# Learning in Binocular Time-to-Contact Perception

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Thesis submitted for the degree of Doctor of Philosophy.

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In memory of my father,
Osmo Untamo Karanka
To whom I own my curiosity.

# Abstract

Time-to-contact (TTC) is defined as the remaining time for an object to reach the observer. This is an important quantity for timing an action such as hitting or catching a ball. This thesis deals with learning processes in TTC perception when binocular vision is available.

Chapter 1 studies the learning of TTC in relative discrimination tasks. We did not find learning in this task, but we found that simple correlates of TTC explained the judgments made by the participants. Chapter 2 studies the learning of TTC in absolute estimation tasks. We found that the variable and constant error of the responses reduced with training. Chapter 3 studied the use of feedback in calibrating the timing of TTC estimates. We found that biased timing produced changes in the constant error, suggesting that TTC calibration is guided by feedback. Chapter 4 studied if the reduction of variable error was due to an increased perceptual sensitivity to TTC. However, we failed to find transfer from the absolute estimation tasks to relative discrimination tasks, suggesting that the learning found in Chapter 2 might not be of perceptual origin. In Chapter 5 we studied a large group of participants in laboratory tasks and a natural hitting task. We found that the performance in relative discrimination and absolute estimation tasks could be used to predict hitting skill. This suggests that the perception of TTC can be linked with interceptive timing.

Taken together, these results suggest that perceptual sensitivity to TTC changes slightly –if at all- with training, but changes in perceptuo-motor mapping and calibration of the estimates that increase interceptive performance do take place.

# Acknowledgments

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I'd like to thank also the people I've shared a lab with, Rod Woodhouse and Jonathan Kennedy. My dearest memories of spending time with them involve painting black the lab and playing zombie board games. Rod was also extremely helpful by providing code for probit fitting, brainstorming crazy maths and analysis, and sitting in the dark. Talking about sitting in the dark, I should thank the participants of my first very long experiments: Andrew Edmonds, Guillermo Ramos Esber, Masoud Fazilat, Jenni Swettenham, Mathieu Albasser, Gareth Linsmith, Alex Holborow, and Paul Hewlett. I should also mention some people from the vision group that I didn't have much chance to tie down for a few sessions, but I had a few beers with: Alex Holcombe, Emer O'Connor, Rhys Davies and Ursula Budnik.

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People that are not in Cardiff that I should thank are David Luque and Joan Lopez-Moliner, who have always been insightful when discussing research. And my mum, who after all these years still acknowledges me as her son!

And finally, thanks to John Wann and Krish Singh for corrections to make this thesis more solid and understandable.

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# General Introduction

In daily life we are surrounded by moving objects. We have to avoid colliding with some of them, such as cars or people, while others have to be intercepted, such as a ball during a tennis match. Knowing the direction these objects are moving, whether they are going to cross our path and whether they are going to hit us is are all important pieces of information that allow us to interact with the world. In the case of crossing a street it seems fairly easy how we might go about doing this. We look to the side, see a car far away and moving slowly and so we decide to cross the road. But under other circumstances, judging the arrival time of an object turns out to be much more complicated. For example, when catching a ball, there are only fractions of a second available for the catcher to judge where to place the hand and when to close it. If the timing of the grasp is slightly miscalculated, the ball will hit against an either open or closed hand and rebound.

Early research pointed out that the expansion ("looming") of an object's image produces defensive reactions. Anecdotal evidence of the first showings of *L'Arrivée du train en gare de La Ciotat* by the Lumiere brothers in 1896 exemplifies this phenomenon. According to contemporary accounts, some of the members of the public stood up when the film – showing a train approaching a station – was first shown. Although the train itself was simply projected on a canvas, its expansion induced some people to react as if it was really approaching. This phenomenon was further investigated in laboratory settings. Schiff, Caviness & Gibson (1962) showed monkeys a simple expanding circle projected against a canvas. This triggered fear reactions that were not found when the animals were exposed to other control stimuli like a screen that got gradually lighter or darker. Their results suggest that the expansion of the image is recognized as a signal of impending collision. Similarly, human infants have been found to react to looming stimuli. Yonas, Bechtold, Frankel, Gordon, McRoberts, Norcia & Sternfels (1977) used a similar setup to that of Schiff et al., (1962) to study whether displaying an expanding image would produce defensive reactions in infants of different ages. They observed that when a looming shadow was cast on a canvas, infants from four months of age onwards tended to blink in anticipation of the collision. Yonas et al., (1977) also found that if the cast shadows were slightly displaced to the side (and so, were not in a collision path) the infants would not present the same rate of defensive blinking. This led them to conclude that humans employ the symmetrical looming of an object as a means to tell whether it will collide with them.

The above studies show how looming stimuli can elicit defensive actions when an object such as a ball or a car approaches us in a collision path. However, the use of looming alone would seem more appropriate for alerting us of the collision with an object than for allowing to us finely timing an action to it. This is due to the relationship between looming rate and the actual time to contact (TTC) of a directly approaching object. TTC is, at any moment, the time remaining for the object to arrive at the observer. We can show this by plotting the looming rate of two objects, a tennis ball and a car, against their TTC. Figure 1 shows that the looming rate for the car is higher during most of the approach than the looming rate of the tennis ball. A short time before reaching the observer, the looming rate of both objects increases dramatically. It has been suggested that defensive reactions are associated to this peak in looming rate (see Schiff et al., 1962). However, the information given by looming rate is less useful in tasks that require more precise timing than the avoidance of an approaching object. After all, for avoiding or deflecting a ball, the action is successful even if it is performed before the ball arrives. On the other hand, using looming rate to time an action to coincide with the arrival of the tennis ball or car is much harder. If the action is triggered by looming rate achieving a certain threshold, it will always be produced earlier by the approach of the car than by the approach of the tennis ball. For example, a threshold of 2 radians / second would lead to an action starting about 100ms before the arrival of the ball but 400ms before the arrival of the car. In addition, image expansion alone does not contain enough information for making judgements about its arrival time as we shall discuss later.

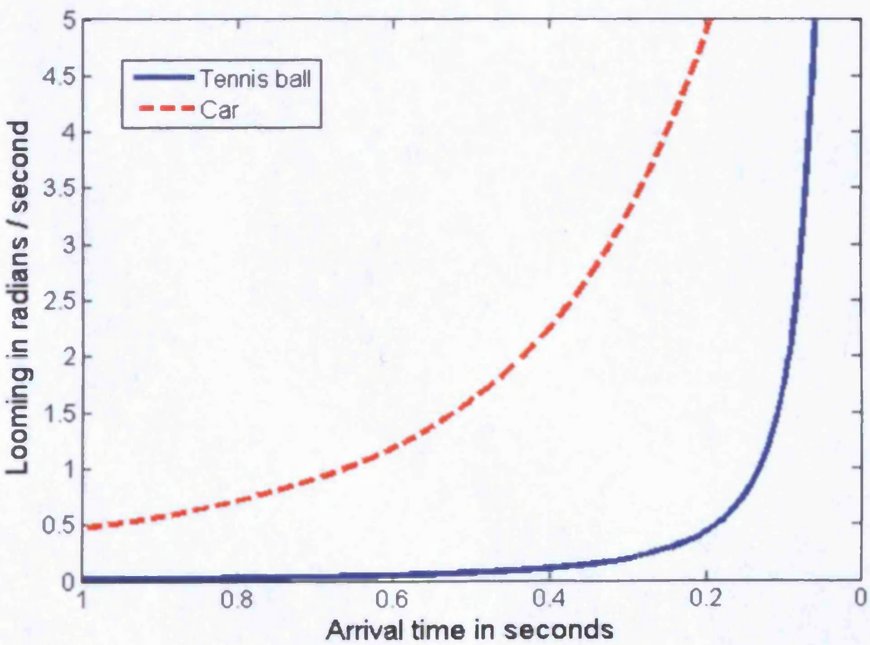


Figure 1. Looming rate over time for a tennis ball and a car. The tennis ball is considered to have a diameter of 7cm and the car a diameter of 200cm. Both are approaching the observer at a speed of 4m/s.

Schiff and Detweiler (1979) designed an experiment to test if humans are able to judge arrival time from looming stimuli. They presented film sequences that showed an approaching square to human participants. In order to see if arrival time could be judged, the square approached for two seconds and then disappeared. After this, the participants had to press a button at the point they thought the square would have reached them. By making the square disappear before the arrival, the participants were forced to produce estimates of time to contact. This is the kind of information that we need in order to close our hand in time to catch a ball, and the disappearance can be seen as akin to blinking or turning the lights off after the ball has been launched. Schiff and Detweiler found that these judgements on time to contact could be made, although they were consistently underestimated over the range of 2 to 16 seconds that they used. In the experiment they also compared presenting the approaching object with and without a background to increase the amount of distance information. In this way, the authors argued, they could test whether the information about time to contact was available in the approaching object itself or whether it was extracted from computing its distance and speed. They found that adding distance information did not increase the accuracy of the judgements, and so, time to contact could be computed directly from looming. Todd (1981) provided similar evidence using discrimination judgements. He found that when two looming squares were presented in a computer screen, participants were consistently able to determine the one that would reach them first across a range of speeds and sizes. Both studies were interpreted by the authors as suggesting that visual information regarding the arrival time of an object is available for human observers.

*Computing arrival time from looming stimuli*

Lee (1976) and previously Hoyle (1957) showed how the time-to-collision (TTC) of an object moving at a constant speed could be computed directly from the retinal image using the relative expansion rate:

$$\tau = \theta / \theta' \qquad [1.]$$

where θ is the visual angle subtended by the approaching object and θ' is its derivative, looming rate. Lee called this variable tau (τ). This optical variable allows for the precise computation of TTC without requiring any knowledge about the object's speed, size or distance, relying only on the expansion of the image in the retina. Tau is therefore a strong candidate for explaining the ability of human participants to judge TTC in the experiments of Schiff & Detweiler (1979) and Todd (1981).

Further support for the use of tau comes from studies in hitting and catching. Tau is a *first order* approximation of time-to-contact because it is only equal to TTC when the approach velocity remains fixed. If an object accelerates or decelerates, the use of tau for control of interception should be revealed by a systematic error, or bias in timing. Lee (1976) identified acceleration due to gravity as a good test case. If a ball is falling under the effects of gravity, the arrival time as computed by tau would be later than the actual arrival time of the ball (see figure 2). This would lead to late initiation and completion of catching movements. Lee, Young, Reddish, Lough & Clayton (1983) tested this prediction. They dropped balls in free fall from different heights and instructed participants to hit them in the air with full strength. The angle of the knees and the elbows was recorded during each trial. The variability of the timing of limb movements for the balls released from different heights was smaller when plotted against tau than against their actual TTC. This was interpreted as reflecting the coupling of the anticipatory movements to tau. Savelsbergh, Whiting & Bootsma (1991) carried out on an experiment to directly manipulate tau. Instead of presenting a ball that accelerated, they designed a special ball that deflated during its approach. They reasoned that because the visual size of the ball's image reduces during the approach, this would lead tau to increase. When the timing of catches of the deflating ball was compared with two fixed size balls they found that the deflating ball was grasped consistently late. This effect appeared both under a monocular viewing condition and a binocular viewing condition, which led the authors to conclude that tau was used independently of binocular cues.

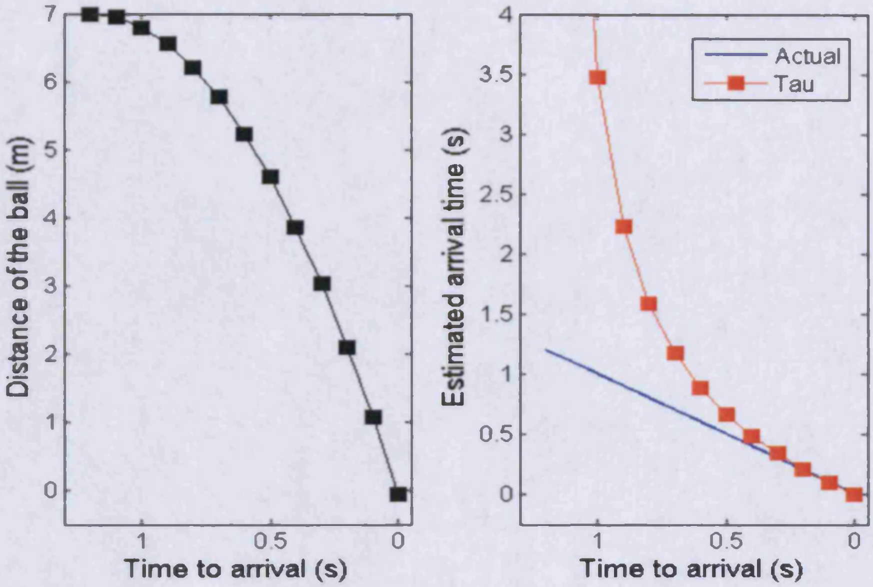


Figure 2. Tau in the case of a free falling ball. This example is for a ball dropped from a height of seven metres from the observer. The left hand side shows the distances from the observer plotted against arrival time. On the right hand side the blue line shows the actual arrival time of the free falling ball, while the red line shows the arrival time estimated by tau.

*Psychophysical evidence for the use of tau*

There is also psychophysical evidence for human sensitivity to tau. As discussed above, Todd (1981) showed that looming stimuli could be discriminated according to their TTC. However, there are several problems with his study. The results were not formalized in terms of sensitivity to TTC. Instead, the amount of correct responses in different conditions was reported. Todd's data suggested that even quite small differences in TTC could be discriminated over chance. Also, the experiment was not designed to rule out the use of other sources of information such as looming rate or the size of the stimuli. On the basis of these limitations, Regan & Hamstra (1993) designed a series of experiments to study TTC discrimination.

Regan & Hamstra (1993) studied human sensitivity to TTC in monocularly presented stimuli. They used two-interval forced-choice procedure, taking special care to examine other variables participants could have used to make their judgements. To do this they played off two variables against one another in a series of experiments. One variable was always TTC and the other variable was changed in each experiment. This second variable was named the *task irrelevant variable* because the participant was instructed to ignore it when judging TTC. In the first experiment the task irrelevant variable was the final projected size of the stimuli, in the second experiment it was the looming rate of the stimuli and in the third experiment it was the change in size of the stimuli during the presentation. The task relevant and the task irrelevant variables were manipulated orthogonally relative of each other. Both variables had eight different values that they could take on, and one of these values was assigned to each variable on each trial. This produced a matrix of 64 different trials, each of them having a unique combination of a TTC value and a value of the task irrelevant variable. The task of the participant is to judge if the stimuli have a TTC shorter or longer than the average of the matrix. Let's assume that TTC increases from the bottom of the matrix towards the top. In such case, the stimuli situated at the lower half of the matrix will have a TTC shorter than the average of the set and those on the upper half a TTC longer than the average of the set. Similarly, the task irrelevant variable increases in magnitude from the left to the right of the matrix. If we give this task to a participant that is sensitive to TTC, we would expect his or her responses to vary across the vertical axis (the axis that contains variations in TTC). The larger the difference between the TTC of the trial and the TTC of the average of the set, the easier it would be for the participant to judge whether the TTC of the trial was below or above the average. Hence, if we add the responses over the vertical axis, this would produce a steep psychometric function. However, if the participant was not sensitive to TTC, the resulting psychometric function would be flat. The same can be done with looming rate, by adding the responses over the horizontal axis. However, it is now expected that the resulting psychometric function should be flat if the participant can judge TTC independently of variations on looming rate.

Regan & Hamstra (1993) found that in this task TTC could be judged independently of variations in final image size, looming rate and change in image size during the presentation. Figure 3 shows the psychometric function for TTC and looming rate. It can be seen that as TTC is increased, the participant judged it less frequently to be shorter than the average of the set. Variations in looming rate, instead, did not have an effect on the judgements. However, the participant was, if instructed to do so, able to judge the same stimuli in terms of their variations in looming rate. This prompted the authors to suggest that the human visual system has independent systems to compute looming rate and the monocular variable tau. Regan & Vincent (1995) replicated these results, expanding them by showing the accuracy of TTC estimation in different parts of the visual field.

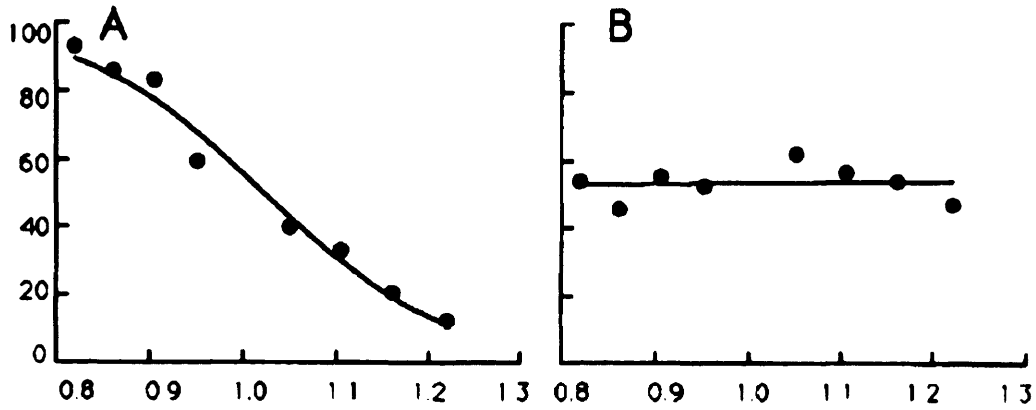


Figure 3. Psychometric functions obtained by Regan and Hamstra (1993) when the results were averaged over variations on TTC (left hand side) and looming rate (right hand side). The units of the horizontal axis are the ratio of the TTC or looming rate of the presented stimulus to the average of the set.

*Problems with the tau literature*

Much of the evidence for the use of tau as a basis for interception has received a notable amount of criticism. For example, the study by Lee et al. (1983) does not provide very good evidence for the use of tau in hitting. In this task the participants had to punch upwards a ball that was falling towards them. The time window during which contact with the ball can be achieved is very large, not requiring any sort of precise timing of the punch. This seems somehow counterintuitive in a study that relies on the subtle timing differences emerging from the use of tau relative to actual TTC. Tresilian (1993) has argued that this leads to a very simple account for the pattern of knee flexion seen in the data: the participants would initiate flexion once the ball is released. Furthermore, Wann (1996) showed that the better convergence of the knee angles for the different release heights is an artefact of the analysis employed.

The study of hitting deflating balls by Savelsbergh et al. (1991) was also subject to strong criticism. They found that the grasp closures to a deflating ball were late, and this was interpreted as evidence for the use of tau. Wann (1996), however, noted that under binocular vision, the deflating balls produced a grasp closure that 5ms later than the control balls. This difference was of 26ms in the monocular condition, suggesting that, contrary to the claim of Savelsbergh et al., binocular vision did give an advantage to the participants. In addition, the deflation of the ball would not only alter the values of tau during the approach but also reduce the looming rate of the ball. This doesn't allow us to rule out the role of looming rate in controlling the grasp for both the constant sized balls and the deflating balls. Also, in Savelsbergh et al's (1991) study the use of a pendulum provides accurate information about arrival time if the period is known (and it can probably be learnt after some trials of practice) and if the release of the ball is detected. Finally, van der Kamp (1999) calculated the quantitative predictions for grasping deflating and inflating balls when compared with constant size balls (see also Wann, 1996). The estimated column in table 1 shows these predictions for the timing of grasp onset, peak opening velocity, moment of hand closure and peak closing velocity. Van der Kamp (1999) used these predictions to test the deflating ball paradigm, but this time replacing the pendulum for a mechanism that allowed the ball to approach at a constant speed. When data was collected in the task, it was found that the effect of the deflating ball was much lower than these predictions. The actual differences in timing can be seen under the observed column in table 1.

| | | Monocular | | Binocular | |
|---|---|---|---|---|---|
| | | Estimated | Observed | Estimated | Observed |
| 1 m/s | Grasp onset | -145ms | -20ms | -126ms | -19ms |
| | Peak opening velocity | -122ms | 13ms | -108ms | -29ms |
| | Hand closure | -102ms | -9ms | -100ms | -14ms |
| | Peak closing velocity | -159ms | -2ms | -119ms | -18ms |
| 2 m/s | Grasp onset | -83ms | -21ms | -79ms | -20ms |
| | Peak opening velocity | -67ms | -16ms | -61ms | -20ms |
| | Hand closure | -46ms | -16ms | -47ms | -12ms |
| | Peak closing velocity | -45ms | -15ms | -44ms | -11ms |

Table 1. Estimated and observed timing differences when grasping a deflating ball for monocular and binocular viewing conditions. Extracted from van der Kamp (1999).

