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Semantic modulation of time-to-collision judgments

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ABSTRACT

Observers are able to make generally accurate judgments of the time-to-collision (TTC) of approaching stimuli. Traditional theories have emphasized the role of optical cues about the expansion of the retinal image in this ability. Recent work, however, has further emphasized the role of semantic information about the object. Here we investigate the role of semantic information in TTC judgments by presenting a range of real-world objects, which varied widely in size, weight, and hardness. Our results show that the physical characteristics of looming stimuli predict observers' TTC estimations. Bigger, heavier, and harder objects were underestimated more, relative to smaller, lighter, and softer objects. As expected, actual TTC and stimulus size were also significant predictors of TTC judgments. In estimating the arrival time of looming stimuli, observers automatically take into account several characteristics of the stimuli, even though these characteristics are completely task irrelevant. This suggests that semantic properties of seen objects and the consequences of their impact on the observer's body are processed automatically.

1. Introduction

To promptly react to approaching objects, observers need to be able to estimate their arrival time. According to the ecological optics approach (Gibson, 1966, 1979; Lee, 1976; McLeod and Ross, 1983) information specifying time-to-collision (TTC) is directly available through the changing optic array at the eyes of the observer. On this view, TTC is specified by the relative rate of expansion of the retinal image over time that is the relative rate of increase in separation between any two points on the surface of the target object. Even if the rate of the expansion unambiguously specifies the arrival time of looming objects, several studies have found that participants consistently underestimate TTC (McLeod and Ross, 1983; Schiff and Oldak, 1990; Neuhoff, 2001). This underestimation has been interpreted by the "margin of safety" theory (Neuhoff, 1998, 2001) as an adaptive response that allows the observer to have enough time to engage in an appropriate response to approaching objects. Indeed, precise perceptual processes allow the organisms to survive. However, responding too late to a looming stimulus is far more dangerous than responding too early, therefore, in this case, an anticipatory bias modulated by the motor abilities of the observer can be advantageous for the survival of the organisms (Haselton and Nettle, 2006).

Recent studies have demonstrated that TTC judgments can also be modulated by the semantic content of the approaching stimulus (Brendel et al., 2012; Vagnoni et al., 2012). For example, we recently showed that the TTC underestimation bias is modulated by the specific fears of the observers, such as of snakes or spiders (Vagnoni et al., 2012, 2015, 2017). Specifically, the more fearful of the approaching objects (e.g., spiders) the participants are, the more they underestimate the arrival time of the looming objects. This stronger underestimation bias in spider-fearful participants has also been replicated by another group of research with a similar paradigm (Brendel et al., 2014). These findings are in line with the 'margin of safety' theory. Indeed, if the underestimation of looming stimuli has an adaptive advantage, this becomes especially true when the stimulus approaching our body is represented by a dangerous object. Moreover, it seems that having a specific fear for the approaching stimulus prompts the use of a more conservative margin of safety.

Snakes and spiders may represent evolutionarily-privileged categories (Isbell, 2009), based on possibly innate perceptual mechanisms (Rakison and Derringer, 2008; DeLoache and LoBue, 2009). Therefore, the semantic modulation of TTC by these categories of stimuli may be advantageous for the observer from an evolutionary point of view. It is, therefore, possible that the semantic modulation of TTC judgments we

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have found in our previous studies (Vagnoni et al., 2012, 2015, 2017) is limited to particular categories which may have a source of predation during human evolution. There is, however, a wide range of semantic knowledge about surrounding objects that not only pertains their dangerousness but to more general information regarding their physical characteristics. For example, we have stored representations of the real-world size of objects as well as other properties of familiar stimuli that we experience in everyday life, like weight or hardness. In the current study, we investigated whether these physical characteristics influence TTC judgments of approaching stimuli.

Interestingly, existing evidence shows that some physical characteristics of objects seem to be accessed by the observers automatically. For example, Konkle and Oliva (2012) reported a *familiar size Stroop effect*, finding that observers are faster at indicating which of two stimuli is bigger on the screen when the difference in the real-world size of the objects is congruent with the difference in displayed size. Crucially, this task does not require taking into account the real-world size of the objects. This effect suggests that people access the familiar size of objects without the intention of doing so, demonstrating that real-world size is an automatic property of object representation (Konkle and Oliva, 2012). The effect of familiar size has also been investigated with the TTC paradigm, and TTC errors are reduced for standard-sized familiar objects (Delucia, 2005) or increased when the objects are presented off-sized (Hosking and Crassini, 2011). López-Moliner et al. (2007) propose that observers use information about the known size to determine the threshold optic expansion rate at which interceptive actions should be initiated. Indeed, the visual angle of an object projected onto the retina decreases with distance and this information can be combined with the stored representation of the object's size to determine the absolute depth of the object. Therefore, prior knowledge can be combined with information about the angle the object subtends on the retina to determine its absolute depth in a scene.

