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Perception of Speed, Distance, and TTC of Familiar Objects

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Andrés Martín
ILAV (CONICET-UNT) and Universidad Nacional de Tucumán

Agustín P. Décima
ILAV (CONICET-UNT)

Jose F. Barraza
ILAV (CONICET-UNT) and Universidad Nacional de Tucumán

It has been shown that knowing the size of an approaching object affects our perception of time to collision (TTC) in a manner similar to the way it affects perception of the physical speed of objects moving in the frontoparallel plane. In this article, we present a series of experiments exploring the effect of object familiarity on the perception of speed and distance in the context of motion in depth (MID), and the interplay among these variables in the perception of TTC. Results of the first experiment show that object familiarity does not help human observers to discriminate the speed of MID. In the second experiment, we show that familiar size may be used to infer the relative distance among objects, in the context of MID, but not to make accurate estimations. Finally, we show that the relative TTCs do not follow the perceived relative distances obtained in the second experiment.

Keywords: speed, distance, time-to-collision, familiar size

Motion pervades the visual world (Marr, 1982). This is so because images in nature are not only unlikely to be static, but also because motion constitutes a rich source of information in interacting with the environment. Humans are highly efficient at avoiding and/or intercepting objects moving in space. This ability requires the sensory systems to acquire information fast and accurately. Over the past few decades, a great deal of research has been devoted to understanding what information mediates these interactions. Since Lee (1976) formulated the so-called tau hypothesis, most research has focused on the idea that humans guide their actions based on the time remaining before the object collides with them or arrives at some specific point (Lee & Reddish, 1981; Regan & Hamstra, 1993; Yan, Lorv, Li, & Sun, 2011). This time is known as time to collision (TTC) and can be computed by dividing the object's distance (d) to the observer by its speed (v). However, Lee (1976), in his seminal work, proposed that the optical variable tau (τ), defined as the relation between the object's angular size and its rate of expansion, may be a good predictor of TTC. What is remarkable about this hypothesis is that all the information needed for estimating TTC is contained in the stimulus that is projected onto the retina, which is why it has served as an example of the theory of direct perception (Gibson, 1961). Consequently, the estimation of TTC would not need estimations of distance and speed, which require costly and cumbersome computations. Several studies in which angular size, rate of dilation, and physical distance were manipulated, have shown that time-to-collision can be perceived by human observers in the absence of information about distance and velocity (Gray & Regan, 1999; Schiff & Detwiler, 1979; Todd, 1981; Yan et al., 2011). More recently, these arguments were

Andrés Martín, Instituto de Investigación en Luz, Ambiente y Visión, ILAV (CONICET-UNT), and Universidad Tecnológica Nacional; Agustín P. Décima, Instituto de Investigación en Luz, Ambiente y Visión, ILAV (CONICET-UNT); Jose F. Barraza, Instituto de Investigación en Luz, Ambiente y Visión, ILAV (CONICET-UNT), and Departamento de Luminotecnia, Luz y Visión (DLLyV), Universidad Nacional de Tucumán.

Correspondence concerning this article should be addressed to Andrés Martín, Consejo Nacional de Investigaciones, Avenue Independencia 1800, San Miguel de Tucuman, Tucu T4002BLR, Argentina. E-mail: amartin@herrera.unt.edu.ar

supported by the finding that humans cannot accurately estimate the speed of simulated flying objects moving in depth (Rushton & Duke, 2009).

In contrast, the tau hypothesis has been largely challenged by other numerous empirical observations and doubts about the assumptions that underlie the hypothesis (for reviews, see Tresilian, 1995, 1999). The size-arrival effect (SAE; DeLucia, 1991) is one interesting example. DeLucia (1991) showed that observers tended to perceive the larger object as arriving sooner even when the smaller object specified an earlier TTC. This finding suggests that parameters such as θ (angular size) or θ′ (rate of expansion) may be critical in the perception of TTC, which led some authors to suggest that they could be good candidates for use in triggering interceptive actions (López-Moliner, Field, & Wann, 2007; Michaels, Zeinstra, & Oudejans, 2001). More recent studies have introduced a new dimension in the analysis of TTC by using familiar stimuli (DeLucia, 2005; Hosking & Crassini, 2010, 2011). These studies have shown that the SAE is strongly attenuated when the size or size relation is specified by the stimuli, which suggests that high-level visual processing may be involved in the estimation of TTC. One interesting result presented by Hosking and Crassini (2010) shows that the lack of coherence between angular and familiar size can also produce large errors in the estimation of TTC. For example, a soccer ball is bigger than a tennis ball, so if the image of the soccer ball projected onto the retina is smaller or equal to that of the tennis ball, one may infer that the former is further away, which could explain why the soccer ball appears to arrive later than the tennis ball in the Hosking and Crassini experiment. Certainly, the information provided by the object's familiarity, in this case, is its size. In accordance with this, it was recently shown that familiar size provides key information to estimate correctly the physical speed of objects moving in the frontoparallel plane (Martín, Chambeaud, & Barraza, 2015). How could the visual system use such information about familiar size in the estimation of TTC? López-Moliner and collaborators (2007), for example, proposed that familiar size may be used to estimate the speed of objects moving in depth, which in turn would be used to calculate the critical time needed to act in response to the approaching object. Another use for familiar size in this context could be the rescaling of the retinal size in order to infer relative distances between different objects. From this rationale, we consider that the perception of distance deserves attention in the context of TTC of familiar objects and, consequently, speed, since their relation specifies TTC.