*Alternative cues for interceptive timing*

If participants were not using tau to time action in the studies cited in the last section, what visual variables do we use for catching? Recently Michaels, Zeinstra & Oudejans (2001) replicated the studies of hitting a ball falling under gravity correcting many of the problems of the original studies. Instead of allowing their participants to move and recording the flexion of the knee, they asked sitting participants to hit a free falling ball and recorded the flexion of their elbow with a video camera. As the distance between the ball and the eyes was known at each moment, they were able to monitor the values of different optical variables that could be guiding the response (tau, visual angle and looming rate) during the approach of the ball. This experiment was performed in monocular and binocular viewing conditions (note that tau as defined by Lee (1976) is a monocular variable and so should yield the same predictions in both conditions). The authors also decided to use two different ball sizes. Varying the ball size should not change the timing of the punch if it is performed on basis of tau, but it would if observers are using visual angle or looming rate. They also varied the height from which the ball was released.

The results differed considerably of those found by Lee et al. (1983). First, the flexion of the arm was triggered by looming rate and not tau. Second, participants timed their punches differently depending on ball size. And third, there were differences in the trajectories of the arm between the monocular and binocular viewing conditions, suggesting that binocular vision contributed some additional information when guiding the punch.

Further support for the use of looming rate in interception comes from a hitting task by Caljouw, van der Kamp & Savelsbergh (2004a). Participants were instructed to laterally hit approaching balls to either a near or a far target. The balls had different speeds that were constant during each trial. All the participants relied on looming rate for guiding their movements. The authors were able to identify for each one of the participants a looming rate threshold, which once reached, would initiate the action a fixed period of time afterwards. In the previously mentioned study of Michaels et al. (2001), different thresholds of looming rate were also identified. These allowed the authors to explain the individual differences of the participants in the timing of their hits.

*Using looming rate*

Figure 2 already suggested how looming rate could be employed for catching. Once a threshold is set for a task, the action would unfold for a fixed amount of time after the approaching ball has reached the threshold. This produces two parameters, the looming rate threshold and the time needed for the execution of the action. With constant speed stimuli the predictions are simple. So long as the looming rate threshold is kept constant, looming rate will reach the threshold earlier before arrival for larger objects and for slower objects. When the objects are accelerating, the choice of threshold can lead to different strategies. Let's return to the study of Michaels et al. (2001) with freefalling balls to explore this point further. In figure 4 we plot the looming rate of the balls that they employed in the study against their TTC. We can compare how different strategies arise from choosing different looming rate thresholds to guide extension. If a threshold of 0.01 radians / second is chosen to initiate an action, it will be reached earlier by the balls released close to the observer. This would result in a pattern of flexion onset in which the size of the ball does not have an effect, but the release height does. As the looming rate threshold increases this pattern changes. If a looming rate threshold of 0.04 radian / second is chosen, the differences in onset timing due to the release height reduce, and there is an effect of the size of the ball. Michaels et al. (2001) found both these strategies in their sample of participants.

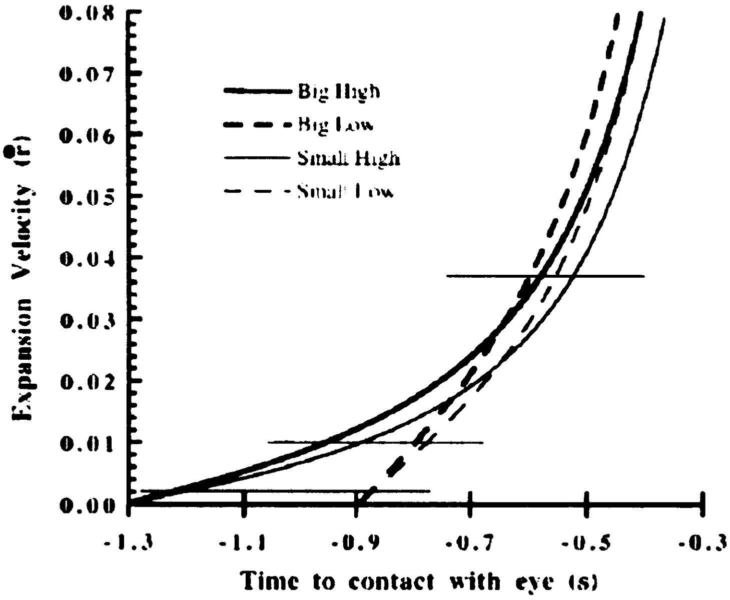


Figure 4. Timing differences in catching a freefalling ball depending on looming rate threshold differences. Note that Michaels et al. refer to looming rate as expansion velocity in this figure. The horizontal lines crossing the curves represent the three different looming rate thresholds. (Extracted from Michaels et al. 2001.)

Some studies in the perception of TTC have also found systematic biases that suggest that correlates of TTC like looming rate could be employed when judging arrival. In a very simple computer based setup, DeLucia (1991) presented participants with a large and a small looming square. When the participants were asked to judge which one of these two squares would reach them first, they tended to choose the large square over the small square. This would lead to conclude that size of the image led the participants to choose one of the squares over the other. Interestingly, the trials could have either a slower or a faster looming rate. Because monocular viewing was used, this is roughly equivalent to the squares having different speeds or starting distances. The bias to choose the large squares was only found in the slow expansion trials, in which the looming rate of the small square was consistently lower than that of the large square. The effect was absent in the fast expansion trials, in which the looming rate of the smaller square surpasses that of the large square towards the end of the presentation. This suggests that their participants relied on looming rate, and not image size, when judging the arrival time of the squares.

Similar results have been found in TTC estimation tasks. DeLucia & Warren (1994) replicated and expanded the task of DeLucia (1991). Their interest was in creating a task that roughly simulates avoiding an obstacle when flying. Participants had to judge arrival to a single square in order to 'jump over it' using a joystick. Even if the approach speed was kept constant for different sized squares, the participants timed their jump earlier for large squares compared with small squares. This might make sense if the larger square needed to be 'jumped' earlier because the simulated vehicle takes some time to rise over it. However, the authors created further conditions in which they changed the square into a rectangle, allowing for manipulating its height and area independently. It was found that, even if the two rectangles had the same height (and so would take the same time to be 'jumped'), the participants would respond earlier for the large rectangles. This suggests that participants were not timing their responses using TTC, but were biased by either the larger size of the stimuli or their increased looming rate.

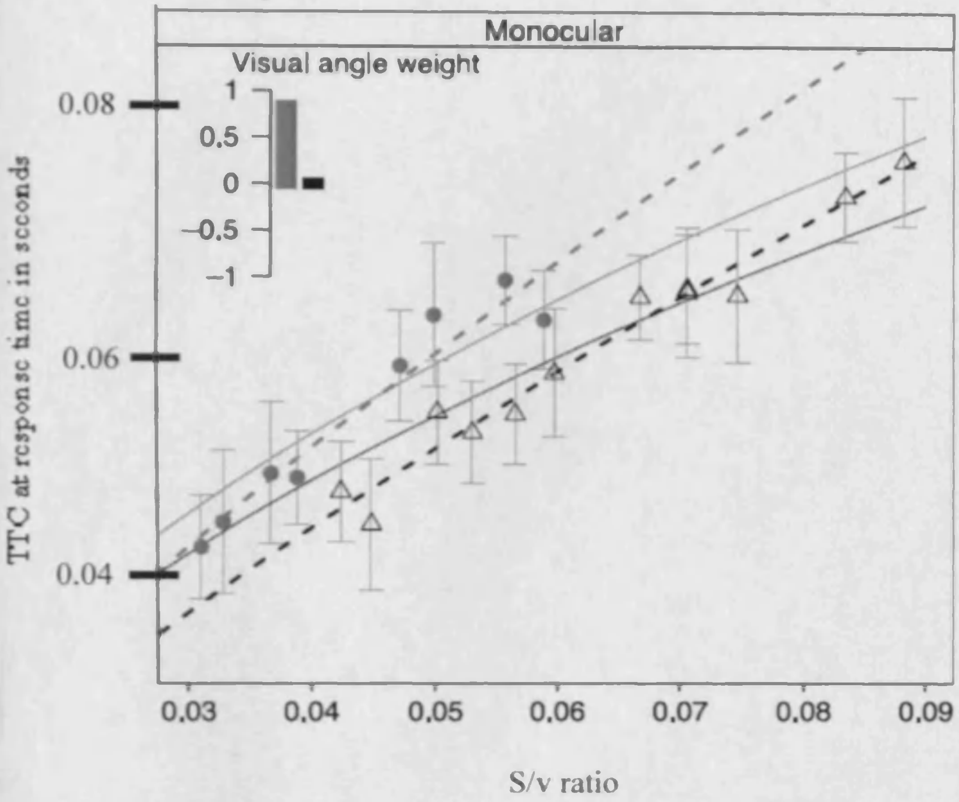


Figure 5. Effect of the ratio of size to velocity on TTC estimates under monocular viewing conditions (extracted from Lopez-Moliner et al., 2007). Red and black lines and datapoints represent two different sets of data. Continuous lines are the best fits of a looming rate strategy and dashed lines the best fits of a looming rate and visual angle combination strategy.

Data from Lopez-Moliner, Field & Wann (2007) also support the hypothesis that looming rate is used for judging TTC. Participants were asked to press a button when they judged that a ball projected on a large screen would have reached them. In some conditions the participants had knowledge of the size of the balls and in others they lacked such knowledge. Lopez-Moliner et al. chose to analyse the effect of the ratio of size to velocity (s/v ratio) on the timing of the responses. At a specific TTC, the looming rate of an approaching object is specified by its s/v ratio, which correlates with looming rate (Sun & Frost, 1998). Figure 5 shows the TTC at response time plotted against the s/v ratio of each trial in the monocular condition of the study by

Lopez-Moliner et al. (2007). In this figure use of TTC predicts a flat horizontal line (no effect of s/v on the response time) and the use of looming rate predicts a power law. It was found that as the s/v ratio was increased, the participants responded earlier. This pattern of performance fitted with the use of looming rate, but not with the use of TTC.

*Binocular cues for the perception of TTC*

Some of the previously cited studies also point towards another shortcoming of the use of tau for explaining catching: the influence of binocular cues. In the study by Lopez-Moliner et al. (2007), arrival time judgements were biased by size and speed of the stimuli in a way best explained by participants relying on looming rate. But this was only the case for monocular conditions: judgements in binocular conditions were unaffected by size or speed variations in the stimuli. Similar reductions in the effect of size and speed variations under binocular vision have been reported in catching studies. For example, in the Michaels et al. (2001) study, the initiation of extension for punching a freefalling ball varied with ball size under monocular viewing conditions, but not under binocular viewing. Under binocular viewing they found that the height from which the ball had been released still had an effect, although ball size didn't. The data by Savelsbergh et al. (1991) also suggests that binocular vision can reduce the late grasp that is associated with catching deflating balls.

Binocular vision introduces new sources of information for the computation of TTC. At least two of these could be used for catching: vergence and disparity. Vergence is shown in the left hand side of figure 6 by the angle $\gamma$. When an observer fixates in an object situated in front of him, both eyes turn inwards to keep the image of the object centred in the retinas. This is called vergence, and the angle of vergence is proportional to the distance from the observer's eyes to the object. The closer the object is, the more the eyes turn inwards. Unfortunately, vergence is a useful cue to distance over short distances, up to approximately two metres (see Howard & Rogers, 2002 for a review). At longer distances, vergence changes slightly over larger changes in the distance of the target. Such slight changes are harder to detect and limit the usefulness of vergence as a cue to compute TTC. The right hand panel of Figure 6 shows two kinds of optical disparity: absolute ($\alpha$) and relative ($\varphi$). Here we define absolute disparity ($\alpha$) as the angle that the object subtends relative to the parallel optic axis, that is, a line drawn perpendicular to the line between the two eyes. Similar to convergence, absolute disparity would increase as an object approaches the observer. However, absolute disparity seems not to produce a percept of motion-in-depth (Regan, Erkelens & Collewijn, 1986). If a reference point at a different disparity is given for the observer, the motion-in-depth percept of the object arises. In these conditions relative disparity ($\varphi$) can be computed. It must be noted that relative disparity doesn't provide information about the distance of the object anymore, but instead, informs the observer about its distance relative to the distance from the observer to the reference point. Interestingly, the main cues for the perception of motion in depth are looming rate and change in disparity over time (Regan and Beverley, 1979; Beverley and Regan, 1979). Both signals are fed into a single channel that computes the amount in which an object is approaching or receding towards the observer.

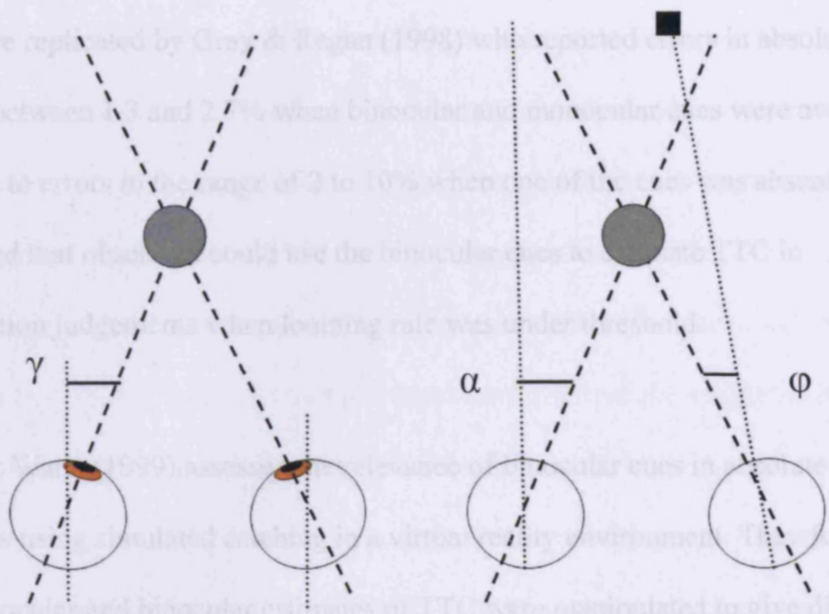


Figure 6. Binocular cues for the computation of TTC. On the left hand side the dashed lines denote the orientation of the eyes and the dotted line the parallel optic axis. Convergence (γ) is defined as the angle between them. The right hand side shows absolute and relative disparity. Absolute disparity (α) is the angle subtended between the line drawn from the object to the retina (dashed line) and the parallel optic axis (dotted line). Relative disparity (φ) is the angle subtended between the line drawn from the object to the retina (dashed line) and the line drawn from a reference point to the retina (dotted line).

Heuer (1993) studied the effects of binocular cues on absolute TTC judgements. In this task, the participants estimated when an approaching simulated stimulus would reach them by producing a key press at the time of arrival. Heuer found that they were more accurate when both looming rate and change in disparity were available. The binocular cues were found to be less reliable than the monocular cues, but if the size of the approaching object was particularly small, the participants tended to rely more on the available binocular cues. Heuer suggested that both change in size and change in vergence contributed to TTC judgements, although his results don’t allow for distinguishing the contribution of vergence from the other binocular cues. These results were replicated by Gray & Regan (1998) who reported errors in absolute TTC estimates between 1.3 and 2.7% when binocular and monocular cues were available (compared to errors in the range of 2 to 10% when one of the cues was absent). They also showed that observers could use the binocular cues to estimate TTC in discrimination judgements when looming rate was under threshold.

Rushton & Wann (1999) assessed the relevance of binocular cues in absolute TTC judgements using simulated catching in a virtual reality environment. They found that when monocular and binocular estimates of TTC were manipulated to give different estimates of arrival time, participants would give more weight to the cue that predicted the earlier arrival. They argued that this weighting was based in summing a TTC estimate computed from monocular cues and a TTC estimate computed from binocular cues in the following manner

$$TTC = {(\theta + \phi)}/{(\theta' + \phi')} \qquad [2.]$$

where $\theta$ is the visual angle of the image, $\theta'$ is looming rate, $\phi$ is relative disparity and $\phi'$ is the rate of change of relative disparity. Notice that this formula is composed of summing together the monocular invariant tau suggested by Lee (1976) and its binocular equivalent suggested by Laurent, Montagne & Durey (1996).

Binocular cues can be manipulated directly in catching experiments by the use of telestereoscopes. The telestereoscope increases the separation between the eyes (IPD), which therefore increases vergence and optical disparity. An object viewed through a telestereoscope will be perceived as being closer than it actually is. This is due to the increased vergence and disparity of increasing the separation between the eyes. In the case of catching, wearing a telestereoscope would lead to biases if the observer is relying on distance, vergence or disparity for timing the catch. However, if tau or a binocular equivalent is being used for timing the grasp, this would result in unbiased catching. In the case of tau, being a monocular variable it will not be affected by the telestereoscope. In the case of a binocular equivalent (such as the suggested by Laurent et al., 1996), although disparity is increased, so will be its rate of change, keeping their ratio constant, its ratio to the rate of change in disparity remains constant. Judge & Bradford (1989) studied the adaptation of catchers to a wearing a telestereoscope. They found that the performance of the catchers dropped significantly when the telestereoscope was placed, but after a few trials the performance returned back to normal. At this point the catchers were adapted to the altered binocular cues produced by the telestereoscope. When they removed the telestereoscope, the catchers showed an aftereffect with their performance dropping again. These findings were further explored by Bennet, Van der Kamp, Savelsbergh & Davids (1999) who recorded the arm movements of catchers under telestereoscopic viewing. They found that catchers wearing a telestereoscope would reach and grasp approaching balls earlier. Also, removing the telestereoscope resulted in an aftereffect (Van der Kamp, Bennet, Savelsbergh & Davids, 1999). These results are incompatible with the sole use of monocular or binocular formulation of tau, as the ratio between absolute cues and their derivatives is not altered by the telestereoscope.

