Interceptive timing: Prior knowledge matters

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Fast interceptive actions, such as catching a ball, rely upon accurate and precise information from vision. Recent models rely on flexible combinations of visual angle and its rate of expansion of which the tau parameter is a specific case. When an object approaches an observer, however, its trajectory may introduce bias into tau-like parameters that render these computations unacceptable as the sole source of information for actions. Here we show that observer knowledge of object size influences their action timing, and known size combined with image expansion simplifies the computations required to make interceptive actions and provides a route for experience to influence interceptive action.

Keywords: interceptive timing, time to contact, cue combination

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Introduction

In sport, highly skilled performers can respond very accurately to balls traveling at considerable speed (e.g., > 100 mph). This remarkable skill and the short time available to prepare a response have supported the case for the direct use of optical variables. The best known example is the parameter tau (Lee, 1976), which combines the objects visual angle θ and its rate of expansion $\dot{\theta}$ as a ratio $\theta/\dot{\theta}$ that provides the time to contact for an object traveling at constant velocity on a direct trajectory toward the eye. Although there is evidence consistent with the use of tau (e.g., Lee & Reddish, 1981), many of the studies do not fare well under close scrutiny (López-Moliner & Bonnet, 2002; Tresilian, 1999; Wann, 1996). Expanded versions of the tau parameter have been proposed, which allow for a more generalized account such as oblique trajectories (Pepper, Bootsma, Mestre, & Bakker, 1994) and the inclusion of binocular information (Rushton & Wann, 1999). There are still a number of common situations, however, such as parabolic trajectories and object deceleration that can render these direct parameters unreliable.

When we hit or catch balls, we are seldom naive to all the task parameters. By interacting with objects in our environment, we rapidly acquire information on their steady-state attributes (e.g., physical size). It is inevitable that, through extensive practice, the elite sport person become very familiar with the size of a tennis ball, cricket ball, or football. In such a situation, the visual system can exploit lawful relations between known size (s), approach velocity (v), and the resulting optical variables (θ, $\dot{\theta}$):

$$v = \frac{\dot{\theta}}{s\theta^2}. \tag{1}$$

Alternatively, a velocity estimate can be gleaned using two consecutive samples of $\dot{\theta}$ across a temporal window of duration Δt (see Appendix A), the approaching velocity of that object is unambiguously specified according to

$$v = \frac{s\left(\sqrt{\frac{1}{\dot{\theta}_1}} - \sqrt{\frac{1}{\dot{\theta}_2}}\right)^2}{\Delta t^2}, \tag{2}$$

where $\dot{\theta}_i$ denotes the rate of expansion at time i and v is the approaching velocity. In both Equations 1 and 2, optical information combined with known size provides a monocular estimate of approach velocity. An equivalent binocular estimate of velocity can be derived by substituting change of relative disparity in place of $\dot{\theta}$ in Equation 2. Once velocity is recovered, in principle time to contact (T_c) can be estimated using known size and optic expansion, without the need to recover object distance:

$$T_c = \frac{\sqrt{s}}{\sqrt{\dot{\theta}_{th}}} v^{-1/2}. \tag{3}$$

For a given task in a specific setting, the skilled actor will need to initiate a response action at some time T_{ca} that

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leaves sufficient time for its execution. Using Equation 3, then for a known size object (s), we can then derive a simple threshold for optic expansion at which the actor should initiate their action.

$$\dot{\theta}_{\mathrm{th}} = \frac{s}{vT_{\mathrm{ca}}^{2}}. \tag{4}$$

Given the known size, it is therefore possible to estimate velocity. Equations 1 and 2 use this in combination with known size to set a simple response threshold based on looming (Equation 4), without the need to continually update something like a tau estimate. A timing strategy based on a fixed threshold of $\dot{\theta}$ has attracted some attention in previous studies. Michaels, Zeinstra, and Oudejans (2001), using real balls, found that elbow extension was modulated by rate of expansion in a punching task. Partial support for the use of a constant $\dot{\theta}$ threshold has been also reported in Caljouw, van der Kamp, and Savelsbergh (2004), where the timing of reach onset but not hand closure was explained by rate of expansion. In a task where observers were presented with small and large simulated balls, Smith, Flach, Dittman, and Stanard (2001) proposed a more complex threshold based on the weighted combination of $\dot{\theta}$ and θ but demonstrated that strategy can change as participants become more familiar with the task settings. In contrast, however, Tresilian, Plooy, and Carroll (2004) did not find evidence for a timing based on a constant threshold of rate of expansion in a context where nine ball sizes were used. Object familiarity may be a critical issue in comparing these results. Caljouw et al. used single size real balls whereas Michaels et al. used a familiar size paradigm where the observer could assume ball size. Where there is uncertainly as to size (e.g., Tresilian et al., 2004), then the weighting placed on timing-relevant variables may well change, compatible with a Bayesian framework (Miyazaki, Nozaki, & Nakajima, 2005). Our proposal is that when there is reliable information (low uncertainty) regarding ball size, observers will switch to a response threshold for rate of expansion, but that threshold will vary across size and speed conditions, and Equation 4 presents a formal proposal as to how the threshold could be set based on assumed size.