The effect of familiarity on distance perception has been studied for many years. Although the earlier studies had suggested that perceived depth is determined by the retinal, not the assumed, sizes of the objects (Hochberg & Hochberg, 1952), later investigations that carefully manipulated familiar and relative sizes, found that the perceived depth between two familiar objects depends on familiar, not relative, size (Epstein & Baratz, 1964; Fitzpatrick, Pasnak, & Tyer, 1982). Gogel and Mertens (1968) have shown that familiar and relative sizes can be subsumed under the concept of perceived size S' per unit of visual angle, in their so-called Size-Distance-Invariance Hypothesis (SDIH), which can be written as

$$\frac{S'}{D'} = tan\,\theta$$

where S' and D' are the perceived size and perceived distance of the familiar object, and θ is its visual angle. According to SDIH, familiar size will determine perceived distance (D') for a given visual angle (θ) only if it also determines perceived size (S'). Thus, SDIH can explain several visual phenomena such as the perception of motion-in-depth (MID) from the dilation of a stimulus presented over a static screen (Swanston & Gogel, 1986). Note that from this relation, D' can be extracted from angular size, if the size of the object is known. This means that, if we were able to estimate its speed, we could estimate the TTC. Previous studies have suggested that speed of self-motion is used in the detection of collision events (Andersen, Cisneros, Atchley, & Saidpour, 1999), which is supported by the fact that self-motion speed can be estimated from ground motion if eye height is known (Larish & Flach, 1990; Warren, 1982). However, it is not clear whether we are capable of estimating the speed of a known object moving in depth. For example, Rushton and Duke (2009) have recently found that human observers cannot estimate the veridical speed of meaningless objects that are approaching them. For their part, López-Moliner and colleagues (2007) proposed that if the object's size is known, and successive measures of θ′ can be discriminated, we could estimate speed by measuring the time between two consecutive estimates of θ′. Unfortunately, as far as we know, there are no studies testing this hypothesis.

The aims of this study are (a) to test whether human observers can discriminate the speed of familiar objects undergoing simulated MID in which most depth cues are removed; (b) to test whether SDIH applies to the perception of relative distance between two familiar objects that undergo MID, and determine how precise this relative-distance perception can be in such situations (MID); and (c) to test whether there is a relation among speed, *D*′ and the relative TTC obtained from the comparison of two different-sized familiar objects.

General Methods

Stimuli

Stimuli were images of a basketball and a tennis ball expanding as if they were undergoing MID, displayed over a black background on a CRT monitor (1024 × 768 pixels, 60 Hz). We also used simulated red spheres the same size as the balls. Stimuli were generated with Sketch Up, and we used Matlab with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) to display them.

The experiments were carried out with two stimulus configurations defined by the angular size relation between reference and test and the familiar size of the objects. In the first configuration, named as "Same θ − Off Size," reference and test subtended the same visual angle θ but reference was textured with a regular sized tennis ball and test was textured with an off-sized basketball. In the second configuration, titled as "Different θ − Standard Size," the tennis ball and the basketball were presented with their regular sizes; hence they subtended different angular sizes. Figure 1 summarizes both stimulus configurations. The regular-sized tennis ball and basketball subtended 7.5° and 27° of visual angle, respectively, from 0.50 m viewing distance, that is, the basketball is 3.6 times bigger than the tennis ball. The spheres adopted the size of the balls in each configuration. More detailed information is given in the description of each particular experiment.