*Motion-in-depth as alternative cue for interceptive timing*

Although the previous section discusses the influence of binocular sources of information in TTC judgements and interception, it is unclear what particular cues are being employed. In following chapters we will propose that motion-in-depth (MID) might be employed in the timing of interceptive actions. Not previously suggested in the literature, MID seems a good candidate to consider as underlying TTC estimation. The main reasons for doing so are the differences between monocular and binocular conditions in interceptive tasks discussed above and the linkage of MID to the detection of motion (Regan & Beverley, 1979; Beverley & Regan, 1979) and estimation of speed (Harris & Watamaniuk, 1995). MID is the sum of looming rate and rate of change in disparity:

$$MID = \theta' + \phi' \quad [3.]$$

As we have previously discussed, looming rate has been linked to the timing of interceptive actions under monocular conditions (DeLucia & Warren, 1994; Michaels et al., 2001; Caljouw et al., 2004a; Caljouw et al., 2004b; Lopez-Moliner et al., 2007). However, under binocular viewing, some of these studies reported that either the biases related to looming rate diminished (Michaels et al., 2001) or disappeared (Lopez-Moliner et al., 2007). This is the pattern of performance predicted by the use of MID. The cases in which use of looming rate have been reported can be seen as a special case of the use of MID, namely, those cases in which binocular viewing was not available. As looming rate is biased by the size and speed of the ball, this leads to characteristic biases in timing. However, the rate of change in disparity is not biased by the object's size. If binocular vision is available, the use of MID would predict a more accurate performance than looming rate alone. Indeed, binocular viewing has been found to reduce the effect of ball size on the timing of catches (Van der Kamp, Savelsbergh & Smeets, 1997). Also, the effect of telestereoscopes on catching (Bennet et al., 1999) is compatible with the use of MID, as the rate of change of disparity will be affected by increasing the separation between the eyes.

*Development and learning in the perception of TTC*

As we discussed at the beginning of this introduction, human infants are from a very early age sensitive to looming stimuli (Yonas et al. 1977). Kayed & Van der Meer (2000, 2007) studied to what visual variable the defensive blinking of infants is timed to. They assessed longitudinally infants at the age of 22, 26 and 30 weeks presenting them looming stimuli corresponding to constant speed and accelerating objects. Their results suggested that before the age of six months a simple strategy explained the timing of the blinks, namely, that these were geared to the visual angle of the stimulus on the screen. After six months, however, the blinking responses were timed to the visual variable tau. Similarly, Hoffman (1994) compared the TTC estimates provided by 5-6 year old, 7-8 year old and 9-10 year old children with adults. For this he used projected footage of an approaching vehicle with different speeds and distances. He found that at an early age the children based their estimates of arrival time on the distance at which they last saw the vehicle. The adults and the older children, however, took its speed in account as well. Although it is unclear from the study what monocular visual variables they might be responding to, the pattern of responses definitively changed with age. However, in Hoffman's (1994) study, there was still a large difference in the performance of the older children and the adults.

Van Hof, Van de Kamp & Savelsbergh (2006) studied the effects of the development of binocular vision in catching. For doing so they tested infants of three to eight months of age under monocular and binocular catching. They found that monocular catching was always biased by the size of the approaching objects, initiating their grasps earlier for larger objects. However, under binocular viewing, this bias was not present in the infants over seven months of age. This suggests that shortly after binocular vision is acquired it is employed for the timing of interceptive actions.

Adults find it hard to catch or hit a fast moving ball but show improvements following training (i.e., Mazyn, Lenoir, Montagne & Savelsbergh, 2004). One way they could do this is to learn to use their cue of choice in a better way, for instance by improving signal-to-noise ratio. Such increased sensitivity to previously used cues have been shown in tasks such as judging the offset of vernier stimuli (Fahle & Edelman, 1993) or estimating the direction of motion of a cloud of dots (Ball & Sekuler, 1987). However, the developmental studies above suggest an alternative mechanism, namely that observers switch from using a cue that is partially correlated with TTC like looming rate, to using a cue like tau that guarantees a higher degree of success in the task. This question was addressed in a series of experiments by Jacobs & Michaels (2006) on lateral interception. Balls released in pendulums were used for all experiments, and these would approach the participant and pass his head by distances between 20 and 90cm to the left or right. Ball size, but not ball speed was also varied randomly from trial to trial. In the first experiment the participants were asked to judge how far these balls passed from them, and in the following two to intercept them. It was found that the judgements of passing distance would improve with training, but most participants would remain biased by the size of the ball in the monocular conditions. The two catching experiments found similar results. First, the number of successful catches increased with training for both monocular and binocular conditions. Second, stronger biases due to ball size were found in the monocular condition than in the binocular condition. And finally, these biases reduced with practice. Overall these results suggest that practice can change the strategy used for catching a ball, although such changes of strategy are less remarkable than increases in performance due to improvements in the use of the current strategy.

Another experiment has also addressed changes in strategy due to learning in the case of interceptive timing. Smith, Flach, Dittman & Stanard (2001) designed a computer based experiment in which the participants had to release a pendulum some time in advance of the arrival of an approaching ball in order to deflect it from its trajectory. The task was presented monocularly and allowed for assessing what monocular variable the participants could be basing their responses. Across several experiments, in some of which ball size was varied from trial to trial, and some in which ball speed was varied from trial to trial, similar results were found. Namely, that with practice the timing of the pendulum release approached more the response predicted by the use of a tau strategy. That is, during the first sessions, participants would respond earlier relative to the actual arrival time for the larger or the slower balls, but these biases would decrease with practice. Smith et al. suggested that participants were learning to combine visual angle and looming rate according to the task constraints.

*Summary*

Humans and other animals are sensitive to looming stimuli, that is, to the expansion of an image in the retina (Schiff et al., 1962; Yonas et al., 1977). Although looming signals immediate collision with an object, it doesn't give a time estimate of when such collision would take place. None the less, human participants have been shown to be able to make estimates of time to contact from looming stimuli (Schiff & Detweiler, 1979; Todd, 1981). Such estimates of TTC are necessary for doing successful interception in tasks like grasping or hitting a ball, as both tasks require very precise timing of an action. In addition to looming, binocular vision has been shown to also provide information that increases the accuracy of TTC estimates (Heuer, 1993; Gray & Regan, 1998; Rushton & Wann, 1999). These results have led to the proposal of a number of monocular and binocular cues to TTC that could explain how humans time their interceptions (Lee, 1976; Laurent et al., 1996).

However, the evidence for the use of these cues to TTC is disputed (Wann, 1996) and it has been suggested that interceptive timing might be instead being performed in basis of simpler correlates of the approach of an object such as looming rate (DeLucia, 1991; Michaels et al., 2001; Lopez-Moliner et al., 2007) or motion-in-depth (Beverley & Regan, 1979; Regan & Beverley, 1979). The use of these correlates leads to a number of biases related to the size and speed of the approaching object. Such biases have been observed in both relative discrimination tasks (DeLucia, 1991) and absolute estimation tasks (Lopez-Moliner et al., 2007), although they tend to be smaller if binocular vision is available.

It is unclear how the extremely precise timing shown in sports can be achieved if the participant relies on these previously mentioned correlates. However, biases in the estimation of TTC decrease with age (Hoffman, 1994; Kayed & Van der Meer, 2000, 2007). This has been suggested to be the product of a change in strategy, where during development the observer switches from employing looming rate or image size to relying on a more accurate cue to TTC. Experience in interceptive tasks has also been shown to increase the accuracy of TTC estimates (Cavallo & Laurent, 1988). This has led some authors to suggest that learning might contribute to TTC perception by producing changes in strategy similar to those found during development (Smith et al., 2001).

*Outline of the current thesis*

The current thesis assesses learning in the perception of TTC under binocular vision. The previously presented research suggests that learning takes place when catching with binocular vision. Little is known about learning in the perception of TTC in perceptual judgements, nor whether such changes underlie the increases in performance in catching tasks. A number of topics are addressed. First, what visual variables are employed in psychophysical judgements of TTC by naïve and experienced participants. In laboratory settings it has been found that human participants can successfully discriminate trials in basis of variations in TTC independently of variations in correlated visual variables (Regan & Hamstra, 1993), but this research relies on expert participants. Our working hypothesis, based on the previous literature, is that inexperienced participants discriminate TTC in basis of variations in looming rate, and with training, learn to base their discriminations in the task relevant variable. Similar results were found by Smith et al. (2001) in simulated hitting tasks, but it's not known if such changes of strategy also hold for discrimination judgements. Second, it has been shown that there are changes in catching (Jacobs & Michaels, 2006) and in simulated hitting tasks (Smith et al., 2001) with training. It remains unclear if these are changes are due to changes in how TTC is perceived. In the following chapters we will address the relationship between the discrimination of TTC and absolute TTC judgements. We assume that discrimination judgements are purely perceptual, while the absolute TTC judgements more closely resemble simulated hitting tasks. Third, we were interested in whether the perception of TTC is related with success in interception. It is an assumption of much of the previous literature that TTC has to be computed in order to successfully catch or hit an approaching ball, although many of the correlates of arrival (like looming rate) can achieve a *good enough* outcome in certain tasks.

In Chapter 1 we study the effects of training on TTC discrimination judgements. On each trial, two approaching balls were shown sequentially and participants had to choose which one was closer to arrival at the end of the presentation. We designed the experiment for having a natural conflict between looming rate and TTC in 25% of the trials, as these were the main variables that participants had been suggested to be responding. The effects of feedback were assessed by alternating blocks with and without feedback. Although learning in catching and collision prediction has been reported, we didn't find an increase in the use of TTC with training. Moreover, we found that the variables that best explained the participants' performance were looming rate and motion-in-depth.

In Chapter 2 we address learning in absolute TTC judgements. We asked participants to estimate the arrival of a ball that disappeared shortly before arrival. We found that the variable and constant error of the estimates decreased with training. Again, response timing biases related with the approaching balls' size and speed lead us to conclude that TTC was not used in the task, and that instead the participants relied on looming rate or a correlate like motion-in-depth.

In Chapter 3 we studied the effects of feedback on the TTC estimates. In an absolute TTC task the feedback was offset relative to the actual arrival time, so it gave temporally biased information about the arrival time to the participants. We found that the participants' responses were quickly biased in the direction signalled by the feedback. This suggests that the participants were aware of the feedback and employing it for correcting the timing of their responses.

Chapter 4 explores whether the learning that takes place in absolute TTC tasks and simulated hitting tasks is related with learning in the perception of TTC. In a series of experiments we measured the participants' sensitivity to TTC and motion-in-depth before and after they were trained on an absolute TTC task. Although variable error reduced in the absolute TTC task, these did not lead to changes in sensitivity.

In Chapter 5 we relate perception of TTC with skill in an unconstrained ball hitting task. We found that those participants that relied on TTC as measured by a discrimination task and those who were highly precise in an absolute TTC task hit more balls than those that were not. This suggests that the accurate perception of TTC gives an advantage on interceptive tasks.

# Chapter 1 – Effects of training on the discrimination of TTC

## Abstract

In order to successfully catch a ball, an observer needs information about its arrival time in order to intercept it. However, it is unclear what visual cues human observers rely on to do this. In the case of monocularly presented stimuli, some studies suggest that the variable tau, that specifies a veridical TTC for an object approaching at a constant speed, can be accessed (Todd, 1981; Regan & Hamstra, 1993; Regan & Vincent, 1995). However, biases that point towards the reliance on simpler correlates of the approach of the object as estimates of TTC have been found in studies on the absolute estimation of TTC (Smith et al., 2001; Lopez-Moliner et al., 2007) and in some studies on the perceptual discrimination of TTC (DeLucia, 1991; DeLucia, 2005).

One of the differences between studies that show evidence for the use of TTC and those that show evidence for the use of simpler correlates is the level of experience of the participants. Expertise and learning have been shown to have an effect on the accuracy of estimation of TTC (Cavallo & Laurent, 1988; Smith et al., 2001). However, little is known about the effect of learning in relative discrimination tasks, such as those of Regan & Hamstra (1993) and DeLucia (1991).

In this chapter we present an experiment to study the effect of training on a time-to-contact discrimination task. We anticipated that participants would initially use looming rate, a simple correlate of TTC, to perform the task but that with training,

they would switch to use information more accurately specifying TTC. Contrary to our expectations, however, participants didn't increase their use of TTC relative to looming rate during the successive sessions of training. Instead, the responses of the participants suggest that they relied on either looming rate or motion-in-depth at all times.

## Introduction

Information for computing the time-to-contact (TTC) of an object approaching an observer at a constant speed is potentially available from its optical expansion (Lee, 1976). It has also been shown, that under binocular vision, TTC information is also available in the rate of change of binocular disparity (Heuer, 1993; Laurent et al., 1996; Gray & Regan, 1998; Rushton & Wann, 1999). However, the availability of these cues does not grant that they are used by the observer. Instead, different variables that correlate with TTC might be used for interception. For example, the looming rate of the object or the rate of change in binocular disparity both increase as the object approaches. Although relying on simpler correlates such as these produces biases when estimating TTC, under some task constraints they can be good enough for guiding an action. There is some evidence suggesting that looming rate can guide the initiation and execution of the action of intercepting a ball (Michaels et al., 2001; Caljouw et al., 2004b).

When it comes to the issue of whether TTC can be perceptually estimated, the evidence is conflicting. In the General Introduction we discussed some studies that investigated this issue. Todd (1981) presented a number of participants with pairs of approaching squares displayed on a computer screen. He found that these could be discriminated in terms of their difference in TTC, suggesting that the monocular variable tau (Lee, 1976) was available and used. However, DeLucia (1991) found that if a large approaching square and a small approaching square were presented at the same time, and participants had to judge which one would arrive earlier, they were consistently biased in choosing the larger square. The participants seemed to be biased by either the absolute size of the approaching object or its looming rate. This led them to ignore information about TTC.

As discussed in more detail in the General Introduction, Regan & Hamstra (1993) followed and expanded these results by a series of discrimination experiments. In each of these experiments, they controlled for one correlate of TTC that the participant might rely on. This was achieved by manipulating it orthogonally to TTC. This allowed them to assess whether the participant could tell TTC independently of variations in the other variable. The variables they chose to control were final projected image size, looming rate and change in image size during the presentation. It was found that TTC could be judged independently of variations in these variables. The authors concluded that the human visual system is sensitive to the ratio tau that specifies TTC from image expansion.

There is one main difference between the studies of DeLucia (1991) and Regan & Hamstra (1993), namely, the amount of experience of the observers. DeLucia employed naïve participants that did not receive feedback when performing the task, while Regan & Hamstra employed a single participant (one of the authors) that had extensive practice with the task and received feedback of his performance. The difference on their results might be due to the learning taking place when the participant receives feedback on the TTC of the sequences. Indeed, the task of Regan & Hamstra (1993) requires the participant to practice. This is because they used an implicit-standard method, where a single interval is presented on each trial and participants judge whether its TTC is shorter or longer than the average of the set (a method they adapted from McKee, 1981).

Expertise in the task has also been found to have an effect on certain TTC judgements (see also the following chapter). Cavallo & Laurent (1988) compared TTC judgements of experienced and inexperienced drivers. The drivers were placed in the passenger seat of a car that approached a target. A certain distance before reaching the target, the vision of the participant would be occluded and they had to press a button when they estimated they had reached the target. The authors found that the experienced drivers were more accurate at this task. Smith et al., (2001) designed a collision prediction task to assess learning. Participants had to release a simulated pendulum in a computer based task a certain amount of time before the arrival of a ball in order to hit it. They found that during the first sessions of training participants would rely on looming rate, but with further training their performance approached that predicted by TTC. Jacobs & Michaels (2006) found some learning in lateral interception tasks. The timing of catches by the participants improved from the earlier trials to the later trials. The authors were able to trace these improvements back to perceptual variables guiding the action. However, note that the experiments by Smith et al., (2001) and Jacobs & Michaels (2006) require the precise timing of actions. The motor demands made by these tasks make it difficult to determine which visual variables are used when hitting and catching. On the other hand, the studies of Todd

(1981), DeLucia (1991) and Regan & Hamstra (1993) have very little, or no, motor demands.

In this chapter we address whether training can increase the use of TTC in perceptual discrimination tasks. As discussed previously, learning is a tentative explanation for the differences between the studies of DeLucia (1991) and Regan & Hamstra (1993). We tried to follow the methods used by Regan & Hamstra as closely as possible but with the following important change. Using an implicit standard to assess learning would confound the acquisition of the average of the set with learning about TTC. To avoid this problem, we used a two-interval task in which the standard was presented explicitly. Each interval showed an approaching ball and participants had to judge which one showed the shorter TTC. This method allowed participants to compare two TTCs more directly. It also meant that performance could be assessed from the first session of data collected. This is especially important if learning is rapid (see Chapter 3).

In order to assess which cue was being used, we designed our experiment to tease apart responses based on TTC and responses based in looming rate. Looming rate was chosen because it has been pointed out numerous times as a simple correlate to TTC that might be used in these tasks (DeLucia, 1991; Regan & Hamstra, 1993; Tresilian, 1995; Michaels et al., 2001; Lopez-Moliner et al., 2007). TTC and looming rate predicted the same responses in 75% of the trials, but in the remaining 25% of trials they predicted opposite responses. These 'catch trials' were called conflicting trials and can be seen in the highlighted quadrants in figure 1. In conflicting trials, if participants were relying on TTC they would choose the interval with the lowest TTC.

Conversely, if they relied on looming rate, the other interval would be chosen. We also tracked several other variables, such as change in size during the presentation, final projected size of the stimulus, rate of change in disparity and motion-in-depth during the experiment. Note that rate of change in disparity and motion-in-depth are binocular variables (further discussed in the General Introduction), and they can change performance in discrimination tasks (Gray & Regan, 1998; DeLucia, 2005).

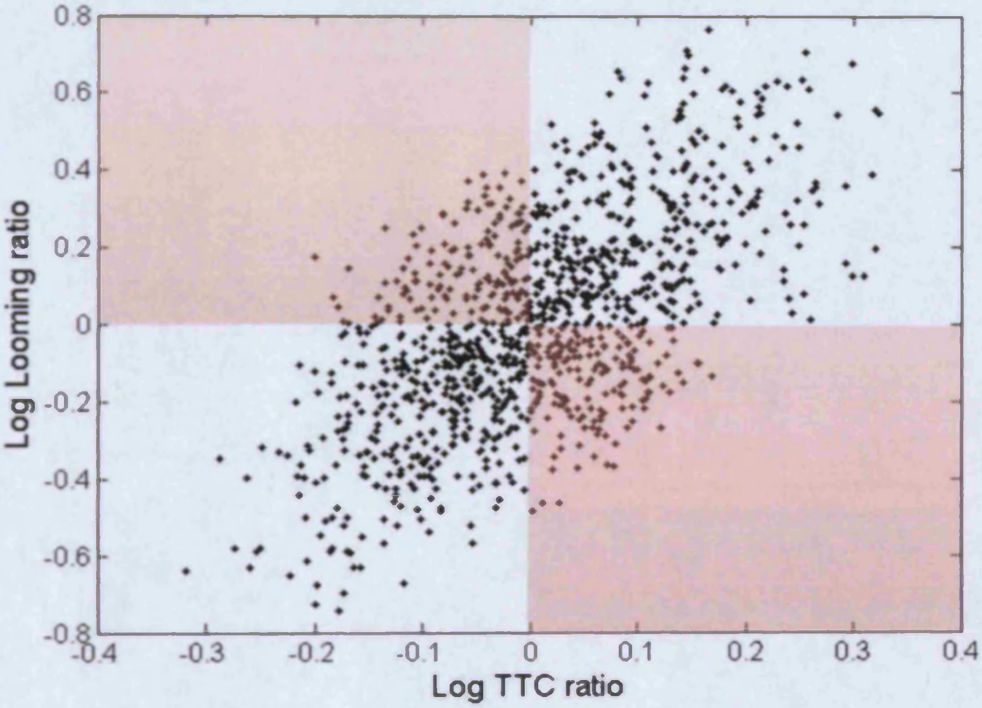


Figure 1. Trial distributions in the experiment for one participant. On the vertical axis we have the log ratio between the looming rate of the 1st and 2nd intervals, and on the horizontal axis the log ratio between the TTC of the 1st and 2nd intervals. The quadrants with the conflict trials are highlighted.