Several pieces of evidence suggest that multiple sources of information may be used as cues for TTC (Hosking and Crassini, 2011; DeLucia, 2004, 2013; Tresilian, 1995; van der Kamp et al., 1997). For example, according to Delucia (2005), the TTC judgments are based both on heuristics and invariants. Numerous studies have shown the use of invariants, such as tau, in TTC judgments (Wann, 1996). Tau is an optical invariant which does not require the knowledge of object speed or distance in determining the TTC (Lee, 1976). The heuristics that influence the TTC judgments are represented by relative size, height in field, occlusion, and motion parallax (DeLucia, 2013) and binocular information sources such as changing disparity (e.g., Regan and Beverley, 1978; Rushton and Wann, 1999). The rate of expansion is an invariant and is immediately accessible, but observers base their TTC judgments also on heuristics, as shown by the *size-arrival effect* in which observers report shorter TTC judgments for bigger stimuli (DeLucia, 1991; DeLucia and Warren, 1994; Hosking and Crassini, 2011).

In our previous studies (Vagnoni et al., 2012, 2015; 2017), we have used a TTC paradigm and presented threatening and non-threatening stimuli looming towards the participants. The images were presented on the screen at two different sizes (400 and 500 pixels). In all of our experiments we have found a significant effect of the size of the images presented on the screen with the arrival time of bigger images being underestimated more relative to the arrival time of smaller ones. The size-arrival effect is an effect that has been replicated several times and has been found in both collision avoidance and interception paradigms. For example, in the work of DeLucia and Warren (1994) participants were asked to jump over an approaching object in a computer simulation. The authors showed that participants jumped later for small objects, relative to bigger objects, approaching from the same distance at the same speed and positioned at the same heights (DeLucia and Warren, 1994). Similarly, in the work of van der Kamp et al. (1997) participants were required to catch an approaching ball. The authors showed that the larger the balls the earlier the hand was opened and closed, and the catch was completed (van der Kamp et al., 1997). Together these results seem to suggest that the size of an object is used as an important cue for depth perception; however, the mechanism underlying the effect has not been unequivocally determined, apparent size-distance relationships, optical size, and optical expansion rate have been mentioned as possible candidates (DeLucia, 1991; DeLucia and Warren, 1994; Hosking and Crassini, 2011).

Here we hypothesized that not only the actual stimulus size but also the stored semantic information about an object's size, weight, and hardness in real-world will influence TTC estimates. It is intuitive, and in line with "margin of safety theory" (Neuhoff, 1998, 2001), to expect a stronger underestimation when the approaching stimulus is represented by a stimulus that is known to be physically big, hard, or heavy in the real world. Indeed, the consequences of colliding with something big, like a refrigerator, are more drastic relative to the consequences of colliding with something small, like an apple. Accordingly, we asked participants to judge the TTC of a range of objects, varying widely in size, weight, and hardness. We then asked an independent group of raters to judge the semantic characteristics of each object. We then investigated how these semantic properties related to TTC judgments.

2. Method

2.1. Participants

Thirty-two members of the Birkbeck community (19 female) between 18 and 59 years of age, mean age 33.4, participated in the time-to-collision task. Participants reported normal or corrected-to-normal vision. Procedures were approved by the local ethics committee.

An additional ten members of the Birkbeck community (5 female) between 20 and 35 years of age, mean age 27.4, rated the images for payment or course credit. Participants reported normal or corrected-to-normal vision. Procedures were approved by the local ethics committee.

2.2. Stimuli, design and procedure

We selected 296 images from the internet, 4 exemplars from each of 74 categories of familiar, everyday objects (see S1 File, Fig. 1). We asked ten participants to rate the images according to three dimensions: real-world size, hardness, and weight. The categories were chosen to reflect a wide range across all three dimensions. Images were cropped and resized using Adobe Photoshop CS5 (Adobe Systems, San Jose, CA). This resulted in images (300 pixels wide, 300 pixels high) in which the object took up the entire image. Backgrounds from the original photographs were replaced with a homogenous white colour (identical to the background of the experimental script). The rated stimuli were then used in the TTC task.