Procedure

We used a two-interval forced-choice paradigm with the method of constant stimuli to measure the point of subjective equality (PSE), which was computed by fitting a Weibull sigmoid to the data and taking its inverse at 50% response, using Psignifit 3.0 (Fründ, Haenel, & Wichmann, 2011). In all cases, stimuli (reference and test) were displayed sequentially, in random order, each for 500 ms, with an interstimulus interval of 500 ms. All experiments were conducted in sessions that were run on different and consecutive days. Sessions consisted of 25 blocks of trials. Each block consisted of six trials corresponding to the six values of the constant stimuli, whose order of

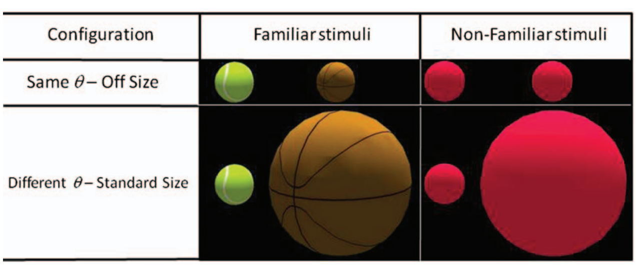

Figure 1. Stimuli and configurations used in the experiments. The familiar size relation between the basketball and the tennis ball is 3.6. Note that, although we illustrated the nonfamiliar stimuli for both configurations, we kept the same names, although it makes no sense to refer to them as "Standard Size" or "Off Size." See the online article for the color version of this figure.

appearance in the block was randomized. Therefore, each psychometric function and the PSEs were calculated from 150 trials. Before beginning those sessions in which the stimuli were balls (not spheres), real balls were provided to the observers for them to become familiar with their sizes after which, their familiar size estimation (S') made through their hands, was controlled. All observers were acceptably good in estimating the size of the balls with their hands (see the Appendix for details about this control).

Subjects

Nine volunteer subjects and two of the authors took part in this study. All volunteers had normal or corrected-to-normal visual acuity and were naive to the purpose of this study. Their ages ranged from 22 to 35 years old. All experiments were carried out with monocular vision through a black viewing tube that prevented observers from seeing the monitor frame. The experiments followed National Council for Scientific and Technologic Research (Argentina) existing protocols for experimentation with human observers, and were in accordance with the principles expressed in the Declaration of Helsinki.

Details about the number and condition of observers in each experiment are given in the description of each specific experiments.

Experiment 1

Speed Perception

In this experiment, we examined the relative speed perception of the test respect to the reference, for simulated MID, for both configurations. The aim of this experiment was to investigate whether human observers could discriminate the speed of simulated MID when stimuli were familiar objects. Note that in our experimental setup, MID is simulated by expanding the stimuli in a manner consistent with a constant-speed MID. In theory, the visual system could perform the task by computing speed from the estimated TTC, such as was suggested by Regan and collaborators (1998). This would be feasible thanks to the observers who would have access to the familiar size of the objects:

$$\left(speed = \frac{S}{\theta} \frac{1}{TTC} \right).$$

Otherwise, an estimate of distance would be necessary, which is restricted in this experiment because of the absence of most depth cues. Because TTC can be, in fact, given by tau (Lee, 1976), the speed computation could be determined by a measure of the rate of expansion. In order to test whether speed can be retrieved directly from the rate of expansion, and not necessarily inferred from TTC, we performed the experiment by keeping TTC constant. In addition, we wanted to study whether manipulating the size of the objects affects the perception of speed.

To perform the experiment, a two-interval forced-choice paradigm was used. We set the simulated approach speed of the reference at 2 m/s, while the test's speed was randomly chosen, in each trial, from a range of six values (0.5, 0.66, 0.83, 1.2, 1.5, and 2 times the reference's speed). Note that the test's approach speed was constant within each trial, but varied from trial to trial. The distance and time-to-collision of objects at the time they disappear will be referred to as dTc and TTC, respectively (see Figure 2). In this experiment, TTC was always the same for reference and test (500 ms); so, because F2

$$dTc = speed \cdot TTC,$$

test's dTc varied from trial to trial with test's speed.

A total of seven observers participated in this experiment: two authors, three naives, and two "fully naives." The "fully naive" observers only performed the experiment with the red spheres (nonfamiliar stimuli) so that they could not associate their size with the balls' sizes. In summary, the experiment using familiar stimuli was carried out by the two authors and the three naives, while the experiment using nonfamiliar stimuli was carried out by all seven observers. Their task was to report, by clicking a mouse button, which stimulus, first or second, was perceived faster. The experiment was carried out with the two configurations: "Same θ − Off Size" and "Different θ − Standard Size," with familiar and nonfamiliar stimuli.