We predicted that inexperienced participants would rely on the looming rate of the stimuli in order to discriminate between them, as was the case in the study of DeLucia (1991). With training in the task, however, we expected their use of TTC to increase and the use of looming rate decrease, leading to a pattern of performance resembling that of Regan & Hamstra (1993). This would suggest that perceptual learning takes place in TTC tasks, allowing the participant to focus on the more relevant variable for the task.

## Methods

### *Participants*

5 participants between 25 and 40 years of age, recruited among the graduate students of the School of Psychology, Cardiff University. All of normal or corrected-to-normal vision. All participated in the study voluntarily and were naïve to the hypothesis of the study.

### *Apparatus*

The stimuli were presented in a 22' monitor (40.5cm x 27cm) with covered with a red filter. The experiment was programmed in Borland Delphi 7 and the stimuli were rendered in OpenGL 2.0, both for the 3D stimuli and the 2D elements (such as the fixation point). The same software was employed in the following chapters. The monitor was situated at 75cm from the observer. The resolution of the display was 1024 x 768 pixels, and the frame rate was 100Hz. The room in which the experiment was carried was dark and only the screen was visible to the observer. LCD shutter goggles were used to provide stereo vision to the participants. The shutter goggles were refreshed at a frequency of 50Hz for each eye. The red filter on the monitor reduced the crosstalk between the eyes during the experiment.

*Stimuli*

In all the trials we used as stimulus a computer-rendered wire-mesh sphere. The sphere was composed of 14 lines across its z axis, and 14 sections across the z axis (see figure 2). The orientation of the sphere was randomized on each trial, as was its speed of rotation, which was between 0 and 300 degrees per second. In piloting we found this stimulus to give a good sensation of a ball moving in depth.

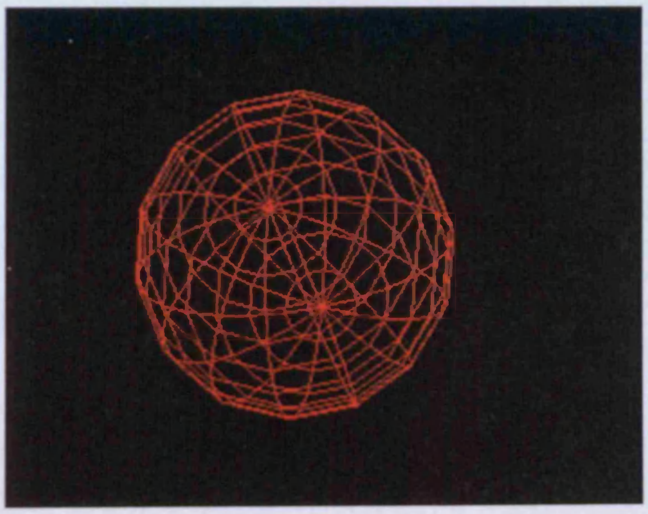

Figure 2. Mesh sphere used as stimulus in the experiment. It has 14 lines across it, similar to lines showing longitude, and 14 sections, as latitude.

The size, speed and distance of the approaching spheres presented on each trial was randomized within the following ranges. The size varied from a radius of 1.6 to 4.8cm (a difference of 300%) the speed varied between 3.6 and 4.4m/s (a difference of 22.2%) and the initial distance between 3.6 and 4.4m (again a difference of 22.2%). The duration of each presentation was varied between 360 and 540ms, in this case being the longest presentation 50% longer than the shortest.

The average TTC of the stimuli was of 540ms, ranging between 278 and 862ms. As the TTC is a result of the speed, distance and duration of the stimuli, its distribution is not linear, but Gaussian. We normalize this distribution in the analysis by transforming it by its logarithm. This range is shorter than that employed by Regan and Hamstra (1993), who used an average of two seconds. Our choice of a shorter stimulus range brings the TTC closer to the needed for actions such as hitting or catching. At times over about two or three seconds, human ability to produce predictive actions breaks down (Mates, Muller, Radil & Poppel, 1994). Similarly, TTC estimates of very long stimuli also are very inaccurate (Schiff & Detweiler, 1979).

During each trial, there was also a background of four objects present. Each of them was placed in one of the quadrants of the screen (bottom left, top left, top right and bottom right). They were identical to the approaching sphere, except they were larger (radius of 8cm) and they had 18 lines and sections. They did not move or rotate. The distance of each of them was randomly assigned on each trial, between three and five metres. Also, their position was randomised on each trial. Each of them had a position of 0.63m towards their corresponding corner of the screen, and then a randomly added displacement of +/- 0.45m on the vertical and horizontal axis. This parameter range was fitted in piloting for them not to be drawn outside the screen or be occluded by the approaching sphere.

Stereo for the participants was provided by synchronizing the shutter goggles to the presentation of the stimuli. For each refresh of the shutter goggles, the scene on the display was rendered from the viewpoint of the corresponding eye. The interpupillary distance of the participants was used for this correction of the viewpoint. At the refresh rate that we used, this technique led to the participants fusing the images of both eyes into a single scene in stereo.

*Procedure and design*

Each observer took part in six sessions, lasting each for between 15 and 20 minutes. A session consisted of six blocks of 30 trials. Blocks with and without feedback were presented. The first block was presented without feedback and it was followed by a block with feedback. Blocks with and without feedback alternated until the end of the session. Our initial interest was to assess whether performance increased more in the blocks that included feedback in them. In each trial two different intervals of an approaching sphere were presented. After each trial the observer had to judge which of the two intervals had the shortest TTC. Before the presentation of the second interval there was a delay. This delay was equal to the largest possible TTC (862ms) from the end of the presentation of the first interval. An extra delay randomly chosen in the range of 100 to 250ms was added to this.

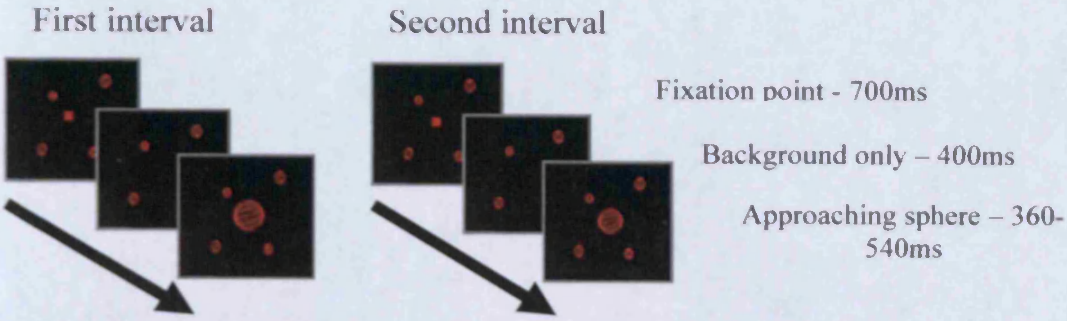


Figure 3. Schematic representation of a trial. Each of the two intervals consists of the presentation of a fixation point, an empty background and then the approach of the sphere.

Figure 3 shows two intervals that could make a trial. First, the background generated for the trial would appear with a fixation point. This fixation point was generated at a randomly chosen distance between three and five metres on each interval, and it stayed on the screen for 700ms. During piloting we found that presentation of a fixation point allowed participants to converge on the range of distances where the approaching ball would later be presented, and so reduced diplopia. After the presentation of the fixation point, the background would remain for another 400ms before the approach of the ball started. At the end of the approach, both the ball and the background disappeared.

The participants had unlimited time to respond on each trial. They were instructed to respond after each trial by using the left mouse button to indicate that the first interval had a shorter TTC and the right mouse button to indicate that the second interval had a shorter TTC. During the blocks with feedback, tones would inform the participant about whether their response was correct or not.

*Analysis*

Discrimination thresholds were calculated session by session by plotting responses as a function of either TTC or looming rate. We also compared these thresholds with those obtained from change in disparity and MID (see later). To assess overall performance, thresholds for a chosen variable were based on all trials regardless of the degree of conflict. To investigate whether observers switched from looming rate to TTC, a separate set of thresholds were calculated based on conflicting trials only.

As the parameters of each trial were unique, the following procedure was used to fit psychometric functions. First, the ratio between the first and second trial for the chosen variable was computed. All the data was then sorted by this ratio and logged. The logarithm transformation normalized the distribution of the TTC of the sample. Figure 4 shows an example based on TTC. A cumulative Gaussian was fit to the data using probit, as shown by the solid curve. The figure also shows the result of a second style of analysis in which the responses are first 'binned' to obtain a more typical measure of percent correct (red points). The probit curve closely follows these points. Both procedures therefore provide similar fits to the data. For simplicity, we decided to fit the curves without binning the data, partly because this avoids making decisions about the size of the bins.

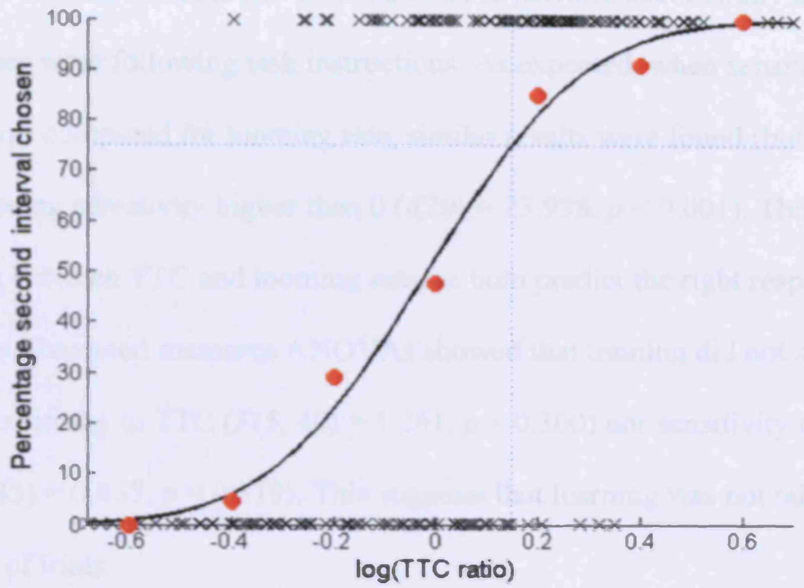


Figure 4. The crosses represent individual responses of a single observer during a session. The fitted curve is the probit function presented in the previous figure. The red circles are the averaged responses for bins with a size of 0.2 log units.

Threshold was defined as the difference between the log(TTC) corresponding to the 75% and 50% points. We transformed these into sensitivities (1/threshold) for convenience of presentation. All these thresholds are provided in the Appendix.

## Results

We started by analysing the performance of the participants across all trials, regardless of the amount of conflict between looming rate and TTC. This allows us to measure overall performance in the task across sessions, although it doesn't inform us about which variable is being used. We found that the participants were able to successfully discriminate between stimuli (top left in figure 5), being sensitivity higher than 0 ($t(29) = 18.339$, $p < 0.001$). This suggests that participants were

The analysis of conflicting trials also shows little improvement to sensitivity over time. In repeated measures ANOVAs the interactions of session x condition (all trials vs conflicting trials) were not significant for TTC ($F(5, 40) = 0.604, p = 0.697$) and for looming rate ($F(5, 35) = 0.594, p = 0.705$). This suggests that learning was not taking place in the sets of conflicting trials. It must be noted that the larger variability in the performance in the conflicting trials is partly due to the smaller sample size (a fourth of the trials over which the other sensitivities were computed).

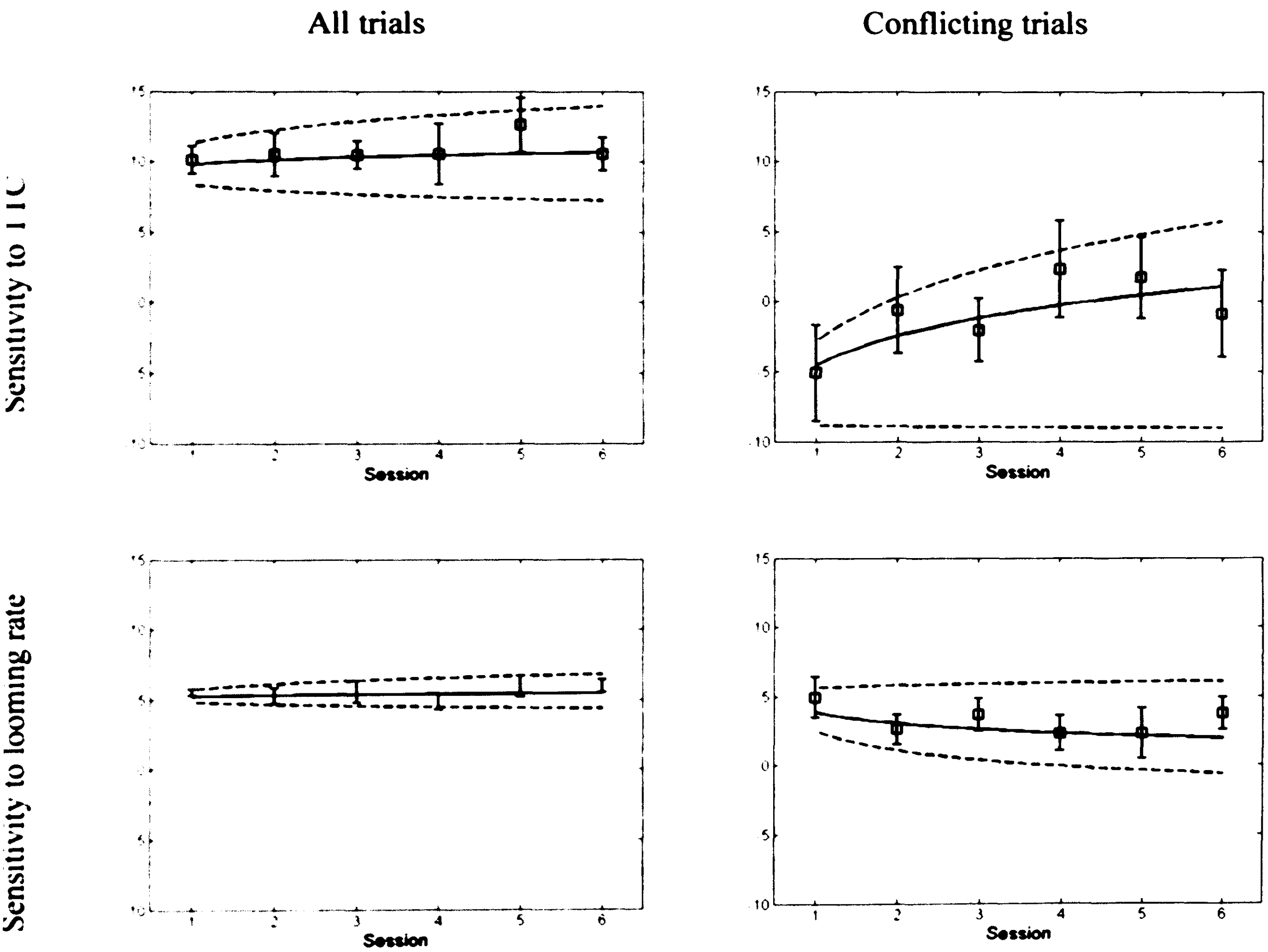


Figure 5. Sensitivity to TTC and looming rate averaged across participants. Top row shows sensitivity to TTC and bottom row sensitivity to looming rate. Left column shows the fits for all the trials and right column for only the conflicting trials. In each of the figures the solid line represents the best fit of a power law. Dashed lines show 95% confidence intervals computed by a bootstrap procedure.

Although the experiment was designed for differentiating between TTC and looming rate, the participants could have based their responses in other correlates of TTC. Therefore we investigated a number of other candidate variables, such as change in visual angle during the presentation, rate of change in disparity, change in disparity during the presentation and MID. We found that of all these variables, motion-in-depth (MID) gave the best fit to the conflicting trials. Although it is correlated with looming rate, MID has a binocular component that makes judgements based on it less influenced by variations in the size of the object (see the section on motion-in-depth in the General Introduction). Figure 6 compares sensitivity to MID in all the trials (left hand side) and sensitivity to MID in the conflicting trials (right hand side). Sensitivity to MID was higher than 0 for all the trials ($t(29) = 22.791, p < 0.001$) and also for the conflicting trials ($t(29) = 7.856, p < 0.001$). There was no difference in the sensitivity to MID between the two groups of trials ($t(58) = 0.115, p = 0.909$). This lack of a difference between all the trials and the conflicting trials is to be expected if MID was employed to respond in the task. As with TTC and looming rate, sensitivity to MID did not change with training ($F(5, 40) = 0.805, p = 0.553$).

Figure 7 shows results for the conflicting trials for individual observers collapsed over all the sessions. For TTC, sensitivities are close to zero or negative, so none appear to be using this cue. Conversely, all participants appear to be using MID.

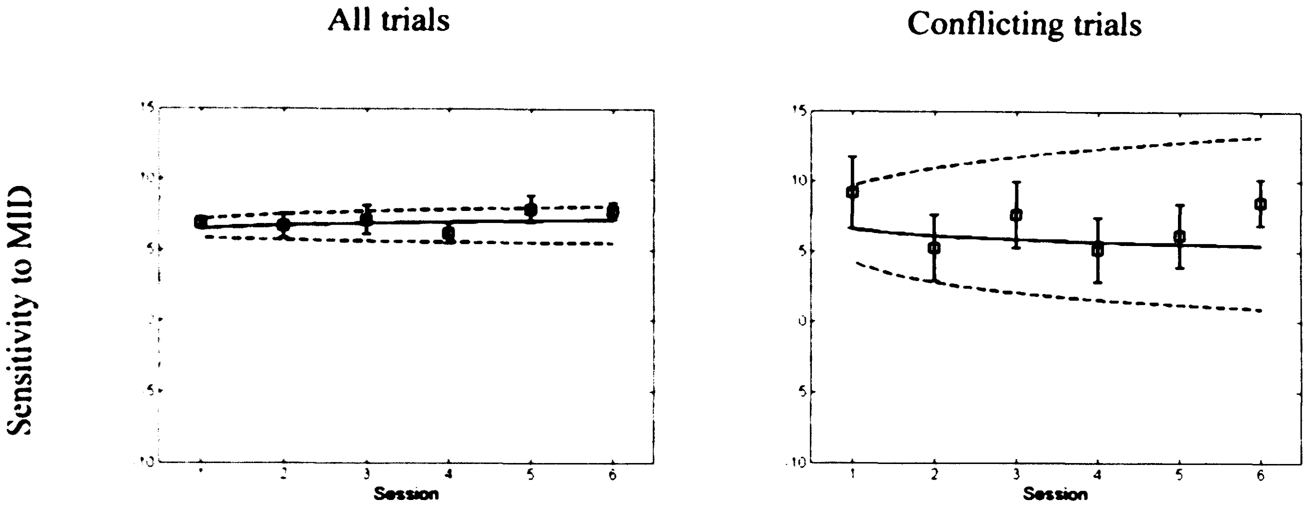


Figure 6. Sensitivity to motion-in-depth averaged across participants. The solid line represents the best fit of a power law. Dashed lines show 95% confidence intervals computed by a bootstrap procedure.