To test this hypothesis and the validity of this proposal, we contrasted settings where ball size was known with when it was unknown. Using a large field of view virtual environment, we tested the accuracy of nine observers in intercepting a simulated ball when it was presented as a monocular looming image and when it was present with appropriate binocular disparity. First we examine performance when observers were presented with balls that varied in size and speed where they had no information about their properties (a classic time-to-contact paradigm). We then primed them with one specific ball size or with two potential ball sizes, by interactively handling one or two real balls of the same size as to used in subsequent simulation trials. To test whether knowledge of size was being used, we interleaved “catch” trials in which the actual size was slightly smaller or larger than that (or those) subjects were expecting. This is analogous to changing the size of a baseball midgame without informing the batter of the change.

In natural interceptive actions, the initiated action would have a chosen speed, duration, and force (e.g., a drop shot vs. a forehand drive in tennis). It has been demonstrated that variations in object speed and size can change the speed at which the interceptive movement is executed (Tresilian et al., 2004). This produces two timing points, the time at which an action is initiated (T_{ca} in Equation 4) and the time at which an action is completed (T_{cc}), and the period between T_{ca} and T_{cc} may vary because of the perceived object trajectory. Because this raises an issue as to which time point action is locked to, in this experiment we used a very brief response where $T_{\mathrm{ca}} = (T_{\mathrm{cc}} - \text{neural delay})$. Participants made a button press that required the application of 0.6 N and an overt movement of 0.2 mm. Hence, even if larger/faster balls prompted a more forceful response, the timing requirement is that an action needs to be initiated (T_{ca}) to allow time for the generation of a fingertip force >0.6 N, but T_{ca} is not affected by modulations in movement completion time.

Methods

Observers

Nine observers (including the authors) participated in the experiment. All of them had normal or corrected-to-normal vision and, except for the authors, were naive with respect to the aims of the experiment. None of the subjects was stereo-blind (StereoFly test, Stereo Optical Co.).

Displays and stimuli

Two identical JVC DLA-G20 projectors provided overlaid images for each eye on a back-projection screen (1 m width and 0.77 m height). Each image was updated at 85 Hz and polarizing filters were used to present binocular stimuli appropriately for the user’s interpupillary separation and viewing distance. In the monocular condition, a null interocular distance was used under the same viewing conditions as in the binocular ones. The viewing distance for participants was 1.5 m. The simulated time to contact at the beginning of the trajectory were 0.6 or 0.8 s The simulated approaching velocities were 1.7, 1.8, 2.0, and 2.12 m/s.

Procedure

The task for the observers was to press a button at the time they thought the ball would hit them. Each trial started with a stationary simulated ball. After 1 s, the ball started approaching the observer at a specific velocity and time to contact. The trajectory remained visible for a time between 85% and 90% of the initial time to contact. All observers had a training phase in which feedback of the timing error was provided. Once they were familiarized with the task, observers were presented with balls that varied between two sizes that were unknown to them (radius 0.033 and 0.05 m). In a second phase, participants were presented with a real ball (0.06 m of radius), which they handled and then presented with simulation trials where they were told that it was the same ball size. An equal number of catch trails were introduced into this series using two different sizes (radius of 0.045 and 0.075 m) to test the reliance on the known size information. In a final phase, two different sized real balls were physically presented and then simulated (radius of 0.033 and 0.06 m) to test the ability to use more than one size estimate, and three catch sizes were used (radius of 0.025, 0.045, and 0.075 m). In the two-size condition, we asked the participants to verbally report which ball (small or large) they thought that they had just seen after each trial. Participants were shown 24 repetitions of each combination of size (including catch sizes), time to contact, and velocity in each of the phases.