2.3. TTC task

The TTC task was similar to that used in previous experiments in our lab (Vagnoni et al., 2012, 2015; 2017). Participants in the TTC task sat at a table, without a chin-rest, approximately 40 cm in front of a 19-inch monitor (75 Hz refresh rate). The height of the monitor was adjusted to be aligned with the participant's eye level. Stimulus presentation and data collection were controlled by a custom MATLAB (Mathworks, Natick, MA) script. On each trial, the stimulus increased in size across 75 frames (i.e., 1 s), consistent with one of five time-to-collisions (2.0, 2.4, 2.8, 3.2, and 3.6 s after the onset of the first frame). The width of the stimulus on the first frame was 300, 350, 400, 450 or 500 pixels (11, 13, 15, 17, 19° visual angle). Starting image size was manipulated so that actual TTC was not perfectly correlated with the size of the image on the final frame. After the 75th frame, the image was replaced by a white background.

There were a total of 296 trials (one involving each image), divided into 5 blocks of 50 trials each and 1 block of 46 trials. Each block included two repetitions of each combination of time-to-collision (5

Fig. 1. Examples of the type of images used, representing six of the categories we used (clockwise from top-left): refrigerator, apple, barbell, feather, anvil, and pillow. The categories were chosen to reflect a broad range of sizes, weights, and degrees of hardness. Due to copyright restrictions, the actual images used cannot be displayed here, but these images are representative.

levels) and initial image size (5 levels) apart from the last block where the repetition of the trials was not the same for each TTC level due to the smaller number of trials. The order of trials within each block was randomized. The 296 images from the 74 categories were randomly assigned to trial types, and each image was used exactly once for each participant. After the participant responded on each trial, the next trial began after a random inter-trial interval of 300–500 ms.

Participants were instructed that they would see objects expanding in size as if they were approaching and that after some time, the image would disappear. They were told that their task was to imagine the object continuing to approach at the same rate and to press the button on the keyboard when they judged that the object would have made contact with their body. The stimuli are perceived as approaching through their expansion. The stimuli, obviously, never moved on a horizontal plane, and the different time-to-collisions were set through a script that controlled the stimuli's rate of expansion.

2.4. *Rating task*

In the rating task, we asked the participants to rate each of the 296 images three times. In the first block, they rated each image for the real world size dimension from 1 to 100 (the low extreme anchor was represented by the word "pea" while the high extreme anchor was the word "elephant"). In the second block for the hardness dimension (the low extreme was represented by the words "cotton ball" while the high extreme anchor was the word "steel"). In the third block for the weight dimension (the low extreme anchor was represented by the word "feather" while the high extreme anchor was the word "car"). On each trial, one image was presented, and the participant was asked to type in their numerical judgment. The scale, including both the low and high anchors, was visible on the screen throughout the block. Stimulus presentation and data collection were controlled by a custom MATLAB script.

2.5. *Analysis*

The aim of the analysis was to identify significant predictors of TTC judgments. We directly manipulated two of the predictors (the actual TTC and the initial size) while three predictors (real-world size, hardness, and weight) varied across the 74 object categories and were quantified based on judgments made by an independent pool of participants. For each participant in the rating task, we calculated the Z-score for each object rating relative to the mean of all ratings of a given dimension (i.e., size, weight, hardness), to remove individual differences linked to idiosyncratic differences in how raters used the given scales. We then calculated the mean Z-score across raters for each of the 296 objects for each of the three dimensions (see S1 File). These mean values were then used as predictors of the TTC judgments.

Regarding the time-to-collision judgments, for each participant, Z-scores were calculated for time-to-collision judgments, separately for each level of actual time-to-collision. Trials with Z-scores greater than +3 or less than −3 were considered outliers and excluded from analyses (<1% of trials).

We used linear mixed-models (Baayen et al., 2008) using the *lme4* toolbox for R (Bates et al., 2015). We first conducted an analysis without including any information about semantic content to assess the effects of stimulus size. We then conducted analyses, including the three semantic features (size, weight, hardness) individually and collectively. All models included random intercepts for participants and models, including semantic information included by-participant random slopes for the effect of each semantic variable. The significance of each variable was assessed using model comparison (Barr et al., 2013).