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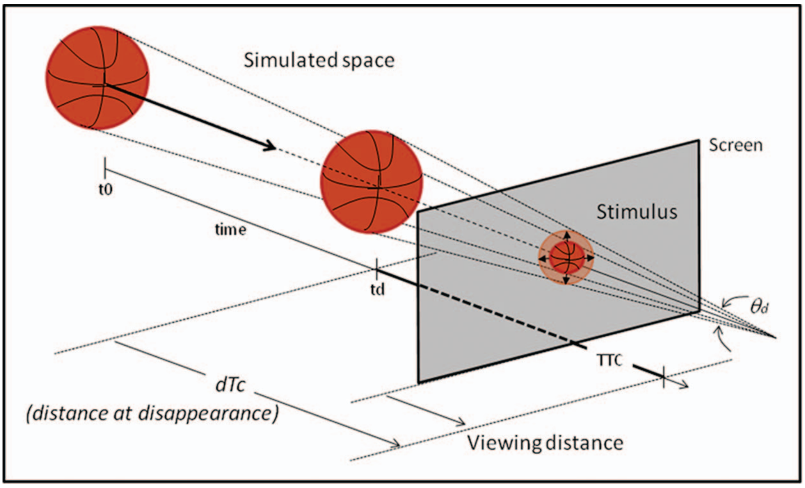

Figure 2. Illustration of the simulated motion in depth. The drawing shows graphically the meaning of distance of objects at the time they disappear (*dTc*): the distance from which an object subtends a given visual angle (θ_d) at the time it disappears (t_d). On the time scale, time to collision is also shown. See the online article for the color version of this figure.

Results and Discussion

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Figure 3 shows the proportion of "first faster" as a function of test's speed, for familiar stimuli in the configuration "Same θ − Off Size" (Figure 3a) and for nonfamiliar stimuli (Figure 3b). Results show that proportion decreases with increasing speed for most observers, which means that observers respond that the test is faster when it is actually slower. This is an interesting result that was obtained because we built the psychometric function. The fact that the proportion of responses "First Faster" decreases with increasing speed indicates that observers have not responded to speed; their data correlate better with size. It should be noted that when speed decreases, the stimulus disappears closer to the observer ($dTc = TTC.\ speed$), and hence, is larger. In the context of TTC, this is very important since it can be interpreted as evidence that, when an object moves directly to an observer, retinal size becomes a critic parameter, for example, for triggering an avoidance

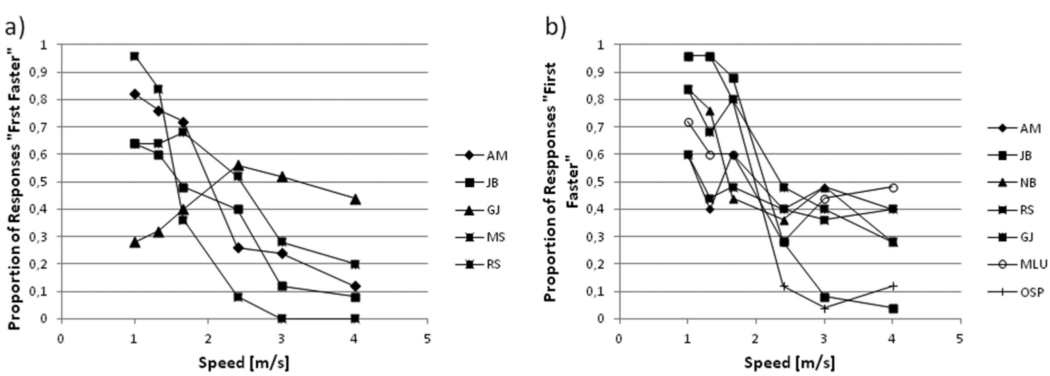

Figure 3. Proportion of "First Faster" as a function of speed for all observers. (a) Configuration "Same θ − Off Size." (b) Nonfamiliar stimuli. Note that the experiment that used images of spheres (panel b) was performed by seven subjects, including two fully naives.

action (Hosking & Crassini, 2011; López-Moliner et al., 2007; Michaels et al., 2001). In addition, it can be observed that, for some observers, the effect is little or null, which suggests that these observers are neither sensitive to speed nor are influenced by size in performing this task. Results are similar for familiar and nonfamiliar stimuli. Interestingly, the fully naive observers did not show different behavior in their data with respect to the rest of the participants. This, plus the fact that there is no difference between data obtained with familiar and nonfamiliar stimuli, suggests that observers are not using familiar size information in this task, which supports the idea that observers are responding to retinal size rather than speed.

F4 Figure 4 shows the results for familiar stimuli in configuration “Different θ − Standard Size” (Figure 4a) and for nonfamiliar stimuli (Figure 4b). In this case, data show that the proportion of “First Faster” does not vary with speed. The fact that observers have a flat response indicates that there is no sensitivity to speed (in fact, the response patterns seem to show the response bias of the observers). In none of the configurations used here does familiarity seem to have an effect on the perception of speed. In other words, it seems that knowing the size of the objects does not help observers in estimating the speed of objects moving in depth. Again, there is no difference between the results of the fully naive observers and those who knew about the balls.