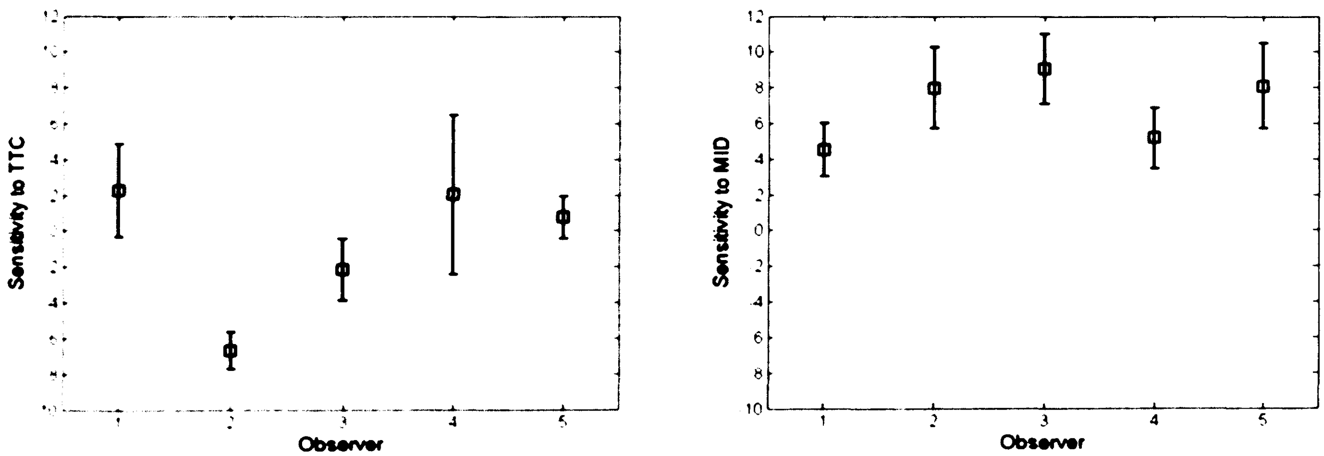


Figure 7. On the left hand side, sensitivity to TTC in the conflicting trials. On the right hand side, sensitivity to MID in the conflicting trials. The error bars show the standard error between sessions for each of the participants.

## Discussion

Although previous evidence for learning has been found in collision prediction (Smith et al., 2001) and catching tasks (Jacobs & Michaels, 2006), we didn't find evidence for learning in a TTC discrimination task. It might be that the ability to discriminate TTC is less prone to change in a discrimination task that involves passive judgements than in a task that involves the participant having to perform an action. The results suggested that participants based their responses on the difference in motion-in-depth between the pairs of presented stimuli instead of in differences on TTC. It has been previously suggested that in TTC discrimination tasks, participants might rely on any variables that differ considerably between the stimuli (see Tresilian, 1995). This could be due to their inability to judge TTC in the task, leading them to rely instead on correlates.

*Use of motion-in-depth*

We did not find evidence of any participant using TTC either at the beginning or at the end of their training. All participants appeared to be using MID. There was no difference in sensitivity to MID when it was computed from all the trials and from the conflicting trials. This suggests that this variable explains the performance of the participants in both sets of data. Taken together, these results suggest that instead of using time-to-contact to discriminate between the stimuli, as analysing all the trials might suggest, the participants were basing their responses in variations in the amount of motion-in-depth between the stimuli.

Why would participants use MID to discriminate between the stimuli? The perception of MID is based on a monocular cue (looming rate) and a binocular cue (change in binocular disparity) that together create the sensation of an object approaching or receding in depth (Regan & Beverley, 1979; Beverley & Regan, 1979). The sum of these two cues can be linked not only to the detection of MID, but also to the perceived speed of an object (Harris & Watamaniuk, 1995). Previous research has pointed to looming rate as being a simple alternative for timing an action when a ball needs to be caught under monocular viewing. Under certain circumstances (limited ranges of speeds or knowledge of object size), looming rate can be good enough to produce a successful catch. The onset of arm extension when punching a falling ball has been found to be triggered by looming rate (Michaels et al., 2001). One study also found looming rate could account for the timing of the grasp when catching a ball (Caljouw et al., 2004b). Under monocular vision, looming rate is the only available cue to MID, but under binocular vision change in binocular disparity is also available. It could be the case that in those experiments that find the timing of a catch to be linked to looming rate, the participants are actually employing MID, which leads to a similar pattern of results but with a reduced effects of ball speed and ball size when change in disparity is also available. It must be noted that although change in disparity is not affected by the size of the ball, an effect of ball size will still remain if MID is computed as a linear sum of these two cues. When catching under monocular and binocular viewing has been compared, reduced effects of ball size (Van der Kamp, Savelsbergh & Smeets, 1997) have been found in the binocular conditions though the effect still remains.

*Learning in perceptual discrimination and learning in action*

As pointed out earlier, we did not find effects of learning, contrary to previous reports by Smith et al. (2001) and Jacobs & Michaels (2006). One possible reason is that these two studies employed tasks in which success depended on the participants performing precisely timed motor actions. In our experiment, participants made perceptual judgements only. This point could be taken to mean that the perceptual discrimination of TTC is completely unrelated from the action of catching or hitting a ball, an issue we explore further in Chapter 5. More important in the current context are the potentially different roles feedback plays in perceptual judgements and actions. Gray, Regan, Castaneda & Sieffert (2006) directly compared discrimination judgements and catching actions for simulated objects moving in depth. The perceptual judgements consisted of judging whether a simulated approaching object would have passed to the right or left of a shortly illuminated LED. For the actions the participants had to simulate catching this object. In both tasks participants had a tendency to judge the object as passing further away from them than where it actually did. When feedback on the participants' outcome was given on each trial, this bias disappeared for the actions, but not for the judgements. This suggests that there are differences in how effective training is for both judgements and actions, and in our case the nature of the task might have hindered the ability of the participants to improving their TTC estimates. For example, suppose that two of our stimuli have a TTC of 520ms and 580ms but also vary on speed, size and presentation duration. Feedback only tells the participant whether they chose the stimuli with the shorter TTC or not, but gives no clue to the size of the difference and so the degree of their failure. In tasks that demand precisely timed actions, participants are more likely to gain some knowledge about how far off they were. Information on the actual TTC of the stimuli was not available to our participants. If the participants' percept of TTC is initially biased in simulated TTC tasks, part of the learning that takes part in the task might be due to the participants recalibrating to match their action to the TTC given by the feedback. In the case of relative TTC discrimination tasks, such calibration might not take place, as knowledge of the actual arrival time is not necessary for responding in the task. Conversely, aiming for the right timing is the main purpose of the response in absolute TTC tasks and catching tasks.

The following chapter therefore investigates learning in an absolute TTC estimation. The notable difference of absolute TTC estimation is that it has a temporal component. The task itself requires the participant to time an action to their estimate. Also, feedback in this task is of absolute nature, providing information about the timing of the action relative to the timing signalled by the feedback. This seems richer information than whether the response was correct or not.

# Chapter 2 – Learning absolute TTC timing


## Abstract

In this chapter we investigate the effects of training on an absolute TTC task. This task differs in a number of ways from the relative TTC discrimination task presented in the previous chapter. First, estimates about time are required for performing in the task. This differs from the discrimination task in which any variations between the two presented stimuli could be used to differentiate between them. Second, the feedback that participants receive is more informative, as it gives an actual estimate of the arrival time of the ball. This introduces a new source of error to the task, the possibility of TTC estimates to be biased.

The task consisted of timing a button press to the arrival of a ball presented on a screen. The ball disappeared a considerable time before the ball reached the participant, although feedback of the arrival was presented on each trial. We found that training decreased the variable and constant error of the responses. That is, the responses became gradually more consistent and closer to the veridical TTC. Both these changes were retained over a period of months during which the participants received no practice on the task.

Analysis of the effect of ball size and speed on the responses suggests that participants relied on looming rate for their timing.

## Introduction

The successful execution of a one-handed catch requires an extremely well timed action. It is assumed that in order to catch a moving ball, the observer must estimate some time in advance where it is going and when it will arrive (e.g. Regan & Hamstra, 1993). There are differing suggestions on how the time to arrival to the catching position is computed. The General Introduction described a number of these solutions. For example, it has been shown that when an object approaches directly towards the observer at a constant speed, the monocular variable tau (Lee, 1976) provides accurate information of its time to contact (TTC):

$$\tau = \theta / \theta' \qquad [1.]$$

where $\theta$ is the visual angle subtended by the approaching object and $\theta'$ is its looming rate (the change of visual angle over time). The strongest evidence for the use of tau comes from relative TTC discrimination studies that show that human observers can judge stimuli by their differences in TTC (Todd, 1981; Regan & Hamstra, 1993; Regan & Vincent, 1995). Binocular cues can also be used (Heuer, 1993; Gray & Regan, 1998; Rushton & Wann, 1999), which when combined with monocular cues produce more robust and accurate judgements (Gray & Regan, 1998). Rushton & Wann (1999) proposed to use the ratio of relative disparity to change in relative disparity as a binocular equivalent of tau. As described in General Introduction, both the monocular and the binocular estimates could be combined in the following form:

$$TTC = {(\theta + \phi)}/{(\theta' + \phi')} \qquad [2.]$$

where $\phi$ is relative disparity and $\phi'$ is its rate of change. This solution provides a single, robust estimate of TTC that takes both monocular and binocular information into account.

However, a number of studies have raised questions on whether these cues to TTC are employed by human observers. Although potentially available, other simpler cues that lead to biased estimates of TTC have been pointed out. For example, in a discrimination experiment by DeLucia (1991), two objects of different sizes approached the participant on a computer screen and the participant was asked which one would reach them first. The participants consistently chose the larger, even if the smaller would have reached them sooner. The author concluded that in this experiment, the pictorial size of the approaching object biased the TTC judgement. Other potential cues on which participants have been found to rely in order to produce relative TTC judgements are looming rate (Lopez-Moliner & Bonnet, 2001) and motion-in-depth (see General Introduction and Chapter 1). Motion-in-depth (MID) is composed of looming rate and the rate of change of disparity of the stimulus. These two cues are integrated to produce the percept of an object advancing or receding from the observer (Regan & Beverley, 1979; Beverley & Regan, 1979). Although the influence of MID on TTC judgements has not been previously studied, there are a number of studies that suggest that looming rate affects TTC estimates in absolute judgement tasks (Schiff & Detweiler, 1979; Smith et al., 2001; Lopez-Moliner et al., 2007).

In this chapter we will focus on the role of learning in absolute TTC judgements. There are a number of differences between relative discrimination tasks and absolute estimation tasks that might influence the learning taking place. Relative discrimination tasks do not require that the participants compute an estimate of arrival time to produce a response. Any differences between the two stimuli presented could lead the observer to choose one over the other (see Tresilian, 1995). In absolute TTC estimation tasks, instead, responses are given explicitly in terms of time. This has two consequences on the possible effects of learning. First, the estimates of TTC can be biased (Schiff & Detweiler, 1979). Potentially, learning could take place in the form of a calibration process that adjusts the bias of the estimates in order to match the actual TTC of the stimuli. Second, the feedback provides more information in absolute estimation tasks than in relative discrimination tasks. Usually, feedback in relative discrimination tasks is simply whether the observer produced the correct response or not. As a number of variables can vary between the presented sequences (size, looming rate, TTC, change in disparity, etc.), this can provide misleading information to the observer. In absolute TTC estimation tasks, feedback informs the observer of the mismatch between the estimated and actual TTC. This provides access to the actual TTC of the stimulus presented, which is not available in relative discrimination tasks.

Here we present an experiment that assesses learning in a binocular absolute TTC task. The performance of several participants was tracked when they timed the arrival of a computer presented ball that disappeared shortly before reaching them. Feedback was given on each trial when the ball would have reached them by briefly flashing LEDs located close to the head of the participant. We assessed the performance of the participants using a number of measures. Our two main variables were the constant error and the variable error of the responses (similar variables are employed in, for example, Gray & Regan, 1998). The constant error refers to the accuracy of the responses. That is, the degree to which the TTC estimated by the participants corresponded to the actual TTC of the trials. The variable error measures the consistency of the responses, independently of whether they were biased or not. We expect that with practice both of these errors will reduce: participants will estimate a TTC closer to the actual TTC and at the same time do so with a higher consistency.

These measures, however, tell us little about whether TTC or one of its correlates is used in the task. To address this question we measured the influence of the speed and the size of the ball to the timing of the response. The use of TTC predicts that these variables do have no influence in the timing of the response, whereas looming rate and MID both predict that constant error is proportional to the ratio of ball size to ball speed (Sun & Frost, 1998; Smith et al., 2001; Lopez-Moliner et al., 2007). This point is discussed in more detail below. If participants switch from the use of these correlates to using TTC then the effect of ball size and speed should reduce with training.

## Methods

### *Participants*

5 observers between 23 and 28 years. All of normal or corrected-to-normal vision. All of them took part in the study voluntarily and were recruited between the postgraduate students and researchers of the School of Psychology. The observers were naïve to the hypothesis of the study and not experienced in psychophysics.

### *Apparatus*

The stimuli were presented in a 21' monitor with a red filter situated at one meter from the observer. The resolution of the display was 1024 x 768 pixels, and the frame rate was 100Hz. The room in which the experiment was carried was dark and no reference points were visible to the observer. As in the previous chapter, LCD shutter goggles were employed for providing stereovision.

Figure 1 illustrates the experimental setup. We provided feedback of the actual TTC by briefly flashing LEDs to the observer. Two red LEDs were attached to the chinrest (about 15 cm away from the chinrest's centre) and placed visible at the sides of the observer's head. The observer was given a button connected to a NI data acquisition card for recording his or her response.

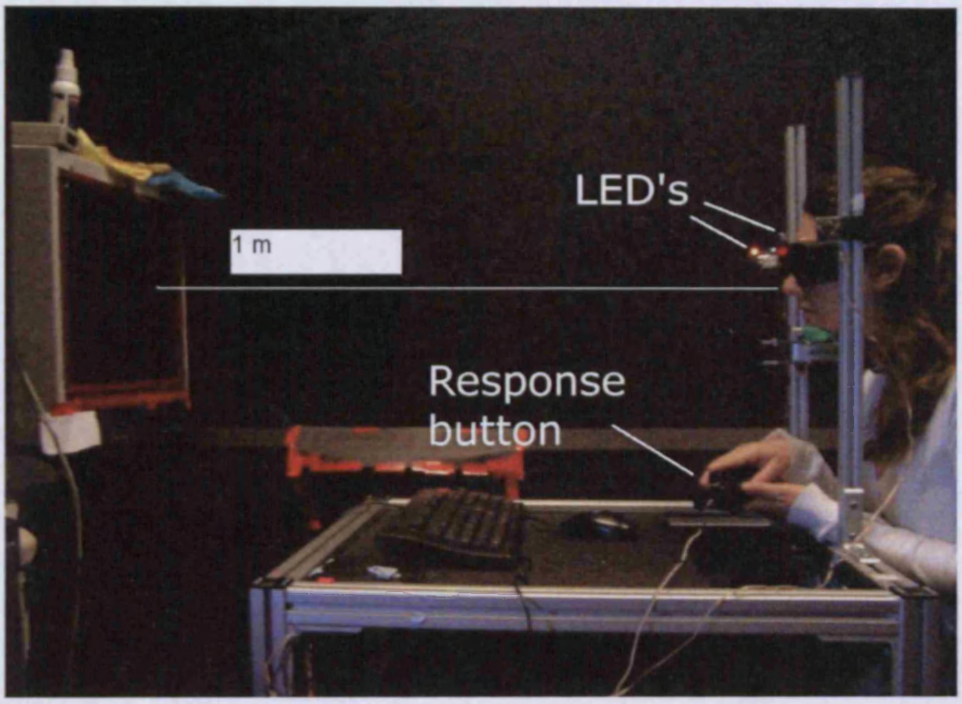


Figure 1. Depiction of the experimental setup.

*Stimuli*

The stimulus used in the task was the same mesh sphere as seen in Chapter 1. In this experiment the parameter ranges were changed. The following variables remained unchanged: the size of the sphere (radius of 1 to 3cm) and the duration of the presentation (360 to 540ms). The approach speed of the sphere was reduced from an average of 4m/s to a range of 1.8 to 2.2m/s for allowing it to be at a shorter distance. Also, we chose to randomize TTC from trial to trial. The range chosen was about the same that resulted from the manipulation of parameters of Chapter 1: 300 to 820ms. This manipulation resulted in the initial distance of the sphere to be of 2.24m. TTC, as in Chapter 1 was measured from the end of the presentation. As argued in methods section of the previous chapter, this relatively short range of TTC was chosen on purpose. The ability to time anticipatory actions becomes very inaccurate over periods of two or three seconds (Mates et al., 1994). Anticipating the arrival of a ball when it's less than a second away seems to better match normal actions such as catching or hitting than longer ranges.

Background objects were used to provide more cues to depth. They were placed closer to the observer than in Chapter 1, at between 1 to 1.9 metres.

*Accurate timing*

For coupling accurately the time of the button response, the feedback (the flash of the LEDs) and the presentation of the visual stimuli, a series of tests were made. Temporal frequency was measured by flickering stimuli and measuring the output of the display with a photodiode. This made sure that the display was running at 100 Hz. For the accurate presentation of feedback, the lag between drawing a frame and the monitor presenting a frame was measured. Double buffering produced already a delay of 10ms and 6ms were due to other processes. The flashing of the LED's was displaced for the total of this amount so it coincided with the actual TTC.

*Procedure and design*

Each observer took part in a total of 16 blocks of 90 trials each. A session consisted of 4 of these blocks and lasted approximately 25 minutes. In each trial a single approaching sphere was presented. At some point it disappeared and the participant had to press the response button the moment they thought it would have reached them. This technique has been used previously in a number of different situations, ranging from computer-based simulations of approaching objects (Regain & Hanstra, 1988) to videos of approaching vehicles (Schiff & Detweiler, 1979) and even the vision of passengers inside a moving vehicle (Cavallo & Laurent, 1988) Feedback was given on each trial in the form of an LED flash of 100ms of duration. The onset of feedback coincided with the moment the ball would have reached the observer.

For the duration of each trial, a background of four small spheres was presented. The distance at which they were presented was closer than in Chapter 1: 1 to 1.90 metres. Each of them was located 17cm towards one of the diagonals of the display, +/- 1cm. In all other aspects they are identical to the ones specified in Chapter 1.

The trial consisted of the presentation of the background only for 500ms. The sphere was added for 1000ms, but without approaching the observer. Then, the sphere approached the participant for a time between 360 and 540ms, randomized from trial to trial. The trial finished when two conditions had been met: 1) the participant had made a response, and 2) time had reached TTC + 200ms.

*Analysis*

To analyse the participants' performance in this task several measures were taken into account. Figure 2 plots the estimated TTC against the actual TTC for two participants. On the top panels we present their estimates during the first block of training and in the bottom their estimates for the last block of training. Participant AE (on the left) shows one of the changes in performance that we want to measure. His responses are less scattered in the last block of training than in the first block of training. Our measure of variable error captures this scatter. We defined variable error as the root mean squared error (RMSE) of the trials compared to the best linear fit to the data. The best linear fit can be seen in figure 2 as a discontinuous line crossing the estimates of each participant. Participant AH (on the right hand side) shows another type of change in performance that we want to measure. His responses are closer to the veridical TTC (the continuous line) in the last block of training than in the first block of training. We measured constant error in order to assess how close to the veridical TTC were the estimates of the participant. Constant error was calculated by taking the average error between the timing of the response and the actual time-to-contact. As a third measure we used the slope of the linear fit as a measure of possible compression of TTC.