Data analysis

To determine which optical variable subjects were using, we employed the same approach as Sun and Frost (1998) and plot the time to contact at the moment of the response as a function of (s/v), which is the ratio of physical size (diameter) to approaching velocity. This helps to separate predictions regarding the use of tau or different optical variables. If the same motor response is initiated at a constant time before ball arrival, that equates to a tau threshold (τ_{th} in Figure 1, left panel), and the initiation time distribution should be invariant with respect to variations of physical size and approaching velocity (Figure 1, right panel). If a response is initiated when a critical value of the visual angle θ is reached (θ_{th} in Figure 1), the initiation time will not be constant but will increase linearly as a function of s/v (e.g., a larger object will reach this threshold earlier and the final time to contact will be larger than for a smaller object traveling at the same speed) with a slope of $1/\tan(\theta_{th})$. If the response is triggered by a critical value of rate of expansion $\dot{\theta}_{th}$, then the distribution of response time will be a power function of s/v with an exponent of 0.5 (red line in Figure 1, right panel) or equivalently a linear function of $\sqrt{s/v}$ with a slope of $1/\sqrt{\dot{\theta}_{th}}$. Details on the derivation of these dependencies can be found in López-Moliner and Bonnet (2002) and Sun and Frost.

These are "pure" predictions, but we do not have a specific prediction for what participants might rely upon in the naive, unknown size trials. For those trials, it is informative to use a similar approach to (Smith et al., 2001) to fit a model based on a linear combination of θ and $\dot{\theta}$. Fitting this model allows us to determine which of the optical variables has been given the most weight by observers ($\omega_s \cdot \theta + \omega_r \cdot \dot{\theta}$). For example, if the estimate of ω_s was very close to zero, it would favor a rate of expansion strategy. A large negative weighting of visual angle θ would imply that it compensates for the growing of $\dot{\theta}$ resulting in a tau-like strategy (Smith et al., 2001). Finally, a positive weight of θ would conform to a strategy close to a response initiation when this variable reaches a critical value. Our model predicts that observers will switch to a $\dot{\theta}$ strategy when they feel that they know the object size. Fitting the Smith et al. model provides a convenient way of determining whether this strategy

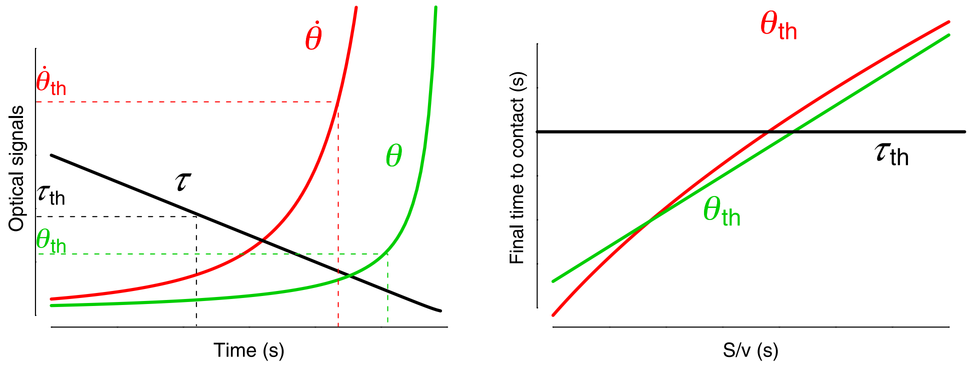

Figure 1. (Left panel) different optical variables as a function of time. Thin arrows illustrate the time at which a sensory threshold (based on the respective sensory signals) would be reached. (Right panel) Predicted relation between remaining time to contact and the ratio between physical size (s) and approaching velocity (v) given that the sensory thresholds shown on the left are used to initiate a catching response. Whereas visual angle would predict a linear relationship, rate of expansion predicts a linear relation between time and $\sqrt{s/v}$. Finally, if a tau-like threshold is used, the response time function would be flat.

switch had taken place. To test for whether the data points deviate significantly from the fitted model, we minimized the χ^2 merit function as in López-Moliner and Bonnet (2002), which compares the residual errors of the fit with the vertical standard deviations in the points themselves. If the data points significantly deviated from the model, then the χ^2 would be above the critical value and we could reject the hypothesis that observers were using the strategy reflecting the fitted model. The number of degrees of freedom is the number of data points minus the number of fitted parameters.