Experiment 2

Distance Perception

In this experiment, we tested the relative distance perception of the test with respect to the reference, for simulated MID, and for both configurations. In addition, we performed, as a control, the same experiment but with no motion (speed = 0). The aim of this experiment was to investigate whether human observers could estimate the relative distance between two familiar objects from the knowledge of their familiar size. In addition, we wanted to assess how accurate this relative estimation can be. Along this line, previous studies had shown that the angular size relation between two identical objects (playing cards) of different physical size provides precise information about their distance relation (Fitzpatrick et al., 1982). This experiment indicates that, when two identical objects are compared (same S'), their relative perceived distances (D') can be accurately inferred from their angular size relation (θ). For their part, Gogel and Mertens (1968) have shown that when two different familiar objects are compared (different S'), the absolute judgments of depth between the objects (d') are neither accurate nor precise, although always consistent with the actual depth order. Interestingly, this was so despite the fact that S' judgments were very accurate. We propose to estimate the perceived-distance relation induced by S' by using a two-interval forced-choice paradigm with the

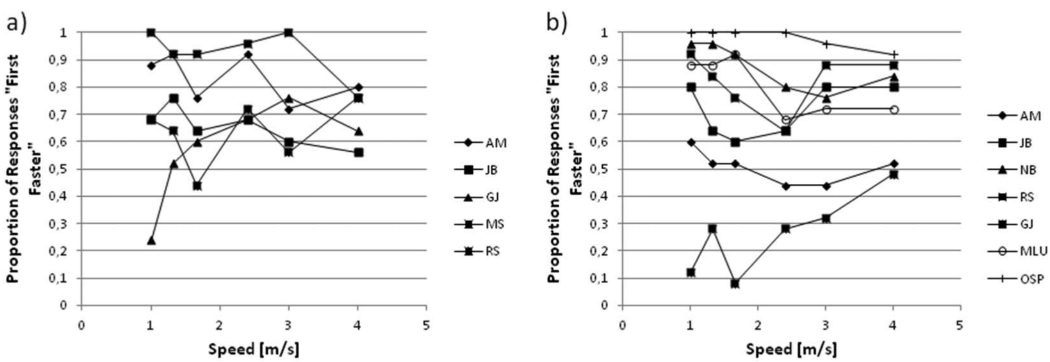

Figure 4. Proportion of “First Faster” as a function of speed for all observers. (a) Configuration “Same θ − Off Size.” (b) Nonfamiliar stimuli. Note that the experiment that used images of spheres (panel b) was performed by seven subjects, including two fully naives.

method of constant stimuli, in a perceived-distance comparison task. Because we simulated MID, the angular size of the stimuli varied during the stimulus presentation, so to characterize the stimuli, we used their angular size at disappearance (θ_d), which is

$$\theta_d = tan^{-1}\left(\frac{S'}{dTc}\right)$$

(see Figure 2). Note that we use S' as perceived size and familiar size interchangeably when we refer to familiar objects. To perform the experiment we used, as the reference, the image of a tennis ball subtending 3.9° of visual angle at disappearance, which corresponded to a dTc of 1 m. The test was the image of a basketball, whose θ_d relative to the reference was calculated from a value of test's dTc, which was randomly chosen, in each trial, from a range of six values predefined in order to build the psychometric function. For configuration "Same θ − Off Size," the values were 0.42, 0.83, 1.20, 2.40, 3.60, and 4.80 m. The range was biased to long distances because we expected the test (basketball) to be perceived as farther away than the reference since, for equal dTc, both subtended the same visual angle. In the configuration "Different θ − Standard Size," test and reference had their regular sizes, so we expected no bias in the relative distance perception. The values adopted in this case for the test were 0.21, 0.27, 0.41, 0.83, 1.20, and 1.40 m. This experiment was performed by setting TTC = 500 ms, for reference and test, and for all values of dTc. This means that speed varied from trial to trial, according to the value adopted by dTc.

The same seven observers of the previous experiment participated in this one. Their task was to report, by clicking a mouse button, which stimulus, first or second, was perceived as closer at the time it disappeared. The experiment was carried out with familiar and nonfamiliar stimuli.

Results and Discussion

F5 Figure 5 shows the perceived dTc (dTc_p) of the test relative to the reference for the two configurations ("Main" in Figure 5) and the control. The parameter dTc_p is defined as the inverse of the PSE multiplied by the reference dTc. For example, a value for dTc_p of 2 means that the test was perceived as twice as far as the reference at the moment of disappearance. Each bar represents the average value for all observers and the error bars represent the 95% confidence intervals. Data show that, for the configuration "Same θ − Off Size," observers overestimate the distance of the undersized basketball with a factor of around 2, for main and control. A paired t test indicates that results for main and control are identical ($t = -0.32$, $df = 7$, $p = 0.7558$). According to the SDIH, and assuming that S' is accurately assessed, if $\theta_{d,T} = \theta_{d,R}$ (subindices T and R refer to "test" and "reference"), which occurs in the configuration "Same θ − Off Size," then