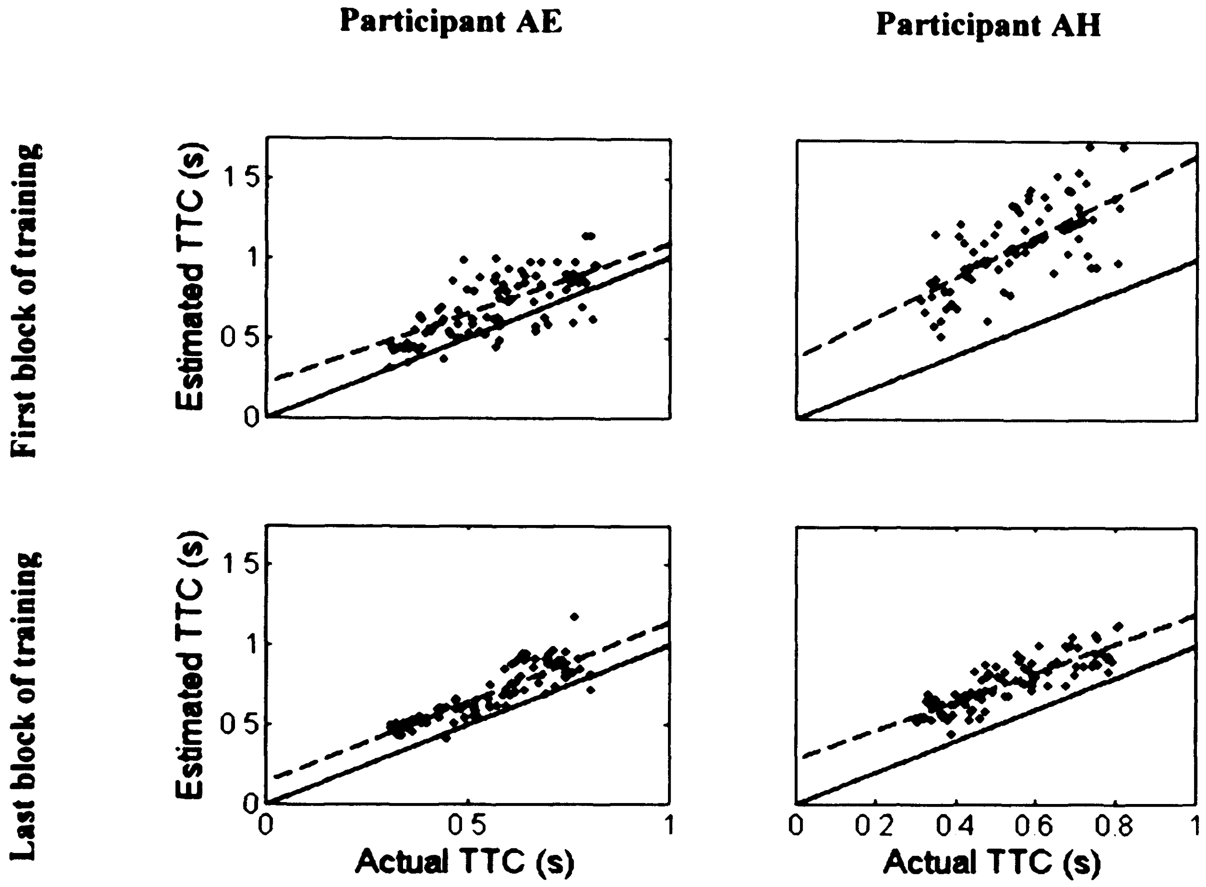


Figure 2. Absolute TTC estimates for two participants. The horizontal axis shows the actual TTC of the trial and the vertical axis the TTC estimated by the button press of the participant. On the top panels is their data for the first block of training and in the bottom panels for the last block of training. The continuous line shows the actual TTC and the discontinuous line the best fit to the participants' responses.

*Analysis – learning and bootstrapping*

To measure the changes due to learning, power law functions were fitted to the constant and variable error across sessions. The power law has been employed in numerous cases to model learning, and for this purpose its fits are usually better than a linear function (e.g. Lu, Chu & Dosher, 2005). The power law functions have the next formula:

$$y = ax^k \qquad [4.]$$

Where **y** is the prediction for a block, **a** is the constant of proportionality, **x** is the block and **k** is the exponent. **a** and **k** are fitted to the data, being **a** roughly equivalent to the value of the first datapoint of the dataset and **k** an index of how fast it decays (negative values) or grows (positive values).

To provide an index of the variability of the model fits, a bootstrap method was used (Efron & Tibshirani, 1993). First, 1000 new sets of training data were built. These sets had 16 blocks like the original dataset, and their value was an average of 5 (the number of observers) values chosen randomly and with replacement from the original observer data. The new sets of data could contain more than one case of one observer's data and none of other observer's data. The 5 and 95 percentiles of the simulated distribution of **k** were used as a confidence interval and the median as an average. Predictions can be drawn on the values that **k** will take. If the variable or constant error reduces, we would expect that **k** will have a negative value. This would be indicative of learning taking place in the task. On the other hand, a value of 0 would imply that no changes take place with training and a positive exponent would indicate that error increases with training.

## Results

*Effects of training on constant and variable error*

Figure 3 shows constant errors for each participant as a function of block number. In each case participants appear to overestimate TTC. The bias decreases with time for 4 of the 5 observers. Participants AH and MA showed the largest decrease, with MA almost reaching unbiased estimates of TTC (i.e. a constant error of 0). These were from 401 +/- 132ms in the first session to 243 +/- 11ms in the last session for AH, and from 290 +/- 22ms to 71 +/- 21ms for MA. The only participant to show an increase in constant error was JS (from 86ms in the first session to 228ms in the last session). When the averaged data of the group was fit with a power law, constant error was found to significantly decrease with training for the confidence interval. This suggests that there is a correction of timing bias in some observers such as AH and MA (see table 1).

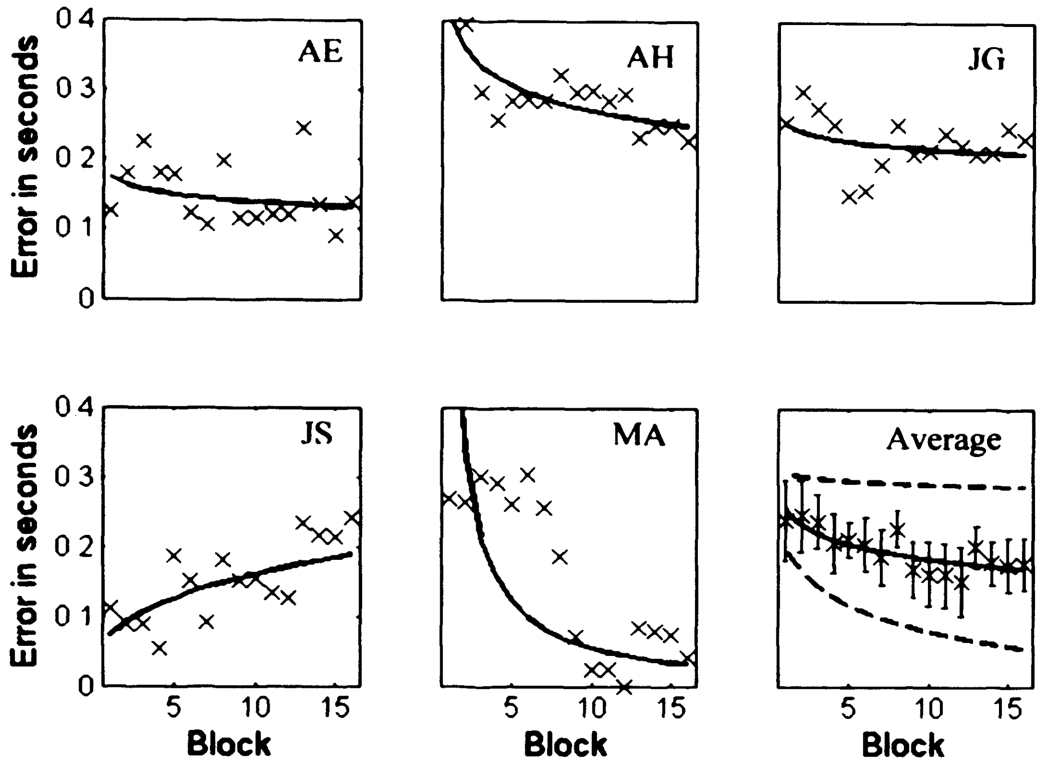


Figure 3. Constant error across blocks. Constant error was the measured as estimated TTC – actual TTC. Crosses represent the mean constant error for a block and the solid lines represent a power law fit on the data. In the average of the group the error bars represent standard error between participants and the dotted lines represent 95% confidence intervals.

| | Mean (s1-s4) | Mean(s13-s16) | Std(s1-s4) | Std(s13-s16) |
|---|---|---|---|---|
| AE | 183ms | 152ms | 44ms | 67ms |
| AH | 401ms | 243ms | 132ms | 11ms |
| JG | 278ms | 227ms | 20ms | 17ms |
| JS | 86ms | 228ms | 25ms | 16ms |
| MA | 290ms | 71ms | 22ms | 21ms |
| Group | 248ms | 184ms | 118ms | 72ms |

Table 1. Constant error for each participant for the first and last four sessions.

Figure 4 plots variable error as a function of block. For each participant, variable decreases over time. This was confirmed by the power-law fit. When a power law was bootstrapped on the participants' data its exponent was significantly lower than 0 for a 95% confidence interval. This indicates that there was a gradual decrease of variable error over the blocks, suggesting that the estimates of the participants become more consistent with training.

The individual exponents of the power law fits can be found in table 2. These confirm the trends described above. The exponents are all negative apart from JS' constant error. The absolute magnitude of the exponents indicates the magnitude of the change. The table also shows the exponents found when fitting power laws to individual slopes of the linear fit between estimated TTC and actual TTC. This measure of compression of the responses shows little change over time as the values are close to 0. Notably the slope of the relationship between estimated TTC and actual TTC was always lower than one (not shown). This indicates compression, being the increase in estimated TTC smaller than the respective increase in TTC.

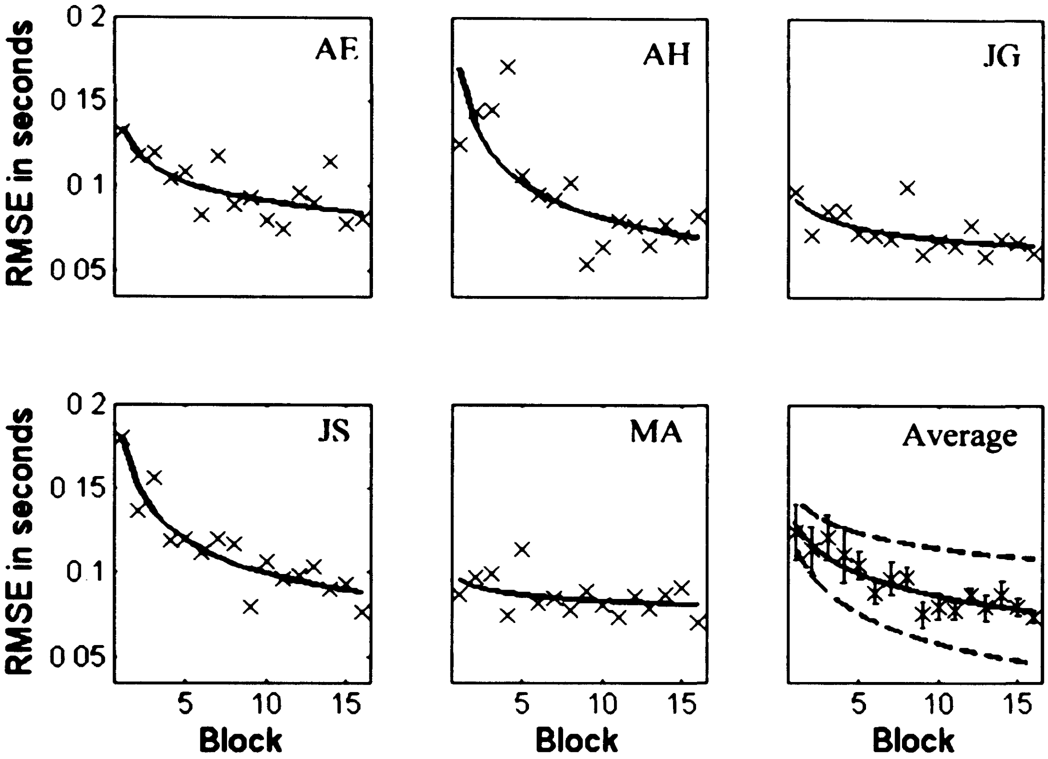


Figure 4. Variable error across blocks. Variable error is measured as the RMSE between response time and the best linear fit to the participant's data. Crosses represent the mean precision of a block and the solid lines represent a power law fit on the data. In the average of the group the bars represent standard error between participants and the dotted lines represent 95% confidence intervals.

| | Variable error | Constant error | Slope |
|---|---|---|---|
| AE | -0.166 | -0.1 | 0.063 |
| AH | -0.32 | -0.175 | -0.223 |
| JG | -0.126 | -0.067 | 0.014 |
| JS | -0.258 | 0.346 | 0.005 |
| MA | -0.059 | -1.501 | -0.053 |
| Group | -0.1864 (-0.242 to -0.132) | -0.287 (-0.563 to -0.078) | -0.038 (-0.081 to -0.001) |

Table 2. Exponents of the power law fits for each of the participants. These exponents indicate the direction in which the variable changes. Positive exponents indicate that the variable increases with training and negative values indicate that it decreases with training.

*Size and speed related biases*

The previous analysis does not indicate whether TTC or one of its correlates are used in the task. However, we can analyse the effect of the size and the speed of the ball in the timing of the responses in order to find what variable is used. For a certain TTC, the looming rate of an approaching object is given by its size to velocity (s/v) ratio. As the s/v ratio is increased, so increases the looming rate of the object. This fact has been used to analyse whether a certain timing pattern is due to TTC or other variables (Sun & Frost, 1998; Smith et al., 2001; Lopez-Moliner et al., 2007). If TTC is used we would expect that variations in the s/v ratio would not produce changes in the timing of an action. On the other hand, if looming rate or, in a lesser degree, MID are used we would expect that the action would take place earlier as the s/v ratio increases. It follows that the extent to which TTC is used can be assessed by the slope of the relationship between TTC estimate and s/v ratio, with TTC predicting a flat line. Figure 5 shows an example extracted from Lopez-Moliner et al. (2007). On the horizontal axis we have the s/v ratio of the trial and on the vertical axis the TTC at the time of the response. It can be seen that as the s/v ratio is increased, the TTC at the time of the response also increases, indicating an earlier response.

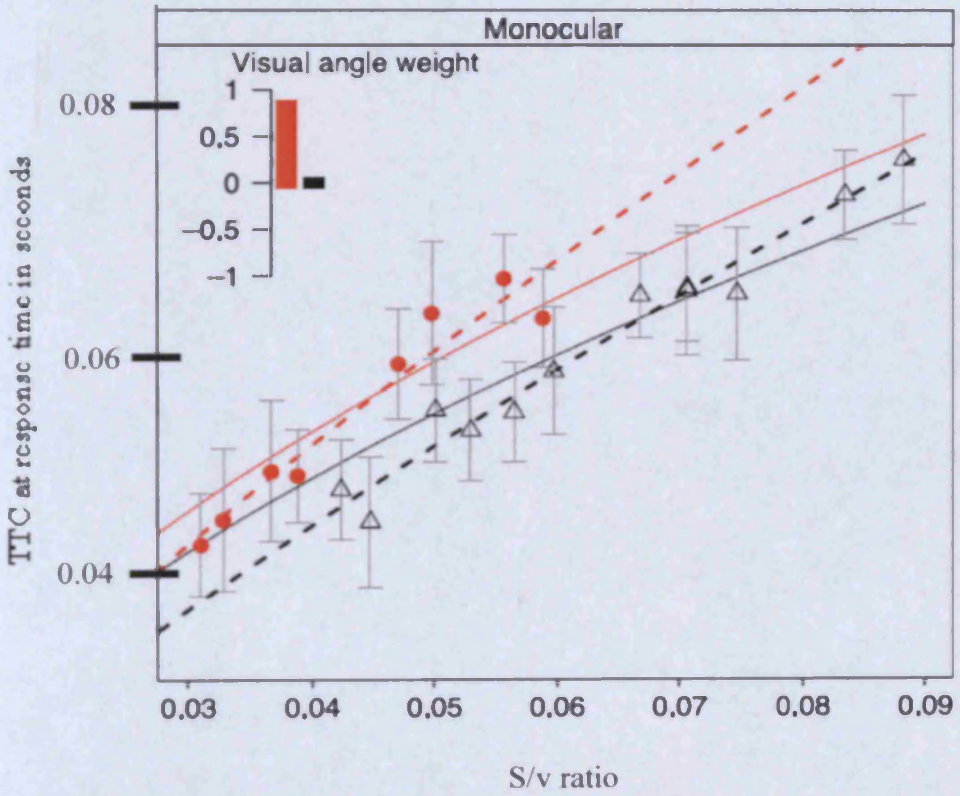


Figure 5. Effect of the ratio of size to velocity on TTC estimates under monocular viewing conditions (extracted from Lopez-Moliner et al., 2007). Red and black lines and datapoints represent two different sets of data. Continuous lines are the best fits of a looming rate strategy and dashed lines the best fits of a looming rate and visual angle combination strategy.

In figure 6 we plot the constant error of the responses of our participants against the s/v ratio, averaged for all the blocks. This is similar to the previously discussed data of Lopez-Moliner et al. (2007), in which, the TTC at response time is effectively constant error. We found that as the s/v ratio increased, the participant tended to respond earlier relative to the actual TTC of the trial. This suggests that participants were not relying in TTC in order to time their responses. The result is more compatible with the use of looming rate or MID.

This is further supported by Figure 7. This shows the slope of the relationship between TTC estimates and s/v ratio plotted for each of the blocks of training. If participants were reducing the biases they show to size and speed of the stimuli, in other words, learning to use TTC, the slopes would tend towards zero with training. However, no significant trend can be seen.

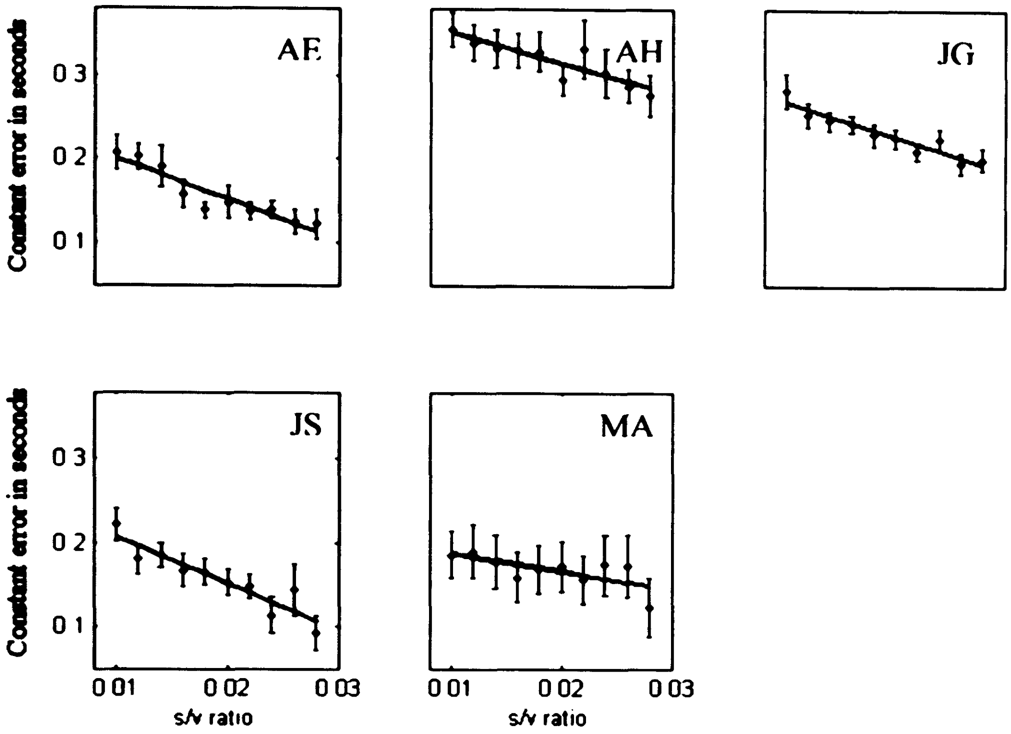


Figure 6. TTC estimates against s/v ratios, for each participant. The error bars show standard error across all the blocks.