3. Results

We first investigated the effects of actual TTC and starting image size on TTC judgments, without including semantic information in the model. There was a clear effect of actual TTC ($\beta = 0.796$ ms/ms, SE $\beta = 0.016$), $\chi^2(1) = 2236.50$, $p < 0.0001$. This effect shows that participants were able to perform the task meaningfully. On average, judged TTC increased by 796 ms for each second of increased actual TTC. There was also a clear effect of initial image size ($\beta = -1.406$ ms/pixel, SE $\beta = 0.127$), $\chi^2(1) = 122.53$, $p < 0.0001$. For every pixel of increased linear dimensions of the starting size of the image, judged TTC decreased by 1.4 ms, an effect consistent with previous results (Brendel et al., 2012; DeLucia, 1991; DeLucia and Warren, 1994; Hosking and Crassini, 2011; Vagnoni et al., 2012, 2015, 2017).

The key question here concerned the three categories related to the physical characteristics of the depicted objects: size, weight, and hardness. We first conducted separate linear mixed-model analyses to investigate the effect of these three dimensions on judged TTC. In each model, we included actual TTC and initial image size as covariates and included random intercepts for participants and by-participant random slopes for the effect of the semantic feature. Fig. 2 shows the estimated effects of each of the three semantic features. There was a clear effect of object size ($\beta = -75.767$ ms/SD, SE $\beta = 17.489$), $\chi^2(1) = 14.76$, $p < 0.0002$. That is, a change of one standard deviation in semantic ratings of object size predicted a 76 ms decrease in judged TTC. There were also clear effects of object weight ($\beta = -84.652$ ms/SD, SE $\beta = 17.241$), $\chi^2(1) = 17.96$, $p < 0.0001$, and object hardness ($\beta = -66.088$ ms/SD, SE $\beta = 16.781$), $\chi^2(1) = 12.65$, $p < 0.0005$. Thus, the semantic features of size, weight, and hardness were all strong predictors of TTC. Increases of ratings of an object on each dimension were linked to reductions of judged TTC.

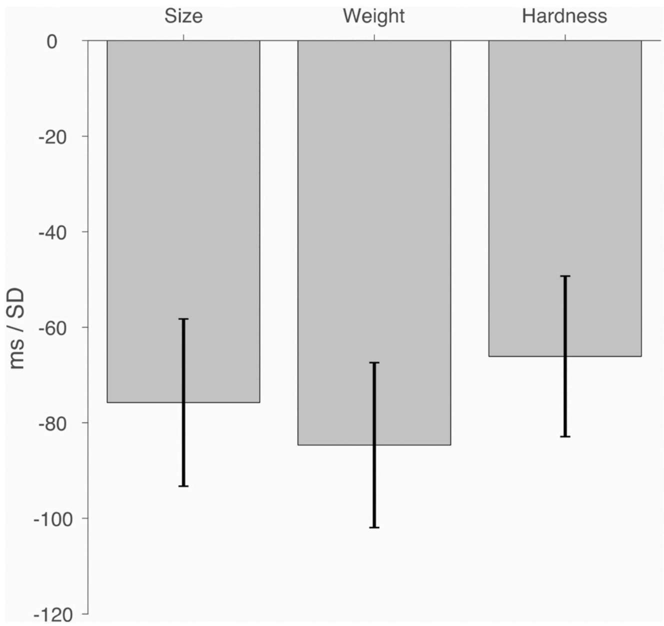

Fig. 2. Mean coefficients for each of the three semantic categories from linear mixed model analyses conducted separately for each feature. In each case, actual TTC and initial image size were included as covariates. Error bars are one standard error. All three semantic features were strong predictors of TTC judgments. Bigger, heavier, and harder objects were judged as arriving sooner than smaller, lighter, and softer objects.

While each of the three semantic features we investigated was a clear predictor of TTC judgments, the preceding analysis does not show that each is an *independent* predictor, nor that each (or indeed any) has a causal influence on TTC judgments. Indeed, the dimensions of size, weight, and hardness are highly correlated. Big objects are often also heavy and hard. Judgments of these three properties in our stimulus set were strongly related, with strong correlations between size and weight, $r(294) = 0.941$, $p < 0.0001$, between size and hardness, $r(294) = 0.461$, $p <= 0.01$, and between weight and hardness, $r(294) = 0.623$, $p < 0.0001$.