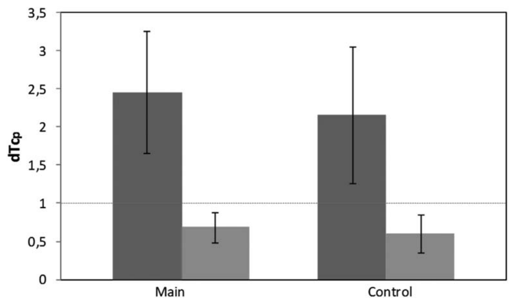

Figure 5. Average distance of objects at the time they disappear (dTc_p) obtained for configurations "Same θ − Off Size" (dark gray) and "Different θ − Standard Size" (light gray). Left-hand bars correspond to data obtained with motion in depth, and right-hand bars to the control. Error bars represent the 95% confidence intervals. We performed t tests with null hypothesis = 1 and show that all means are significantly different from 1 ($p = 0.0243$ for Main condition [dark gray]; $p = 0.0351$ for Main condition [light gray]; $p = 0.0441$ for Control condition [dark gray]; $p = 0.0295$ for Control condition [light gray]).

$$\frac{S'_T}{dTc_{p,T}} = \frac{S'_R}{dTc_{p,R}}$$

Since $S'_T = 3.6\ S'_R$, and we found that $dTc_{p,T} = 2.4\ dTc_{p,R}$, replacing in the previous AQ: 3
equation, we obtain the inequality

$$\frac{3.6\ S'_R}{2.4dTc_{p,R}} \neq \frac{S'_R}{dTc_{p,R}}$$

which indicates that our result is not consistent with predictions of the SDIH. The similarity between these and the results obtained with the control condition (speed = 0) indicates that this inaccuracy is not due to MID but, perhaps, to an inaccurate visual assessment of S'. Remember that, before each experimental session, we provided the observers with real balls for them to get familiar with their size, and controlled their hand-made size assessment. Apparently, although observers are good at reporting the size of the balls with their hands, this is not transferred to visual use. Another explanation could be that, although we removed all pictorial distance cues from the stimuli, and the task was performed monocularly, accommodation was still present. Given that the viewing distance was 0.50 m, accommodation could have been very important. Perhaps, the fact that accommodation did not vary throughout the experiment produced a compression in the effect of familiar size on relative distance perception.

Furthermore, the dTc_p obtained in configuration "Different θ − Standard Size" indicates that the regular-sized basketball is perceived as closer to the observer when both test and reference have the same *dTc*. In this case dTc_p = 0.63, which means that the basketball is perceived at almost half the distance of the tennis ball. This is also inconsistent with the prediction of the SDIH if we assume that S' is correctly assessed. According to our interpretation, accommodation cannot explain the bias, in this case, because the SDIH does not predict any bias when the *dTc*s are the same. Again, there are no differences between these and the results obtained in the control condition ($t = -0.52$, $df = 7$, $p = 0.6173$).

Experiment 3

TTC Perception

So far, we have shown that observers cannot discriminate the speed of familiar objects undergoing simulated MID, and that relative distance estimates between two familiar objects are not accurate under our experimental conditions. In this experiment, we wanted to study whether the relation between the TTCs obtained by comparing two different approaching balls, under the same conditions in which we performed the distance experiment, resembles the relation between relative distances found previously. We can predict from previous studies (Hosking & Crassini, 2010) that, in the configuration "Same θ − Off Size," we will obtain a longer TTC for the basketball, which could be interpreted as the result of this ball's being perceived as further than the tennis ball. However, for the configuration "Different θ − Standard Size" we should expect, according to DeLucia (2005) and Hosking and Crassini (2010), an important reduction or the total cancellation of the size-arrival effect (same TTC). In this case, this effect could not be interpreted as consistent with the results obtained with the configuration "Same θ − Off Size" in the distance experiment, in which the basketball was perceived as closer than the tennis ball. Hence, we proposed to measure the relative TTC predicted by observers under the same experimental conditions that we used to obtain the relative distance estimation.

To perform this experiment, we used the same procedure as in the previous experiment; but now, we fixed the reference and test *dTc* at 1 m, the reference TTC at 500 ms, and the test TTC varied from trial to trial, according to a predefined set of values. These values were 0.25, 0.31, 0.415, 0.6, 0.8, and 1 s for all cases except for the configuration "Different θ − Standard Size" with control stimuli (spheres), in which the values were 0.31, 0.62, 1.25, 2.5, 5.0, and 20 s. This very wide range was used in order to be able to capture the SAE.

