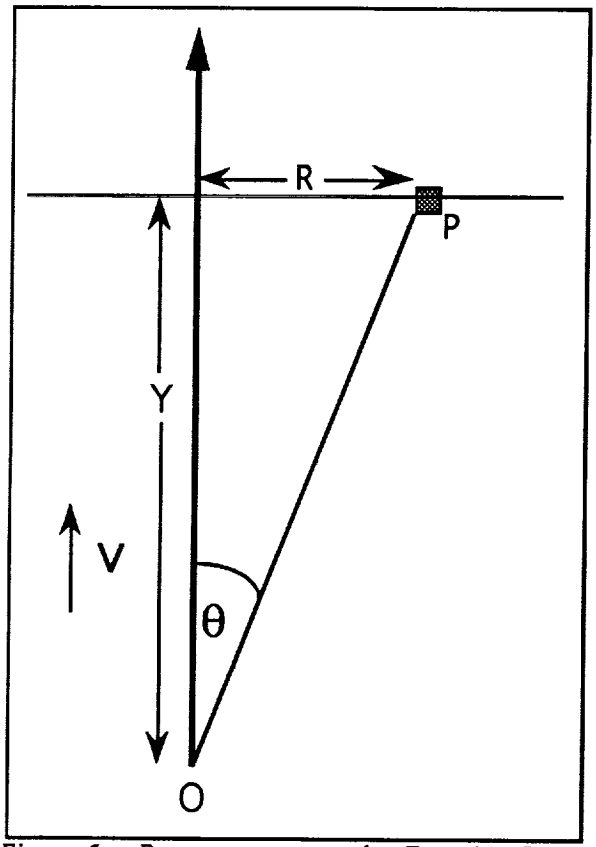

Figure 1. Passage geometry for Equation 2. An observer (O) is moving with velocity (V). A target (P) lies some distance (R) from the track vector, forming angle θ.

Despite the generality of Lee's formulations, empirical studies of human performance have focused almost exclusively on the direct collision, or TTC, situation (Ref. 2 and 3). These studies examined people's intercept (e.g., catching) and avoidance behaviors. However, for many skilled activities, particularly vehicular control, it is also important to judge the temporal range of objects which are not on a direct collision course. In our laboratory, we have examined observers' sensitivity to visually specified TTP information. Our findings suggest that people are adept at making both relative and absolute TTP judgments.

TTP EMPIRICAL STUDIES

We conducted a series of studies in a low-fidelity, fixed-based simulator. Observers were required to make either relative (i.e., which of two targets they would pass first) or absolute judgments (i.e., indicate when a target that was no longer visible would pass them).

Method

The experimental setting is shown in Figure 2. Observers were seated 2.13 m from a 2.44 m X 1.83 m rear-projection screen, creating a horizontal field of view (FOV) of 46°. Viewing was monocular to reduce anomalous depth cues. Displays were generated by a Silicon Graphics Personal IRIS 4D/25TG, with a refresh rate of 60 Hz, and a vertical resolution of 1024 lines. Displays consisted of a cloud of white dots (n=600) distributed in a virtual volume 17.37 m deep. The eyepoint was translated forward at 1.5 m/s. The projected size of the dots did not vary as a function of distance (or change as the observer approached). Thus, there were no object-expansion cues to temporal range.

For the relative TTP judgments, two of the dots were color-coded (green and purple) as targets. The two targets appeared on opposite sides of the heading vector. After viewing durations of 3 or 4 sec, the display was terminated, and observers predicted which of the two targets they would pass first. In the absolute judgment task, only one colored target was visible. It would pass from the observers' FOV after 3 to 5 seconds. The observers estimated when the target would pass their eye-plane by pressing a mouse button. This button press terminated the display.

Target positions were selected such that TTP was fully independent of the time the target was visible on screen, and largely independent of its initial angular projection from the heading vector. In the relative judgment task, the display terminated when the far target was 2 to 4 sec to passage. In the absolute judgment task, the target was between 1 and 3 secsonds from passage when it exited the FOV.

The relative judgement task was conducted with feedback, i.e., observers were informed after each trial whether their response was correct or incorrect. The absolute judgment task was conducted both with and without feedback. When feedback was given, observers were informed by a message on the screen after each trial how early or late their response was (in msec).