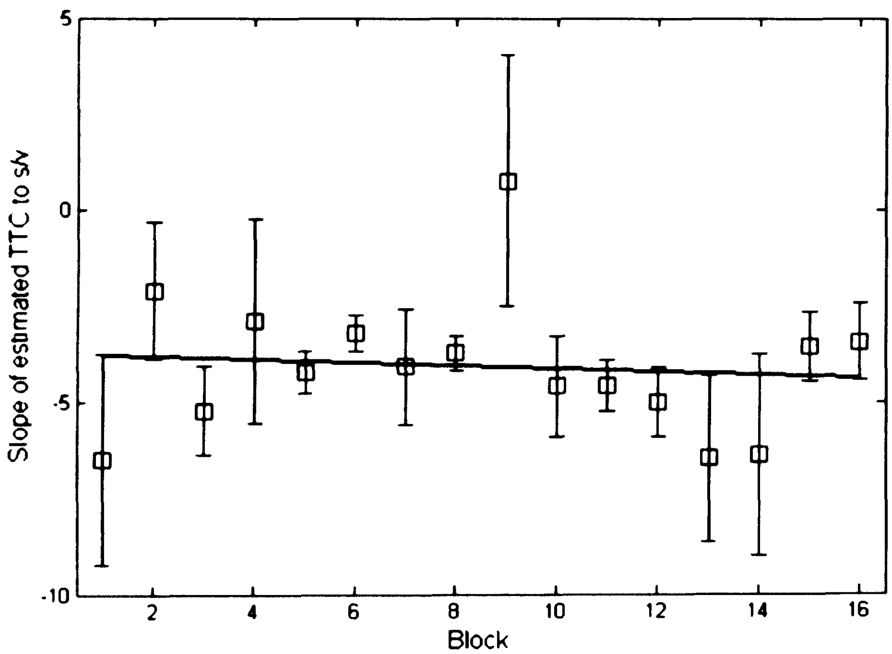


Figure 7. Slopes of the relationship between constant error and s/v ratio for all the blocks of experiment 2. Error bars represent standard error between participants.

The individual participant data does not show any specific trend either (table 3). Participant JS showed the most consistent effects of the s/v ratio, but none shows that the size of this effect diminishes with training.

| | AE | AH | JG | JS | MA |
|---|---|---|---|---|---|
| Block 1 | -9.29* | -7.26 | -0.41 | -14.89* | -0.58 |
| Block 2 | -1.93 | 4.35 | -2.57 | -6.28* | -4.07* |
| Block 3 | -4.08 | -5.35* | -5.89* | -8.88* | -1.90 |
| Block 4 | -5.44* | -8.09* | -4.1* | 7.31 | -4.10* |
| Block 5 | -4.8* | -3.67 | -3.85* | -6.03* | -2.80 |
| Block 6 | -1.75 | -3.77 | -4.28* | -2.41 | -3.82* |
| Block 7 | -2.59 | -3.20 | -4.03* | -9.73* | -0.84 |
| Block 8 | -4.90* | -2.22 | -3.77 | -4.22 | -3.50 |
| Block 9 | 0.11 | -2.98* | -2.19 | -4.60* | 13.52 |
| Block 10 | -3.89* | -1.38 | -5.31* | -9.17* | -3.19 |
| Block 11 | -5.24* | -4.52* | -2.30 | -6.31* | -4.53* |
| Block 12 | -7.77* | -5.42* | -2.03 | -4.85* | -4.94* |
| Block 13 | -2.46 | -3.45* | -14.68* | -5.4* | -6.32* |
| Block 14 | -16.20* | -2.22 | -2.07 | -6.89* | -4.48* |
| Block 15 | -1.90 | -4.21* | -3.61* | -6.49* | -1.55 |
| Block 16 | -5.63* | -5.33* | -3.97* | -0.84 | -1.37 |
| Average | -4.86* | -3.67* | -4.07* | -5.61* | -2.15* |

Table 3. Slopes for each block of training. Asterisk mark significant regressions. When the data was analysed across sessions all the participants showed a significant effect of s/v.

The fact that participants responded, on average, 242ms late during the first session could imply that they were waiting until the feedback was presented before making a response. Reaction times to the LED alone were therefore measured in a second experiment. Each trial showed the same stimulus arrangement as the main experiment but without the approaching sphere. The results for a participant are shown in Figure 8. The reaction times were consistently higher than the constant error reported in the previous section. In average these were of 447ms with a standard deviation of 52ms across participants. Hence the results of the main experiment were not contaminated by reaction to the feedback LEDs themselves.

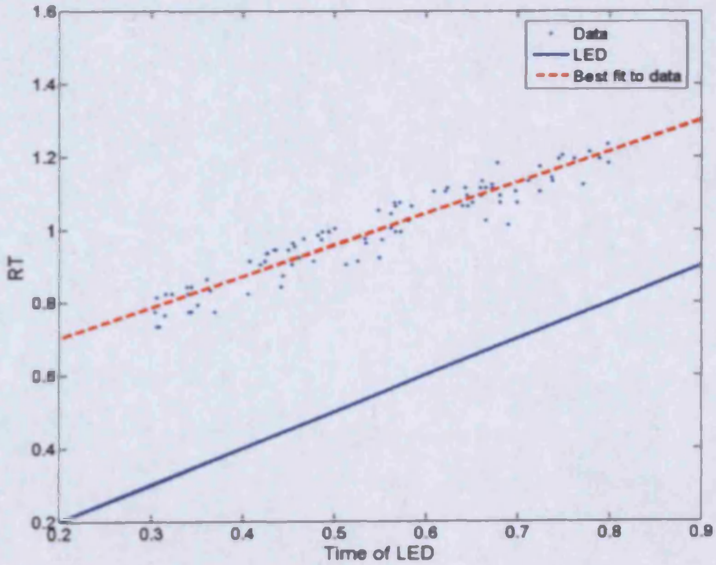


Figure 8. Reaction time for participant MA. Response times are on the vertical axis and the time at which the LED flashed on the horizontal axis. The blue line represents the flash of the LED and the dashed red line the best fit to the participant's data.

*Overestimation – 2D TTC condition*

There have been previous reports of overestimation of TTC (Freeman, Harris & Tyler, 1994; Seward, Ashmead & Bodenheimer, 2007). Freeman et al. found overestimations of 496 and 300ms using a set of stimuli with mean TTC of 1517ms. We therefore collected data in a condition that had the same temporal constraints as the original 3D task of the main experiment, but did not involve judgements on an approaching ball. Instead, judgements are made on the TTC of a laterally moving ball.

Observers performed 2D TTC judgements in four blocks of 90 trials each. Average overestimation for the four blocks is presented in table 4.

| | Mean | Standard deviation |
|---|---|---|
| AE | 274ms | 48ms |
| JG | 219ms | 29ms |
| JS | 173ms | 42ms |
| MA | 122ms | 32ms |
| Group | 197ms | 65ms |

Table 4. Overestimation for the 2D TTC estimation task.

The data shows that observers consistently overestimate TTC in the 2D task. These overestimations are lower than those in the main task before training, but similar to the overestimations reported after training. This is most probably due to the fact that this control was carried on after all the data of the main experiment had been collected.

*Retention of learning*

Perceptual learning is typically retained for long periods of time. For example, increases in performance in texture discrimination tasks have been found to be retained up to 32 months (Karni & Sagi, 1993). We therefore tested three of our participants (JG, JS and MA) two months after the main task had been carried on. During this time they did not receive any practice in the task. Two months after having trained the participants in the absolute TTC task, three of them (JG, JS and MA) were tested again. Figures 9 and 10 show the constant and variable errors for both the training and for the retest. The curves from the main training and retest suggest that the performance that was achieved after the initial training was retained. This was particularly clear in the case of variable error (figure 10), which had lowered during the training and showed no signs of further reduction two months after. With constant error, the biases from the previous training were also retained. In the case of participant JG, there seemed to be somewhat less tendency to overestimate when retested. Power law fits on the data of the participants during the retest, and on group averages, show exponents not different from 0. This can be seen as mostly flat curves in the retest blocks, suggesting that no further learning was taking place.

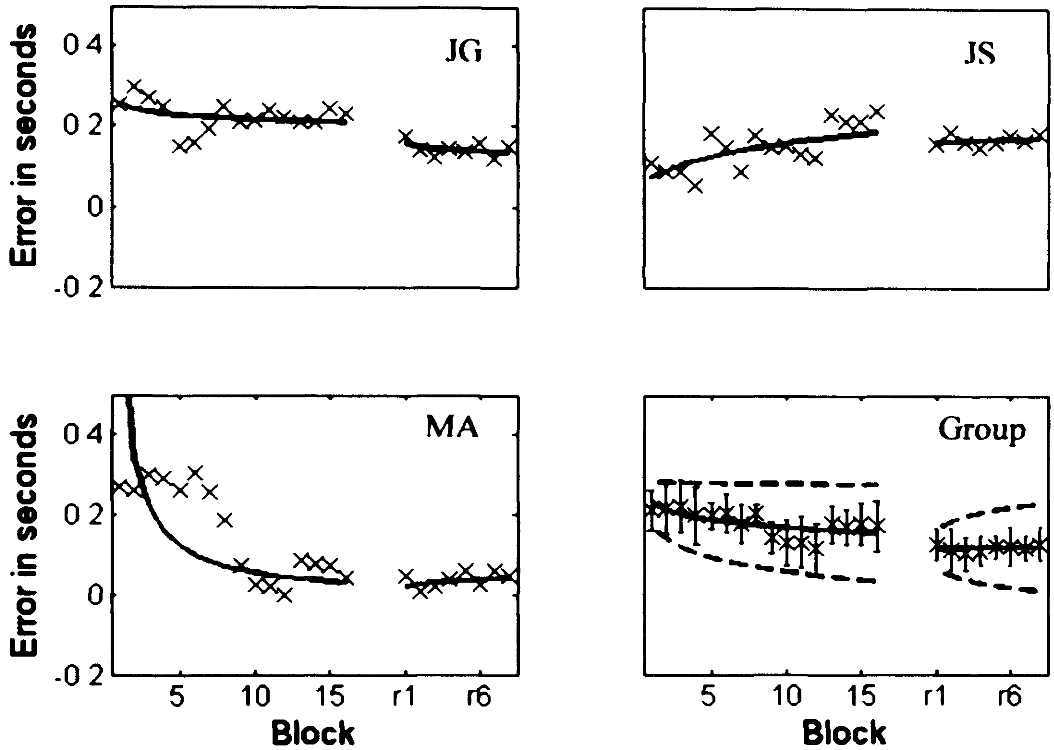


Figure 9. Constant for three observers during the initial training and when retested two months later. The data from the retests starts at r1, after the gap. The left hand side figure shows constant error and the right hand side figure shows variable error. Crosses represent the average of the block, and error bars, when present, the standard error between participants. Continuous lines show the best fit of a power law. In the group average, discontinuous lines represent a 95% confidence interval for the power law fit, based in a bootstrap.

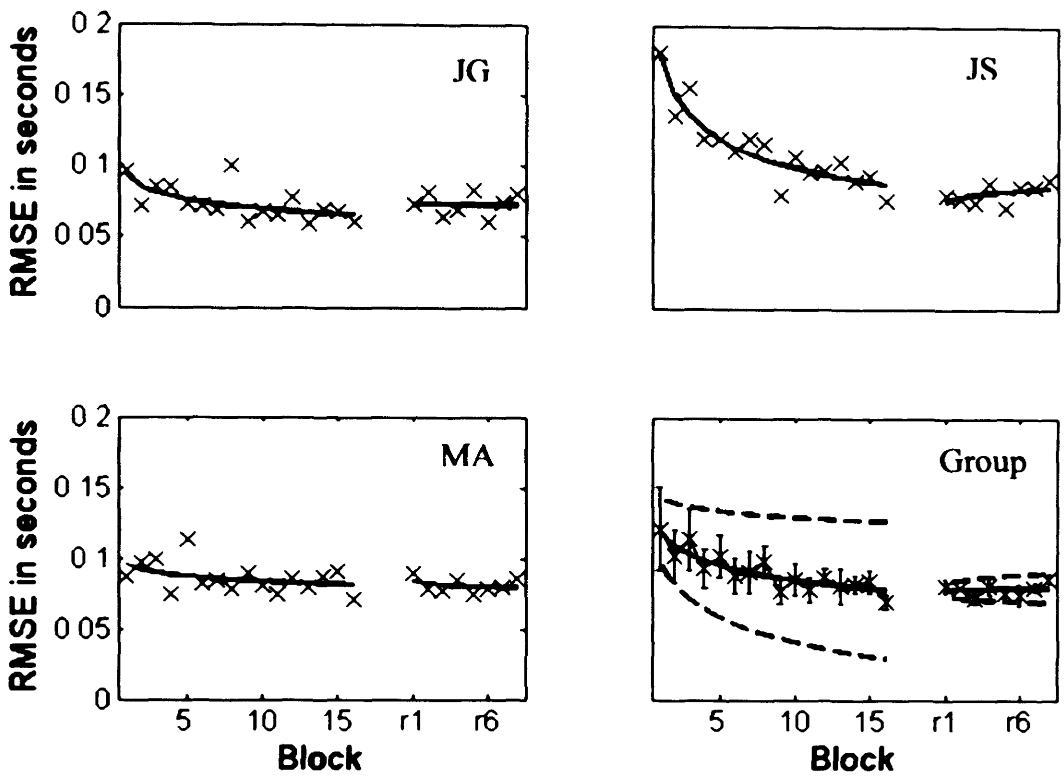


Figure 10. Variable for three observers during the initial training and when retested two months later. The data from the retests starts at r1, after the gap. The left hand side figure shows constant error and the right hand side figure shows variable error. Crosses represent the average of the block, and error bars, when present, the standard error between participants. Continuous lines show the best fit of a power law. In the group average, discontinuous lines represent a 95% confidence interval for the power law fit, based in a bootstrap.

## Discussion

The results show learning in a binocular absolute TTC judgement task. Both variable error and constant error decrease with time, suggesting that participants get more consistent and less biased. The reductions in variable error could be due to a number of reasons such as an increase in the perceptual sensitivity to the guiding variable or an improvement in the translation of the perceptual estimate into a motor response. In the first case there would be an increase in the signal to noise ratio that would allow finer estimates to be produced, and so, less variable responses. In the second case, the perceptual stage remains unchanged, but the estimate that is produced is more accurately transformed into an action, and so produces less variable responses. We also found reductions in the constant error of the responses. The estimates of TTC seem to be calibrated in order to achieve a timing that is closer to the TTC signalled by the feedback. This is further explored in the following chapter, where we claim that calibration of the responses follows a trial-by-trial reduction of the difference between the timing of the response and the timing of the feedback.

Changes in both variable and constant error were retained after a period of two months during which they were withheld of the task. We can compare the influence of training with the distribution of performance in the population. In a large sample the distribution of variable error ranged from around 75 to 200ms (see chapter 5). In the current experiment, our participants started with a variable error between 100 and 200ms, with all of them reducing it below 100ms with practice. This reinforces our claim that learning is taking place in the task. Further analysis of the pattern of responses in the task showed that although the timing of the responses was becoming more consistent, all the participants' timing was influenced by variations in the size / velocity ratio of the stimuli (figure 5). These biases suggest that the participants were not relying on TTC, but instead might be making use of correlates such as looming rate (Michaels et al., 2001; Smith et al., 2001) or motion-in-depth. With training the influence of the size and speed of the stimuli on the TTC estimates did not reduce.

We also discarded an alternative strategy on which the participants could be relying, namely, that the participants were waiting for the feedback to appear and responded to it. The pattern of results that this strategy would have yielded would be equivalent to that of TTC but with a large delay added to it. We compared the delay of the participants to the feedback alone (a reaction time task) with the overestimates found in the TTC estimation task. If participants were waiting for the feedback to respond, these reaction times would be of similar magnitude to the overestimates. The average reaction time of our participants was 447ms while their overestimates were slightly larger than 200ms at the beginning of the training and slightly lower towards the end of the training. Another indication of the implausibility of this strategy to account for our data is that if participants were waiting for the feedback in order to respond, a relationship between TTC estimates and s/v ratio would not be expected either, as the feedback was given independently of variations in size and speed.

Overall, our results are compatible with those of Jacobs & Michaels (2006) who showed that on a catching task, practice produces calibration of the underlying visual variables. That is, although the participants were relying on the same visual variables, they do so more skilfully (as shown by the decrease in variable and constant error in our study). When comparing with the results of learning in discrimination of TTC (chapter 1), two main points can be drawn. First, the visual variable underlying the judgements in both experiments seems to be MID. In the discrimination task, when TTC was put in conflict with looming rate it was found that participants were not using TTC for solving the judgement. In this chapter a similar result is found, with the participants responding earlier to the balls that have a higher looming rate or MID during their approach. Second, the effects of training seem to be larger in the absolute TTC judgement shown in this chapter than on the TTC discrimination task. This is compatible with the results of Gray et al. (2006), who found estimates of 'passing distance' to improve with feedback when the participant's task was to perform simulated catches as opposed to discrimination judgements.

The extent of learning shown in our experiment is much smaller than reported by Smith et al. (2001). There are two main differences between our study and theirs. The first is that the experiments by Smith et al. (2001) were done under monocular viewing, while ours was performed with binocular viewing. Under monocular viewing the catching performance of participants has been reported to be lower than when binocular vision is available (Mazyn, Lenoir, Montagne & Savelsbergh, 2004; Jacobs & Michaels, 2006). TTC estimates are also more accurate when binocular vision is available (Gray & Regan, 1998). The higher performance under binocular vision over monocular vision conditions has an effect on how much learning we can expect to take in each condition. It has been shown in numerous visual perceptual learning tasks that the amount of learning is inversely proportional to the initial performance level of the participants (Fahle & Henke-Fahle, 1996). This suggests that under monocular vision there is more room for improvement than under binocular vision, and so, we would expect larger effects of training to take place. A second difference between our experiment and that of Smith et al. (2001) is that in their experiment the participants had continuous viewing of the approaching ball, while in our experiment the approaching ball was presented for a part of its trajectory and then disappeared. This would lead to our participants having less informative feedback compared to theirs.