Results

Figure 2 shows the remaining time to contact at the moment of response as a function of s/v for the setting where they had no ball size information or when they assumed there was a single ball size. We include all catch trials, so in a number of cases the observers' assumption of ball size would have been incorrect. If the observers had been combining visual angle and rate of expansion (i.e. using tau), the ball size manipulations in the catch trails would be irrelevant and we would expect a flat relationship between the remaining time and the s/v. If they were using our $\dot{\theta}_{\mathrm{th}}$ proposal (Equation 4), we would predict a negatively accelerating linear function (Figure 1). Solid lines on Figure 2 show the best fitting prediction for our $\dot{\theta}_{\mathrm{th}}$ proposal and broken lines show the least squares fit for the $\omega_s \cdot \theta + \omega_r \cdot \dot{\theta}$ model. Under monocular viewing, there is no support for the use of tau, but the $\dot{\theta}_{\mathrm{th}}$ prediction fits both sets of data quite well, $\chi^2(7)=2.67$, $p = 0.91$ and $\chi^2(11) = 3.86$, $p = 0.97$ for unknown size and known size conditions, respectively. When size was not known, there is a strong linear function. To clarify this, we can use the weights from the least squares $\omega_s \cdot \theta + \omega_r \cdot \dot{\theta}$ model (dashed lines). The inset bar graph presents proportional weighting of visual angle relative to $\dot{\theta}$; that is, ω_s/ω_r. In the case of one known size, the weighted sum closely resembles the rate of expansion strategy (e.g., ω_s was very close to zero). When size was unknown, a proportional weight is attached to θ, making this condition closer to a visual angle strategy.

Under binocular viewing, when the size was known, the results were again in line with the $\dot{\theta}_{\mathrm{th}}$ prediction, the data points do not deviate from the $\dot{\theta}_{\mathrm{th}}$ model $\chi^2(11) = 8.6$, $p = 0.66$), and the ω_s/ω_r ratio tended toward zero. When size was not known, the function was variable but flat. As a consequence, a linear fit produced a slope not different from zero, $F(1,6) = 0.78$, $p = 0.41$, and the ω_s/ω_r ratio had a negative value somewhat in line with a tau prediction (Smith et al., 2001).

The linear weight model using $\omega_s \cdot \theta + \omega_r \cdot \dot{\theta}$ has more free parameters than a pure $\dot{\theta}_{\mathrm{th}}$ strategy and as a result produce a tighter fit to the data. But there are no proposals as to how ω_s and ω_r would be chosen to provide an optimal response for the range of conditions. The important contrast is how ω_s changed when size was known (black vs. red bars in Figure 2, inset). When size was known, the visual angle θ was given much less weight resulting in a strategy closer to using a simple $\dot{\theta}_{\mathrm{th}}$ response model. Statistical tests confirm that a $\dot{\theta}_{\mathrm{th}}$ model was consistent with the data when size was known.

To check whether the change of strategy resulted in a significant decrease of the deviation of the response time, we ran an F test on mean reaction time averaged across