We, therefore, conducted a further analysis in which all three semantic features were simultaneously included in the model, along with actual TTC and initial image size as covariates. Fig. 3 shows the estimated effects of each of the three semantic features. There was a significant effect of object weight ($\beta = -132.998$ ms/SD, SE $\beta = 38.424$), χ^2 $(1) = 11.84$, $p < 0.001$. A one SD increase in object weight predicted a decrease in TTC judgments of 133 ms. In contrast, there were no effects of object size ($\beta = 55.888$ ms/SD, SE $\beta = 36.208$), χ^2 $(1) = 2.38$, $p = 0.123$, or of object hardness ($\beta = -4.122$ ms/SD, SE $\beta = 18.144$), χ^2 $(1) = 0.05$, $p = 0.820$. Thus, while object size, weight, and hardness all predict TTC judgments when considered individually, only weight appears to have an independent effect over and above the effect common to all three categories.

4. Discussion

People judge big, heavy, and hard objects as approaching more quickly than small, light, and soft objects. Ratings on the real-world size, hardness, and weight were used together with the actual TTC and initial images size on the screen of the stimuli, as predictors of TTC judgments. Each of these dimensions significantly predicted TTC judgments. However, given that size, weight, and hardness ratings were mutually intercorrelated, only the effect of weight remained as an independent effect when the effect of the other dimensions was controlled.

Traditionally, looming has been viewed as a purely optical cue for time-to-collision, without any consideration of the identity or features of the approaching object (e.g., Schiff et al., 1962). The present results add to emerging literature showing that the semantic content of the approaching object modulates TTC judgments (e.g., Brendel et al., 2012; Vagnoni et al., 2012). Critically, however, our results show that it is not only specifically threat-related categories (e.g., snakes, spiders) that affect TTC judgments, but also basic semantic information about the physical characteristics of everyday objects.

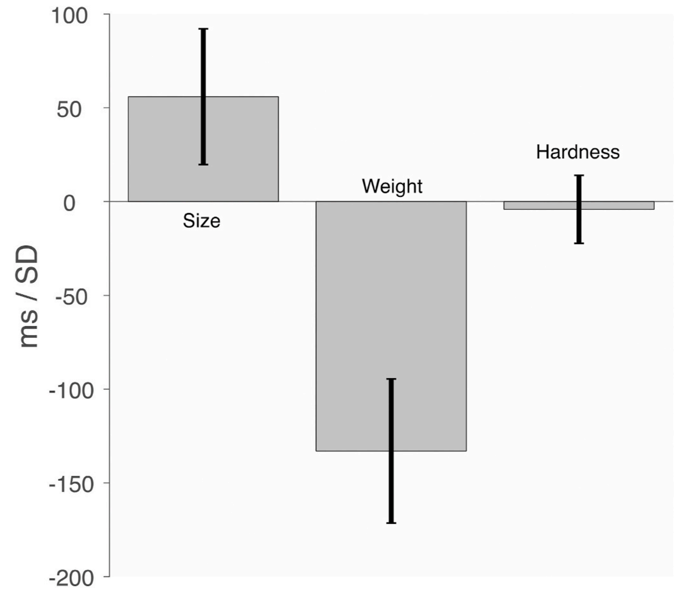

Fig. 3. Mean coefficients for each of the three semantic categories from linear mixed model analyses conducted simultaneously on all three features. Actual TTC and initial image size were included as covariates. Error bars are one standard error. Only weight was an independent predictor of TTC judgments over and above the effect common to all three features.

Our results are in line with the 'margin of safety' theory (Neuhoff, 1998, 2001), given that it is adaptive to underestimate more the arrival time of bigger and heavier stimuli because a collision with them would result in a more negative outcome relative to a collision with smaller and lighter stimuli. Previous results have found that the bias to judge categories which are commonly considered threatening (e.g., spiders) as arriving sooner than non-threatening categories (e.g., butterflies) is related to the specific fears of participants (Vagnoni et al., 2012, 2015; 2017; Brendel et al., 2014). The present results show similar semantic modulation of TTC judgments by simple physical attributes of common objects, which are unlikely to be the object of specific fears of our participants. This suggests that semantic modulation of TTC judgments is not limited to a particular class of fear-related stimuli, but rather may be a general characteristic of our interactions with objects in our environment.