Four more volunteers were included in this experiment. Two of them performed all conditions and the other two were "fully naives" (see the last paragraph of the Method section in Experiment 1) and only performed the control in the configuration "Different θ − Standard Size." This was done to test the SAE. Therefore, we had four fully naive observers, five naives, and two authors.

Results and Discussion

Figure 6 shows the TTC_p for main and control conditions for both configurations. First, in the configuration "Same θ − Off Size" (dark gray bar of the Main condition), observers perceived that the basketball arrives, on average, 1.28 times later than the tennis ball. A *t* test with null hypothesis = 1 shows that this relative TTC is significantly different from 1 (p = 0.0224). The light gray bar of the Main condition shows that, when balls are displayed with their regular sizes ("Different θ − Standard F6

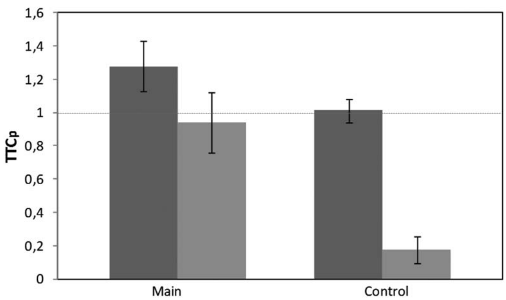

Figure 6. Average time to collision (TTC_p) obtained for configurations "Same θ − Off Size" (dark gray) and "Different θ − Standard Size" (light gray). Left-hand bars correspond to data obtained with balls (familiar objects), and right-hand bars to data obtained with spheres (Controls). Error bars represent the 95% confidence intervals.

Size"), observers perceive both balls arriving with the same TTC ($TTC_p = 0.94$). The *t* test in this case shows that this relative TTC is not significantly different from 1 ($p = 0.5680$). This indicates that the SAE does not appear when stimuli are familiar objects. The other two bars represent the results of the Control condition. The dark gray bar shows the relative TTC of two identical red spheres ($TTC_p = 1.01$; $p = 0.7350$). The light gray bar shows the SAE. It represents the relative TTC of two spheres whose relative sizes were determined by the relative sizes of the basketball and tennis balls. In this case, the relative TTC_p is 0.18 ($p = 0.0004$).

In relation to the goal that we formulated at the beginning of this experiment, these results do not show a consistent relation with those obtained in the distance experiment. In principle, one could argue that the $TTC_p = 1.28$ obtained with the configuration "Same θ − Off Size" could be explained by the relative distance perception obtained with this configuration; however, the $TTC_p = 1$ obtained when the stimuli are regular-sized objects does not maintain the same relationship with the perceived relative distance obtained with the configuration "Different θ − Standard Size." A similar analysis can be made with the Control condition.

Conclusion

Summary of the Results

We performed three experiments in which we investigated the effect of object familiarity on the perception of speed, distance, and TTC. In the first experiment, when observers are required to discriminate the speed of MID, results show that they respond to other variables such as angular size or just give a flat performance, depending on the configuration. We could not determine for any observer or experimental situation, a PSE that gives information about speed discrimination. In the second experiment, we showed that distance may be inferred from size familiarity, although quite inaccurately. We also showed that this effect did not change depending on whether the object was moving in depth or not. In the third experiment, we showed that an incorrect size relationship between two familiar objects induces a bias in the perception of TTC. In addition, we showed the SAE in the control stimuli and how knowledge of the object's size nulls it out.

Main Conclusions

The first conclusion of this study is that humans cannot discriminate the speed of objects that move in depth from their rate of expansion, even though the objects are familiar, that is, of known size. Previous studies have shown that in some situations, stereoscopically defined stimuli that simulate MID are effective in eliciting speed perception, although performance in speed discrimination was quite poor (Rushton & Duke, 2009). When they increased the depth cues, accuracy considerably increased as well, but still observers cannot make veridical estimates of speed. Our results show that, when the only cue available for estimating speed is rate of expansion, speed cannot be discriminated. This implies that, in scenes with impoverished depth cues, such as those used in these experiments, TTC cannot be computed based on speed information, even for familiar objects. In real life, humans can face these situations, for example, in low-light-level conditions. Rather, our results suggest that angular size is the critical parameter in situations of approaching objects. This conclusion deserves a special discussion since, in theory, a knowledge of the prototypical size of an object could make the estimation of speed of MID feasible (Lopez-Moliner et al., 2007). It turns out that, if we know the size of the object and are capable of discriminating successive measures of θ′, we can estimate speed by measuring the time between two consecutive estimates of θ′. This approach was used by Lopez-Moliner and collaborators (2007) to explain how speed can be computed in order to estimate TTC without the need to measure distance. One possibility of explaining our results in the context of the Lopez-Moliner et al. model is that, although we seem not to have perceptual access to speed in MID, it could be estimated by its exclusive use in action. This assertion is supported by the well-known two-visual-systems hypothesis, which was proposed by Goodale and Milner (Goodale & Milner, 1992; Milner & Goodale, 1995), and has gained many adherents over the years. According to this hypothesis, the visual system processes the information for perception and for action in independent streams, which would explain much of the discordances between visual illusions and motor estimates (for a review, see Westwood & Goodale, 2011).