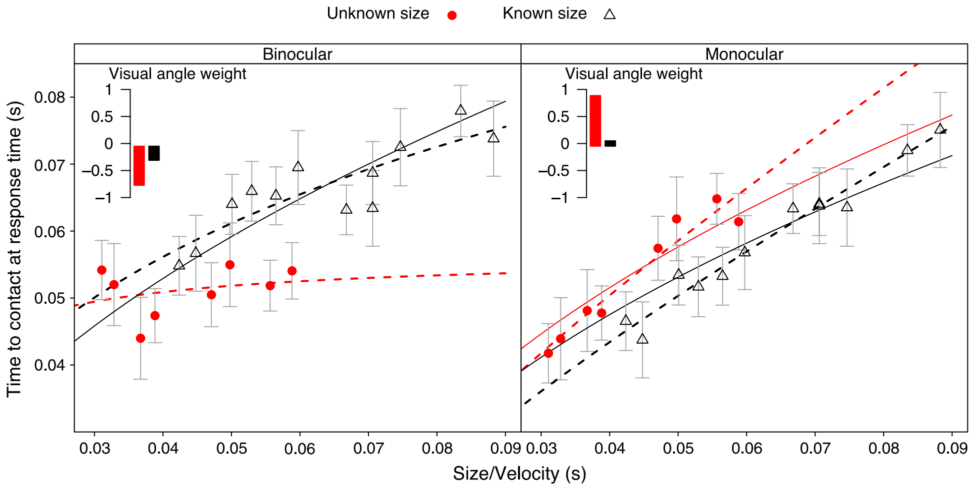

Figure 2. Plot of the time to contact at the response time as a function of the ratio of size to velocity for the two viewing conditions. Data points are grouped by whether size was known or unknown. The solid lines denote the prediction of the θ threshold strategy. Dashed lines show the best fitting prediction from a linear weighted sum: $\omega_s \cdot \theta + \omega_r \cdot \dot{\theta}$ to each condition. The insets show how θ is weighted for this: a negative weighting would resemble a tau-like strategy (e.g., left panel) whereas a positive weighing would be a consequence of relying on a θ threshold strategy, which should result in a linear relation between response time and size/velocity.

subjects individual trials to compare the variances of the response time distributions when size was known to those when size was not known. Testing the hypothesis that the ratio of the variances (unknown to known size) was greater than 1 produced a significant difference: $F(8,8) = 4.87$, $p = 0.0382$ for the binocular condition and $F(8,8) = 9.07$, $p = 0.005$ for the monocular condition. The degrees of freedom are derived from the number of participants—one for each sample variance.

Figure 3 presents the equivalent case for the situation when the participant was primed with two possible sizes. When they verbally reported which size ("large" or "small") had just approached them, this correlated very well with physical size for the binocular condition. We plot the results as two sets separated based on assumed size, but again this includes the full set of catch trials, so a number of the balls that observers assumed were larger, were smaller, and vice versa. In the binocular case, there appears to be a clear separation of the stimuli set and the responses times cluster around the different $\dot{\theta}_{\mathrm{th}}$ predictions for the different ball sizes (0.033 and 0.06 m radius). The data points are well explained by the $\dot{\theta}_{\mathrm{th}}$ fits, $\chi^2(11) = 8.22$, $p = 0.69$ and $\chi^2(11) = 5.92$, $p = 0.87$ for small and large judgments, respectively. On the basis of the fits, the $\dot{\theta}_{\mathrm{th}}$ values are 7 and 13 deg/s for small and large sizes, respectively. So viewing under binocular conditions does allow observers to adopt different $\dot{\theta}_{\mathrm{th}}$ settings based on recognized/assumed size.

To further explore whether these fits are meaningful, we can compare the slopes obtained from linear fits as a function of $\sqrt{s/v}$ with those predicted by using a $\dot{\theta}_{\mathrm{th}}$ strategy based on the values of rate of expansion at the response time. For the large ball, the slope (0.15) was very close to that predicted by using a $\dot{\theta}_{\mathrm{th}}$ strategy (0.17). For the smaller size, we would predict that the slope should increase by a factor of 1.35 ($1/\sqrt{s_{\mathrm{change}}}$; Equation 3). The observed slope did increase although its value (0.37) would suggest that optical size may also bias judgments to some extent as indicated by the positive weight given to visual angle (green bar of the inset of the binocular panel of Figure 3).

Under monocular conditions, however, the situation is less clear and the two $\dot{\theta}_{\mathrm{th}}$ predictions generate toward the same threshold comparable to the larger size under binocular viewing. Again the data points did not deviate from the fits predicted by a $\dot{\theta}_{\mathrm{th}}$ strategy, $\chi^2(11) = 13.3$, $p = 0.27$ and $\chi^2(11) = 3.4$, $p = 0.98$ for judgments small and large, respectively. But unlike the binocular condition, one single fit explained both sets of data, $\chi^2(23) = 17.59$, $p = 0.78$. This was not the case in the binocular condition, $\chi^2(23) = 109.7$, $p < 0.001$. The reason for the difference between the monocular and the binocular conditions is not clear. It seems that observers used a single estimate of $\dot{\theta}_{\mathrm{th}}$ for all balls, whether large or small; this may be due to a lack of confidence in their size categorization when the balls are presented monocularly.