Actual TTC was a very strong predictor of TTC judgments, suggesting that participants were able to use information about the rate of optical expansion of stimuli as a basis for their responses. The additional semantic features of the stimuli were entirely irrelevant to the participant's task, but nevertheless affected responses, suggesting that they were processed automatically. Such automatic processing of task-irrelevant features is unsurprising in cases where specifically threatening stimuli such as spiders or snakes are presented (Vagnoni et al., 2012), but is more striking for basic physical characteristics of common objects. These findings are consistent with the familiar-size Stroop effect described by Konkle and colleagues (Konkle and Oliva, 2012; Long and Konkle, 2017), which provided clear evidence for automatic processing of real-world size, even when entirely task-irrelevant. Analogous results have also been described in other contexts, such as judgments of numerical value (Gabay et al., 2013). The current results suggest that in addition to real-world size, characteristics such as weight and hardness are similarly accessed in an automatic way, and are used to make judgments of the arrival time of looming stimuli. Some recent studies have suggested that certain mid-level characteristics of objects (e.g., curvature) may be perceptual cues for real-world size (Long et al., 2016; Long and Konkle, 2017). It is plausible that there may be analogous features for object hardness or weight. It is possible that it may be such mid-level features, rather than physical characteristics per se that are driving our effects. This is an intriguing question for future research.

While all three tested semantic dimensions predicted TTC judgments when considered individually, they were strongly inter-correlated, making it difficult to determine what the critical semantic cues are that affect judgments. Weight was the only dimension that we found to have an independent effect when controlling for the other dimensions. This finding is intriguing, as research on naïve physics has found that the perceived weight of an object is known to influence expectations regarding object motion (Kozhevnikov and Hegarty, 2001). Nevertheless, caution is required in interpreting the independent effect of weight. There are numerous other semantic dimensions that we might have measured, which would have affected whether or not an independent effect of weight was obtained. It would be interesting in future research to assess a broader set of semantic features to try to identify which specific semantic features of object shape perception of object approach.

In addition to the effects of real-world size, we replicated the size-arrival effect related to the displayed size of the object on the monitor (e.g., Vagnoni et al., 2012; Brendel et al., 2012; Caird and Hancock, 1994; DeLucia and Warren, 1994; Hahnel and Hecht, 2012; Hosking and Crassini, 2011; Michaels et al., 2001; Smith et al., 2001; van der Kamp et al., 1997). Indeed, the size of the image displayed on the screen influenced the TTC judgments with big stimuli judged as arriving sooner relative to small ones. Even if the size-arrival effect has been widely replicated there is no consensus on the mechanism underlying it. Indeed, apparent size-distance relationships, optical size, and optical expansion rate are all considerate plausible candidates (DeLucia, 1991; DeLucia and Warren, 1994; Hosking and Crassini, 2011). According to DeLucia (2004), the size-arrival effect is due to the fact that observers rely on the visual angle of approaching objects to infer their distance from the viewpoint. In contrast, according to Hosking and Crassini (2011), relative TTC judgments based on the rate of expansion would also produce size-dependent TTC errors given that under many conditions a larger object has a greater rate of expansion than a smaller object.

When considered individually, real-world size, weight, and hardness were all significant predictors of TTC judgments. However, the ratings on three dimensions were not independent, but strongly inter-correlated. This is a basic feature of the statistical distribution of the real-life objects we encounter in our daily lives. Objects that are big also tend to be hard and heavy. For this reason, three regressions were performed, including only one of the ratings as predictor together with actual TTC and initial size. When controlled for the multicollinearity artefact in this way, also the real world size and hardness ratings predict the TTC judgments. It seems, therefore, that the effect of weight was covering the effect of real-world size and hardness.

Previously looming effect has been investigated as a purely optical phenomenon (e.g., Schiff et al., 1962). Indeed, the rate of the expansion on the retina gives immediately the information about the TTC of the stimulus. However, from the present findings, it seems that when observers have to make TTC judgments, they take into account the characteristics and the consequences of the stimulus impact on their body.

CRediT authorship contribution statement

Eleonora Vagnoni: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing, Funding acquisition. **Lee Lingard:** Investigation. **Shanette Munro:** Investigation. **Matthew R. Longo:** Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing, Funding acquisition, Supervision.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2020.107588.

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