Eight observers (four males and four females) participated in both the relative judgment and absolute judgment with feedback tasks. They

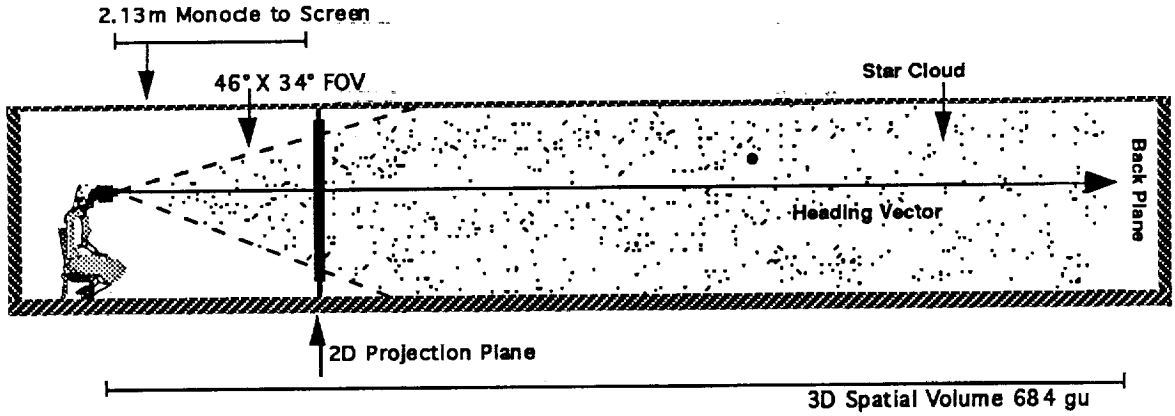

Figure 2. The experimental setting for laboratory experiments. Observers viewed events monocularly with their dominant eye.

ranged in age from 19 to 42 yr; all had normal or corrected to normal vision and were right-eye dominant. Four additional observers (3 males, 1 female) participated in both the feedback version and the no-feedback version absolute judgment task (performing the no-feedback task first). They ranged in age from 24 to 34 yr.

For the relative judgment task, observers completed a total of 160 experimental trials, 80 at the 3-sec duration and 80 at the 4-sec duration. For the absolute judgment task, trials were arranged in blocks of 66 trials. Following initial training trials, observers completed 3 blocks of trials, with 10 min breaks between blocks.

Results

Analyses of the relative judgment data indicated that observers were able to judge above chance level which target they would pass first for all but the shortest (250 msec) temporal separation. The percentages of correct responses averaged across observers are shown in Figure 3. Performance was not affected by whether observers viewed the targets for 3 or 4 seconds. Percent correct differed for the longest temporal difference (1000 msec) only, however this difference was not statistically significant [$F(1,15) = 1.05$, ns].

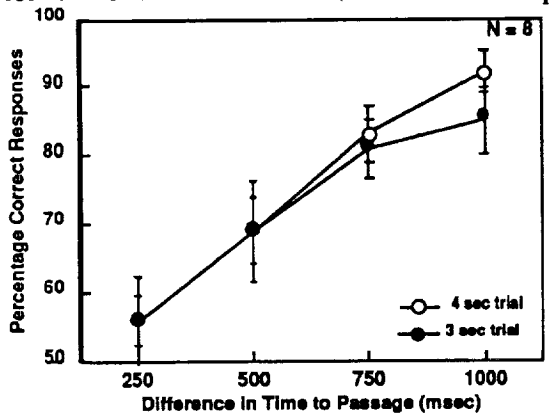

Figure 3. Average percent correct on relative TTP task for the four temporal separation and two display exposure times.

The absolute judgment data were analyzed by performing linear regressions. Judged TTP was regressed against actual TTP. The linear fits (R^2) for the data ranged from 0.55 to 0.85, with a mean of 0.73. The regression slopes for all observers were less than 1 (the mean value was 0.84), indicating a temporal compression (i.e., an additional sec in actual time resulted in less than one sec increase in judged time). The intercepts were all positive (the mean value was about 500 msec). This, coupled with the less-than-unity slopes, indicates that shorter TTPs were overestimated and longer TTPs were underestimated. Across observers, the correlation between constant error and extrapolation time was $r = -0.94$.

For the four observers who participated in both the feedback and no-feedback conditions, the presence of feedback did not significantly impact the linear regression fits, either in terms of slope and intercept, or the goodness of fit.

Discussion

Taken together, the findings from our empirical studies suggest that people are able to make reasonably reliable TTP judgments.

Observers could reliably discriminate differences in TTP of a half sec or more.