Discussion

The ecological approach to visual perception (Gibson, 1979) deliberately avoided the use of prior knowledge in guiding action. Here we have shown that prior knowledge acquired by experience can modulate which retinal information we rely on for interceptive actions. This effect was present for both monocular and binocular stimuli when a single object size was assumed. When there was a choice of two object sizes, observers seemed

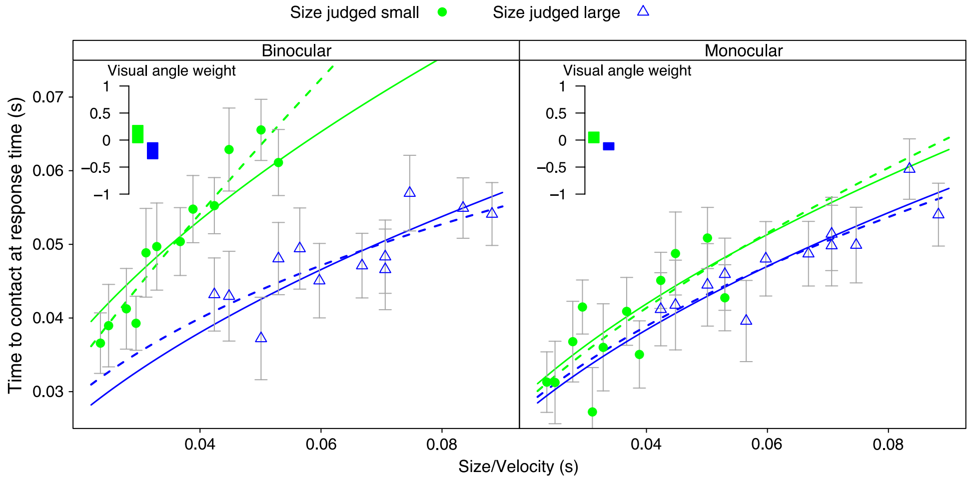

Figure 3. Plot of the time to contact at the response time as a function of size/velocity when two known sizes were shown. Data points are grouped by size judgments made by the observers, but catch trials are included in each set. This means that when they judged the balls to be small, a significant number of balls were larger and the responses were made earlier and when they judged the balls to be large, the reciprocal effect is that the catch trails push the responses to be large. We fitted the same functions as in Figure 2 to these data sets.

able to switch between two threshold settings (Equation 3) provided that binocular information was available. This could be due to additional size information arising from disparity or the ratio $\dot{\theta}$ (Regan & Beverly, 1979), resolving ambiguities in size categorization.

DeLucia (2005) presented observers with two objects that approached at the same velocity and had the same TTC but asked participants to make a judgment as to which would arrive first. Observers erred toward the object that was larger, but providing information about size differences eliminated this size-arrival effect. This demonstrated a general size bias in a forced choice judgment, but here we demonstrate an effect of size on setting an arrival threshold for finely timed responses for a direct interception judgment. Our findings complement those of Battaglia, Schrater, and Kersten (2005) who found that similar tactile priming of ball size lead to more reliable judgments as to where a ball would cross a prespecified interception line. Battaglia et al. were not able to show precise localization of crossing point, but their findings do suggest that known size may help to cue an approximation of "how far" to the interception point to supplement the "when" that we demonstrate.

In the Introduction section, we suggested that a skilled performer familiar with their task may need a particular response time to complete an action and may vary their response threshold based upon that. In the present experiment task conditions, the mode of response was kept to a minimal finger movement and instructions about when to respond in relation to the objects trajectory were held constant. This generates toward a constant time requirement (T_{ca}) for initiating the action (e.g., López-Moliner and Bonnet, 2002; Michaels et al., 2001; Smith et al., 2001), but this does not equate to a constant threshold for looming. To maintain temporal accuracy, the looming threshold needs to scale with object size and approach velocity to yield the equivalent T_{ca} (Equation 4). The results from our two ball task suggest that the threshold is not just scaled within blocks of trials, but that it can be reset rapidly between trials as new objects of a different apparent size are presented. We did have a curious finding that tau-like responses were present when size was not known but there was binocular information (Figure 2). Rushton and Wann (1999) proposed that looming and binocular stimuli are flexibly combined to yield an arrival estimate, but if this veridical estimate was available when size was unknown, it is curious that it was not then used for all other binocular conditions.