The second conclusion of this study is that, even though observers know the object's size (familiar size), they cannot discriminate accurately their relative distances from their angular sizes, as predicted by SDIH, which is consistent with the results of Gogel and Mertens (1968). This occurs both in static conditions and when the balls are moving in depth. One possible explanation for this result could be that, although our observers recognized the balls, they were not sufficiently familiar with them since none of the observers were basketball or tennis players. Importantly, before beginning each session, we provided the observers with real balls so they could become familiar with those objects, and controlled for their reproducing the balls' sizes with their hands. However, it seems that the motor representation of the balls was not used, at least immediately, for visual perception. Another explanation for these results could be the accommodation. Because the stimuli were always displayed on the same monitor, accommodation was invariable and, thus, in conflict with other distance and MID cues.

Another interesting conclusion relates to TTC. Assuming that speed of MID cannot be estimated and knowing that when familiar size is known D' can be inferred from θ (according to SDIH), we had hypothesized that an experiment of TTC discrimination could reflect the perceived relative distances found in the second experiment. We show that this is not the case. The relative TTCs obtained in our last experiment do not follow the perceived relative distances found in the previous experiment. Our results show, in consistency with previous studies (DeLucia, 2005; Hosking & Crassini, 2010, 2011), that the relative TTC would be determined by θ or θ′, and that familiar size helps to rescale these measures in order to get a more reliable estimate. This is consistent with the results obtained for speed perception of familiar objects moving in the frontoparallel plane (Martín et al., 2015). The authors showed first that, when two different-sized familiar objects are displayed with the same angular size, the larger object (basketball) is perceived faster than the smaller object (tennis ball). This is comparable to what we obtained with the configuration "Same θ − Off Size" (see dark gray bar of Main condition in Figure 5). Second, the speed bias found when two different-sized meaningless stimuli are compared disappears when familiar size accounts for such a size difference. This is comparable to the suppression of the SAE found for the configuration "Different θ − Standard Size" (see light gray bar of Main condition in Figure 5). This means that, although TTC is, perhaps, something inferred rather than perceived by the observer, it seems to be affected by familiarity in the same manner as speed in the frontoparallel plane. AQ: 4

Finally, we want to pose a final consideration, which is that reducing any physical problem to laboratory conditions in which a variety of cues are, or could be, in conflict, imposes restrictions on the analysis of the results. For example, the results obtained with the control stimuli (meaningless) in the configuration "Same θ − Off Size," which replicate many of the results present in the literature, show that when the experiment requires fewer cognitive aspects, the TTC perception is quite precise and can be explained by the optical information present in the stimulus itself. We understand that, when familiarity is introduced (and the bias appears), the system has to give a coherent response to the stimulus, given the proposed task: perhaps, being aware that such a task is not a real situation, that is, the balls are not really approaching the observer.

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Appendix

Subsidiary Experiment

AQ: 5

In this section, we explain how the handmade ball's size estimation was controlled, and present the data. We took two measures of the ball's estimation: before and after giving the real ball to them to manipulate it. To perform this measure, we used an inside diameter measuring tool whose scale was in millimeters. We taught the participant to make a standard hand gesture to indicate the ball size. Then, we took the measurements in the center of the hand palm. This was only possible for the basketball because the tennis ball is too small and we could not apply our standard criterion to take the measure. In any case, we qualitatively observed the estimates of the tennis ball and found them to be acceptable. We took all precautions to avoid modifying the participant estimation when interacting with them to take the measurement. Table A1 shows the data for both situations and seven observers (the four fully naive observers were not included). We performed a two-tailed t test to examine whether manipulating the balls had an effect on the estimations. In the line below the means, we show the errors in the ball's estimation calculated as the ratio between the estimated size and real size. It can be seen that this error was reduced, in average, from 19% to 10% after the ball manipulation. The t test indicates that the means are significantly different ($p < 0.02$).

TA1, AQ:6

Table A1
Ball Size Estimations Using Hand Gestures

Observer	Before (cm)	After (cm)
AM	28.0	26.0
JB	27.7	27.0
NB	28.9	25.5
RS	31.2	27.5
GJ	26.5	25.0
AD	31.0	27.2
MS	27.2	27.3
Mean	28.6	26.5
Error	1.19	1.10

Note. Basketball actual diameter = 24 cm.

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AQ5—Author: Is the appendix title ok as added? If not, please provide an appropriate title for the appendix.

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