Observers' absolute judgments did demonstrate non-veridical temporal scaling (i.e., slopes less than unity and positive intercepts). This bias, however, could either represent a warping of the perceptual space (e.g., a target four sec distant appears to be less than twice as far as a target two sec distant), or result from systematic error in the cognitive extrapolation component of the judgment task. Further research is needed to decompose this bias into its components. Despite this bias, however, observers' judged TTPs were highly correlated with actual TTPs. Further, observers did not require any training or feedback to achieve well-calibrated judgments.

USING TTP TO CONTROL FLIGHT

Optical tau variables thus provide a useful metric for control related activities. Given such temporal metrics, how might a pilot utilize them for vehicular control? We propose that pilots tend to maintain a window of safe maneuverability, which is defined in terms of the handling qualities of the aircraft. For example, consider the geometry shown in Figure 4. For any given eyeheight (i.e., altitude), the forward field can be scaled in terms of eyeheights: the terrain along the 45° declination is one eyeheight distant, a gaze angle of -26.5° corresponds to 2 eyeheights, -18° to 3 eyeheights, and so forth. The time it takes to traverse 1 eyeheight is a function of speed relative to altitude (AGL). If the vehicle is at an altitude of 31 m, a speed of 30 knots will create a flow of 1 eyeheight/sec . If that altitude is doubled, the speed must likewise double to create the same flow rate (or TTP) at a given gaze angle. We suggest that pilots are most comfortable with speed/altitude profiles which allow them to maintain acceptable TTP values at some nominal gaze angle. Acceptable TTP values are defined by the time required to allow the pilot to safely perform necessary flight maneuvers.

In a normal walking gate, people move at about 1 eyeheight/sec. Our sense of subjective speed is geared to this metric. The same objective speed feels faster at lower eyeheights (thus the thrill of low-slung sports cars) and slower at higher ones (thus the boredom of minivans and the early tendency of pilots to taxi B747s too fast). Likewise, as a pilot reduces altitude, the natural tendency will be to reduce speed such that the temporal lead time along a given gaze line is consistent. The flight environment is scaled in a temporal, rather than spatial domain. This temporal scaling is highly relevant for flight control. However, this metric will bias the pilot against maintaining constant speed during altitude change.

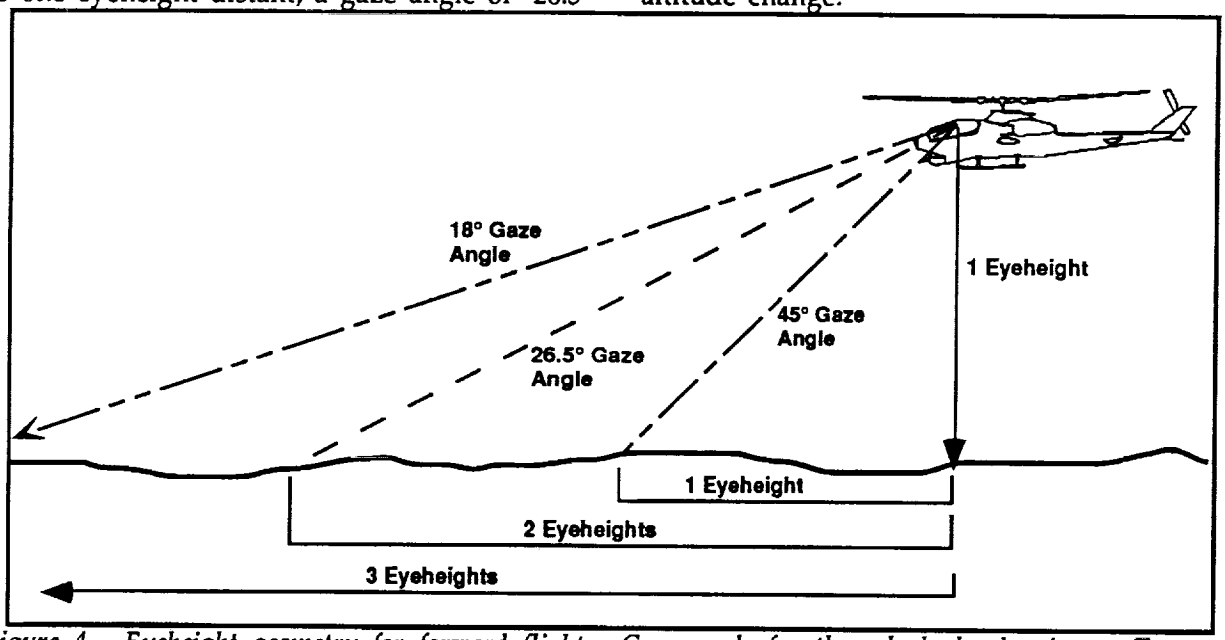

Figure 4. Eyeheight geometry for forward flight. Gaze angle for three look-aheads given. Temporal value of look-aheads determined by velocity in eyeheights/sec.