An essential part of our proposal, however, is the use of known size to recover the approaching velocity (Equations 1 and 2). We propose that this stage cannot be bypassed. Once velocity is recovered, then it is possible to set a response threshold ($\dot{\theta}_{\mathrm{th}}$), based upon prior experience of how long the response action will require (Tresilian, 1999). But recovering velocity would not only be useful for obtaining an accurate temporal signal but also for modulating the motor response (e.g., determining the kinematics of the catch). This approach is able to account for how near optimal performance can be obtained when using only monocular information, given suitable experience (Gray, 2002). The observer would need to estimate the size of the ball but this could be gleaned by prior information or by combining different cues during the trajectory. As experience increases, the need to estimate size is replaced by known size. If knowledge of size were not available, the system must default to combining $\dot{\theta}$ with visual angle θ, but the accuracy of the time-to-contact estimate depends on the strong restrictions applying to optical combinations alone. This mechanism would also explain previous findings in which larger velocities produce later or slower responses (Smith et al., 2001). The scaling arises as a direct consequence of adopting a strategy $\dot{\theta}_{\mathrm{th}}$ when there is some uncertainty as to object size. Interestingly, if there was an error of 12% in estimating the velocity (Harris & Watamaniuk, 1995), the potential error in the time-to-contact computation, with a velocity range of 20–30 m/s, would be very small (≈4 ms). This timing error would be tolerable for most successful interceptive actions and applies to balls traveling along a noncollision trajectory.

Overall, these results show that observers make use of prior knowledge about the size of an object in judging its interception and present a model as to how it is used. Known size combined with expansion rate $\dot{\theta}$ allows one to recover velocity and set a threshold value for looming at which to initiate an interceptive action, and this ensures reliability in the temporal estimate of arrival. Known size does not need to be considered as a cognitive, declarative parameter. It represents a process of calibration whereby, through experience, the skilled sports person adapts their action to judging the flight of a specific, size-constant object. The tuning of action in this manner does not need to be at odds with an ecological approach to perception, but it does provide a more explicit process whereby experience and extensive practice can optimize performance. How experience can shape the pickup of optical information is a topic that has not been addressed within the ecological approach. Our model bridges this gap.

Appendix A: Math Appendix

Here it is shown how approaching physical velocity can be obtained from rate of expansion after some integration time.

The rate of expansion at time t, $\dot{\theta}_t$, for a direct approach of an spherical object can be approximated as

$$\dot{\theta}_t = \frac{s \cdot v}{d_t^2}, \tag{A1}$$

where s is the diameter of the object, v is the approaching velocity, and d_t is the distance at time t between the object and the observer. Equation A1 makes the approximation that s is nearly equal to $d_t \cdot \theta_t$.

We have that for a defined time interval $(t_1 - t_2 = \Delta t)$, the traveled distance is

$$\Delta d = d_1 - d_2 = v \cdot \Delta t. \tag{A2}$$

Substituting Equation A1 in Equation A2,

$$\sqrt{\frac{s \cdot v}{\dot{\theta}_1}} - \sqrt{\frac{s \cdot v}{\dot{\theta}_2}} = v \cdot \Delta t \tag{A3}$$

and

$$\sqrt{s \cdot v}\left(\sqrt{\frac{1}{\dot{\theta}_1}} - \sqrt{\frac{1}{\dot{\theta}_2}}\right) = v \cdot \Delta t. \tag{A4}$$

If we square Equation A4, we have

$$s \cdot v\left(\sqrt{\frac{1}{\dot{\theta}_1}} - \sqrt{\frac{1}{\dot{\theta}_2}}\right)^2 = v^2 \cdot \Delta t^2. \tag{A5}$$

Apart from the trivial solution $(v = 0)$, v has the solution

$$v = \frac{s\left(\sqrt{\frac{1}{\dot{\theta}_1}} - \sqrt{\frac{1}{\dot{\theta}_2}}\right)^2}{\Delta t^2}. \tag{A6}$$

Equation A6 expresses the fact that physical approaching velocity is available to the system from rate of expansion and known size after sampling the rate of expansion at two times separated by interval Δt.

Once velocity is recovered, a time-to-contact signal T_c based on a constant threshold $(\dot{\theta}_{th})$ can easily be obtained from Equation A1 by using the fact that time to contact equals d/v:

$$T_c = \frac{\sqrt{s}}{\sqrt{\dot{\theta}_{th}}} v^{-1/2}. \tag{A7}$$

If an action needs to be initiated at a specific time before contact T_{ca} to allow its execution, then this could be achieved for a known size object according to

$$\dot{\theta}_{th} = \frac{s}{v T_{ca}^2}. \tag{A8}$$

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