LIMITATION OF TTP INFORMATION

Given that pilots may utilize optical tau variables to orchestrate control and avoidance maneuvers, it is important to consider limitations and degenerate cases of these variables. As mentioned above, such temporal scaling can result in undesired speed changes during altitude transitions (although a consistent "safety window" is maintained). In addition, there is an interesting degenerative case of TTP that occurs when the observer and a moving target are on a collision course, but the object is not on the observer's track vector. If the observer and object maintain constant velocities, the center of the object maintains a fixed angle to the observer's track vector, as shown in Figure 5.

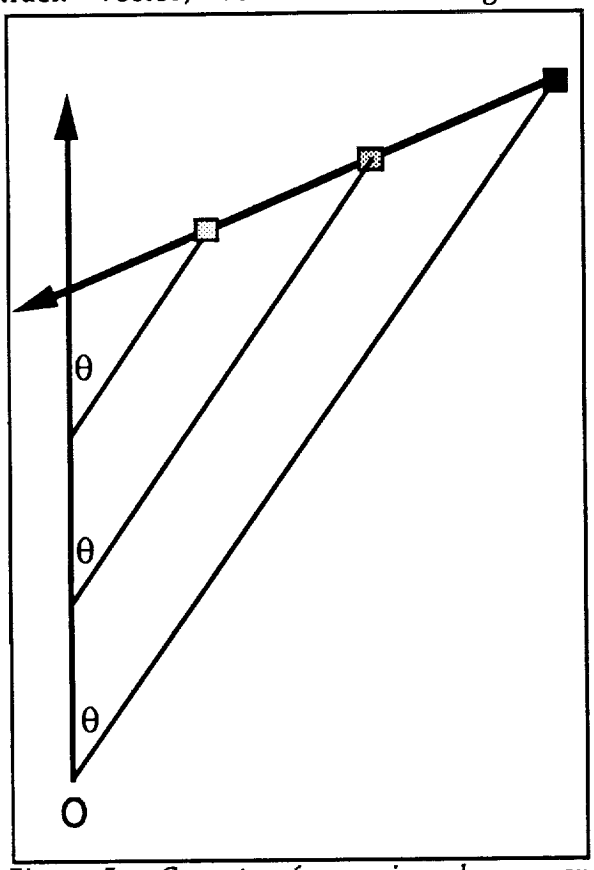

Figure 5. Geometry for moving observer and moving target on collision course. If both maintain a constant velocity and track, θ is constant.

Thus, θ for the centroid of the target is constant (i.e., $\delta\theta/\delta t$ is zero), and $\delta\theta/\delta t$ for all other points is small, reflecting only image expansion. Consider what value of TTP is specified in this condition: TTP = $\theta / \delta\theta/\delta t$, so as $\delta\theta/\delta t$ approaches zero, TTP approaches infinity. Thus, an object on such a collision course can be mistaken for an object at a very large distance, since the TTP information is virtually identical. Image expansion will differentiate these cases, but may not be salient at large distances. Only when image expansion becomes noticeable (or if the observer is cued by some non-motion information, such as familiar size) are the two cases discriminable. Since image expansion may not become salient until the object is temporally proximal, the observer may be required to make a last second correction to avoid collision. Such maneuvers are highly undesirable in flight situations. This examination of the TTP information lends insight into how such mishaps may occur, particularly in visually impoverished (e.g., night flight) environments.

CONCLUDING REMARKS

This "unmoving objects on a collision course" scenario, however, represents a degenerate (albeit interesting) case of TTP information. Most of the time, optical tau variables provide reliable information concerning objects' temporal distance. Moreover, our empirical studies demonstrate that observers possess a robust ability to utilize this information. We propose that these tau cues provide a useful temporal metric for pilots to employ in planning and orchestrating vehicular control. However, the maintenance of such temporal windows result in altitude-related speed changes, which are undesirable in some flight profiles.

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