An important question is whether it is perceptual learning that is taking place. The biases due to the looming rate of the stimuli do not decrease with training (figure 7), and evidence of learning comes from the decrease in variable error and a tendency to reduce overestimation. Although the reduction of the overestimates could be seen as legitimate calibration of the variable controlling the response, the increase in the consistency of the estimates might not be so. During practice the participants might be as well learn to produce more reliable button presses, as they are unfamiliar with this way of giving responses at the beginning of the task. This might also be the case with the Jacobs & Michaels (2006) task, as the fit between the responses and the predictions of several of the different fitted models increased with training. It is a possibility that these increases in performance arise from the participants translating more precisely their percept into an action, as even marginally successful strategies for catching will increase their effectiveness if they are performed more skilfully. It has been suggested that a faster perception-action coupling contributes to the well timed actions of professional sportsmen (Le Runigo, Benguigui & Bardy, 2005). It is possible that in the case of TTC estimates in which the ball has been presented for only a part of the trajectory, our case, not an increase in the speed but the quality of the perception-action coupling could lead to the reduced variable error we report. After all, it is not of much use to increase the perceptual system's sensitivity to TTC if the estimate produced will lead to an action that is imprecise and biased by over a hundred milliseconds.

In overall, this experiment suggests that participants don't rely on TTC in a binocular absolute TTC timing task, but instead on simpler correlates such as looming rate or MID. Learning does take place over time, but it is limited to two aspects. First, participants learn to produce more skilful responses that increase their rate of success in the task. Second, participants learn to calibrate their bias during the task. This calibration might be based on the perceived mismatch between the feedback and their response, and is explored in the next chapter.

# Chapter 3 – Effect of temporally biased feedback on absolute TTC judgements


## Abstract

In the previous chapter we found that training with feedback in an absolute TTC task improves participants' performance. Two main findings were reported, a decrease in the variability of the TTC estimates, and a reduction of the bias to overestimate TTC. We suggested that this reduction of overestimation might be caused by a calibration process guided by the mismatch between the observer's response and the feedback. In this chapter we manipulate the relationship between feedback and TTC in order to assess the role of calibration. To do this, we added constant timing offsets to the feedback. If feedback is attended to and used to calibrate the TTC estimates, biasing the feedback should produce an equivalent bias in the TTC estimates.

We trained two groups with biased feedback and a third one with accurate feedback. For one of the biased feedback groups the feedback was given consistently before the arrival of the ball (early feedback group), and for the other biased feedback group, feedback was given consistently after the arrival of the ball (late feedback group). We found that compared to the control group both biased feedback groups quickly changed the timing of their responses in the direction signalled by the feedback. This suggests that feedback is not only attended to, but that it is also taken in account for setting the timing of future responses.

## Introduction

In the previous chapter we have reported that practice with feedback improves absolute TTC judgements. One of the changes that we found was a decrease of the participants' tendency to overestimate TTC. Under or over estimating the TTC of an approaching ball would lead to consistently fail to catch it. In this chapter we study the role of feedback in calibrating the match between the actual TTC of the ball and the perceived TTC. Such a calibration process would allow for successful catches under novel conditions, given some experience in the task. The easiest way of picturing this is as a trial by trial change in the bias of the response based on the mismatch between response and feedback. For example, if when catching a ball we closed our hand too early, the next time we will wait slightly longer before closing it.

There is some evidence that feedback can be used to calibrate the timing of actions. Pesavento & Schlag (2006) used biased feedback in order to change the pace of tapping. In their experiment, participants had to press a button in pace with a square that was flashed every second. The button press would flash another square (the feedback) that helped the participants to match the pace of their button press with the pace of the presentation of the target. Unknown to them the square that provided feedback about the button press was delayed during the task. This resulted in responses being delayed by about 40ms after training, with none of the participants perceiving the delay in the feedback. This delay transferred to a task without feedback –line crossing- suggesting that the delay had generalized and was not specific to the pacing task.

Severe biases in the judgement of absolute TTC have been found through a number of studies. Gray and Regan (1998) used a staircase measure in which participants judged on each trial whether an approaching ball would have arrived at them before or after an auditory signal. The timing of the auditory signal was adjusted on each trial on basis of the responses, allowing perceived TTC to be measured. They found that the TTC of binocularly defined stimuli were overestimated by about 10% and the TTC of monocularly defined stimuli underestimated by around the same amount. They did not find such biases when both monocular and binocular cues were available. In tasks that involve the participants pressing a button in order to time the arrival of the object, biases have been found to be greater than these (Schiff & Detweiler, 1979). Also, it has been reported that TTC tends to be overestimated when it is short, around a second or less, and underestimated when it is long, over two seconds (Heuer, 1993; Freeman, Harris & Tyler, 1994). A potential use of feedback in absolute TTC tasks is to reduce these biases with training as found in Chapter 2.

In the current chapter we studied whether feedback re-calibrates the timing of an interceptive response. Under natural catching, such feedback is available from multiple sources. For example, information through the hand is available about the moment of ball-hand contact and its relation to the time of hand closure, and visual information on whether the hand reached the ball early or late is also available. In our setup, feedback has been replaced by a single source (a flash of lights in line with the eyes) that could easily be manipulated. We trained one group of participants with feedback that signalled that the ball arrived earlier than it did and another group with feedback that signalled that the ball arrived later than it did. If feedback is taken in account by the calibration process then responses should become biased.

## Methods

*Participants*

22 participants with ages ranging between 19 and 28 years took part in this study. Participation was rewarded with course credits. All participants had normal or corrected-to-normal vision and took part in the study voluntarily. The observers were naïve to the hypothesis of the study and not experienced in psychophysics. Participants were randomly assigned to the three groups: early feedback, control and late feedback.

*Apparatus and stimuli*

The setup and stimuli are the same as used in chapter 2.

*Procedure and design*

Each observer took part in a total of eight blocks, of 90 trials each. A session consisted of 8 of these blocks, taking in total 60 minutes with a 10 minute break after block four. At the start of the first session, participants were instructed on the task and given ten trials of practice without feedback.

The range of parameters of the stimuli and the design is the same as that of chapter 2. The only difference is that the three groups are given different feedback. In the early group, the feedback is always presented 150ms before the arrival of the ball to the observer. In the late group, the feedback is always presented 150ms after the arrival of the ball. The control group was presented with veridical feedback, being their task identical to the experiment of chapter 2.

*Analysis*

See chapter 2.

## Results

*Effect of feedback on timing*

Figure 1 shows the constant error in seconds for each of the groups. The control group, which received unbiased feedback during the session, does not show any drastic changes in timing. Both at the beginning and the end of the session they present a slight overestimation of about 60ms. In the other hand, the groups that received biased feedback show a change in their constant error. The timing of their responses is changing in the expected direction: later responses for the late feedback group and earlier responses for the early feedback group. This was confirmed by a repeated measures ANOVA that found a significant effect of group ($F(2, 18) = 7.582$, $p = 0.004$) and of block ($F(7, 18) = 3.307$, $p = 0.003$). In the figure we can see that these biases are acquired early, during the first block of training and that they remain for the following blocks. There are no differences in constant error between the groups for the first fifteen trials of the first block ($F(2, 19) = 0.141$, $p = 0.869$) while there are for the last fifteen trials of the first block ($F(2, 19) = 4.494$, $p = 0.030$). Relative to the control group these biases amount to 120ms for the late feedback group and 60ms for the early feedback group. When the participants were debriefed, none of them noticed that the timing of the feedback had been manipulated. When explicitly questioned, they judged it to be accurate. The only exception was one participant in the early feedback group that reported that the feedback might be presented late.

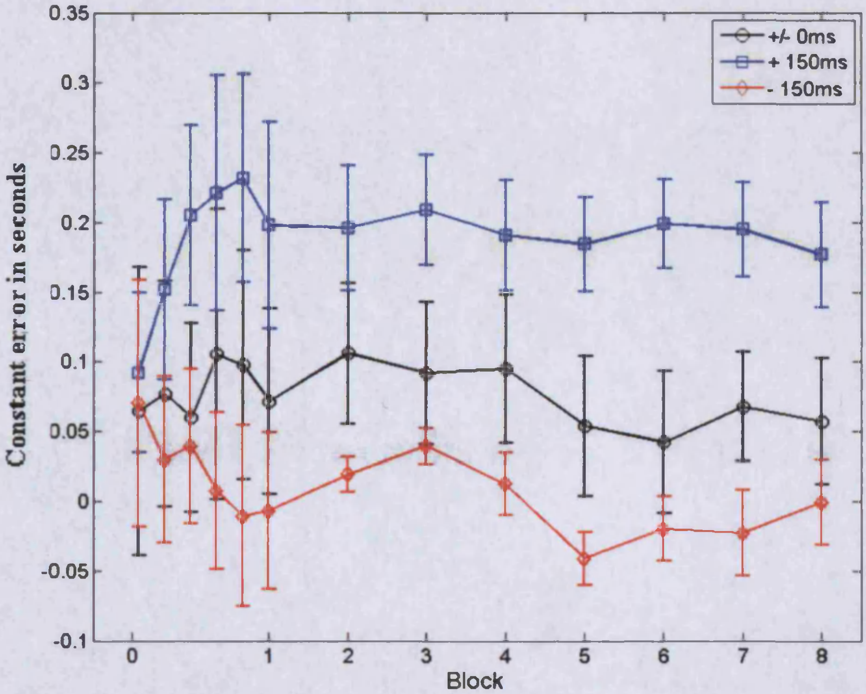


Figure 1. Constant error plotted for all the blocks of the experiment. The first block has been highlighted and divided into groups of fifteen trials. The control group is represented by the black line, the late feedback group by the blue line and the early feedback group by the red line. Error bars represent the standard error between participants.

*Effect of biased timing on variable error*

Figure 2A shows the variable error for the early, late and control groups plotted against blocks. The three groups decrease their variable error with training ($F(2, 18) = 8.814, p < 0.001$), which is compatible with our results from chapter 2. There is a difference between the three groups, with the late feedback group showing more error than the control group, and the control group showing more error than the early feedback group, but this difference was found not to be significant in a repeated measures ANOVA ($F(2, 18) = 5.754, p = 0.218$).

It seems counter intuitive that one of the biased groups is more precise than the control group. Note, however, that participants are responding to different ranges of TTCs once they have acquired the biases determined by their respective groups. If we take in account their respective constant errors, the control group is responding on average to a TTC of 560ms (actual TTC) + about 60ms (the constant error). This makes an estimated TTC of about 620ms. Following this, the average TTC estimated by the late group is of 740ms and the average TTC estimated by the early group is of 560ms. We would expect that the variability of the estimates increases with the range of the stimuli if the noise in the system is constant, which is predicted by applying Weber's law. To test this we adjusted the variable error by dividing it by the average estimated TTC of each block. In figure 2B we can see the variable error relative to the range that the group is judging. Again, the difference between the groups was found not to be significant ($F(2, 18) = 0.276, p = 0.762$).

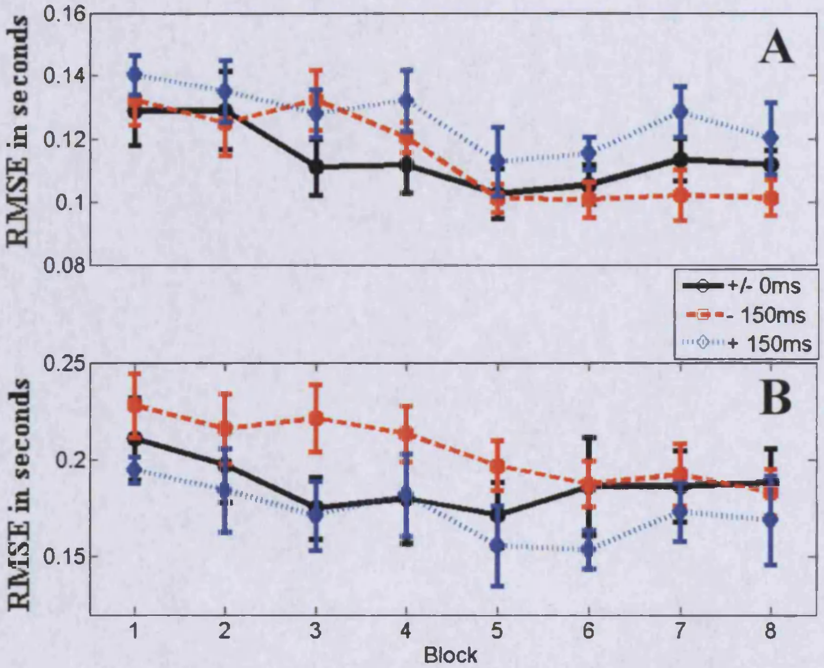


Figure 2. Variable error across blocks. For both figures the black line represents the control group, the blue line represents the late feedback group and the red line represents the early feedback group. A) Variable error in RMSE for the three groups. B) Variable error in RMSE corrected by the perceived range. Perceived range is defined as the average TTC plus the constant error of the observer.

## Discussion

We found that in an absolute TTC judgement task, the estimated TTC can be consistently altered by biasing the feedback given to the participants by a constant amount. The results are similar to those studies of absolute distance perception, where practice is required before participants can provide accurate judgements (Morrison & Whiteside, 1984) and information about the range of distances affects the judgements (Isenhower & Pagano, 2008). The case with the estimation of TTC seems to be similar, as giving inaccurate feedback modifies the range of estimates given by the participants. In many tasks the estimation of TTC has been found to be biased, with observers under or over estimating consistently depending on the range of TTC and presentation conditions (Schiff & Detweiler, 1979; Heuer, 1993; Freeman, Harris & Tyler, 1994; Gray & Regan, 1998). Some of these experiments did not present the participants with feedback of the outcome of their responses, or information about the actual TTC of the trial (Schiff & Detweiler, 1979; Heuer, 1993; Gray & Regan, 1998). We have previously found that when presented with feedback in an absolute TTC task, the tendency to overestimate TTC reduced yielding more accurate estimates (see Chapter 2). In the current experiment, we have shown that TTC estimates can be consistently biased by manipulating feedback. Taken together, these results suggest that feedback is not ignored in absolute TTC tasks but instead is used for calibrating the timing of the responses.

There are some situations in which learning to bias the timing of interceptive actions could be useful. For example, when playing badminton, early on in a game we might find that the shuttlecock is often missed by underestimating its arrival. This is due to the unusually slow, decelerated fall of the shuttlecock when compared to other balls. If we try to hit it the same way as a tennis ball, we will consistently hit too early. In the case of a badminton match, learning a bias that delays our response by a certain amount of time might be an effective strategy to hit the shuttlecock. Similarly, acquired biases can be useful in the more general scenario of intercepting freefalling objects. There is evidence pointing out towards the visual system being unable to take acceleration in account when computing TTC (Benguigui, Ripoll & Broderick, 2003).

This leads to the actual arrival time of the object being overestimated: if only instantaneous TTC is computed, the object will reach the observer before predicted. None the less, when catching a ball under the effects of gravity and at 0g, the difference in the timing of the response is very small (McIntyre, Zago, Berthoz & Lacquaniti, 2003). A recent review of the literature on intercepting free falling objects suggests that although acceleration is not taken in account when intercepting, when the task suggests that the object is falling, an approximation of the effects of gravity is employed (Baures, Benguigui, Amorim & Siegler, 2007). This could be approximated by the participants adding or subtracting a delay from their catch if they have detected that the ball is accelerating or decelerating. Although acceleration itself seems not to be computed by the visual system, changes in the speed of an object can be detected (Calderone & Kaiser, 1989; Werkhoven, Snippe & Toet, 1992). Potentially, feedback could be employed for optimizing the bias over a series of trials.

Our results raise several issues about the biases that the participants exhibited. First, it is difficult to draw conclusions about how participants acquired the bias. There are two main possibilities. The bias could affect the earlier perceptual stage of the response or the later motor response stage. If the percept is being changed, TTC could be perceived as shorter or longer after training with biased feedback, correspondingly triggering the response earlier or later. On the other hand, if the bias is acquired in the motor response stage, the percept of TTC would remain the same after the training, but just the timing of the response be modified. Second, it is not clear from our data if the biases are producing temporal or spatial adaptation. This far we have discussed the results as if the responses were displaced in time in order to match the TTC given by the feedback. It could also be the case that the participants are adapting their responses as if the interception point was displaced in front of them (early feedback) or behind them (late feedback). A third open issue is whether several of these biases can be stored or combined. If the perception of TTC is limited to its instantaneous value and so ignores acceleration (Benguigui, Ripoll & Broderick, 2003) or is based on simple correlates that can be prone to error if task constraints are changed (Smith et al., 2001), the storage of several biases could explain how in different situations catching is still successful. For example, independent biases could be stored for responding early to falling tennis balls but responding late to falling badminton shuttlecocks. Such process could compensate for the inaccurate TTC predictions that relying only on the available visual variables would lead to.

In summary, the current experiment shows that participants are aware of the feedback in absolute TTC tasks. One of the roles of feedback in the task, namely, its use for calibrating TTC estimates was investigated. As expected, manipulating the TTC signalled by the feedback produced consistent biases in the participants' TTC estimates. In the following chapter we will explore whether feedback can also increase sensitivity to TTC.

# Chapter 4 –Does learning in absolute TTC transfer to relative TTC discrimination judgements?

## Abstract

We have previously shown that learning takes place in absolute TTC tasks, but we have failed to find this effect in TTC discrimination tasks. In this chapter we investigated if the learning acquired in absolute TTC tasks would result in increased sensitivity in TTC discrimination judgements. Participants performed a TTC discrimination task before and after being trained in absolute TTC judgements. Although the variable error of the responses in the absolute task decreased, no increases in sensitivity were found. The result was replicated twice with different parameter ranges and training schedules, suggesting that the increased performance of the participants in the absolute TTC task is not related to changes in their perception of TTC. This lack of perceptual learning points towards the learning in absolute TTC tasks being of perceptuo-motor nature.

## Introduction

It has been suggested that accurate perception of the time-to-contact (TTC) of an approaching object underlies the exceptional displays of skill seen in professional sports such as tennis, cricket or baseball (Gray & Regan, 1998). In these sports, the time window during which the sportsman can successfully hit the approaching ball is in the range of a few milliseconds. In order to produce a movement that is likely to meet the trajectory of the ball, the time at which it reaches the observer has to be known in advance to prepare the movement or its position at a given time must be anticipated via an estimate of TTC (Rushton, 2004). Experienced observers in laboratory settings are able to judge TTC even when only monocular cues are available (Regan & Hamstra, 1993). When both monocular and binocular cues are available to judge TTC, performance is more accurate than when the participant has to rely on monocular cues only (Heuer, 1993; Gray & Regan, 1998; Rushton & Wann, 1999). The smallest TTC differences that can be judged when the participant can use monocular and binocular cues are in the order of 1.3-2.7% (Gray & Regan, 1998), compared to differences in the order of 9-10% when only monocular cues were available (Regan & Hamstra, 1993). Although very accurate, this performance is not yet accurate enough to explain the fine timing shown in professional sports.

One of the main differences between normal psychophysical observers and professional sportsmen is the amount of experience they have in the task. It has been found that practice can increase performance in different visual tasks: estimating the direction of motion (Ball & Sekuler, 1987), judging the offset of vernier stimuli (Fahle & Edelman, 1993) or detecting a target among distractors (Sigman & Gilbert, 2000). For example, a vernier discrimination task consists of judging the offset between two very closely placed lines. With practice, the smallest offset that can be judged reduces to about half of the initial one (Fahle & Edelman, 1993). If the stimuli are changed in certain ways, as having new offsets or locations, the performance in the task is similar to the level it reached after training. This generalisation to novel situations suggests that perceptual learning, and not only learning specific to the task, is taking place. There are a number of reasons why we should expect that learning has a role in tasks that involve the perception of TTC. First, it has been suggested that more learning takes place in complex tasks than in simple tasks (Fine & Jacobs, 2002). A number of processes contribute to the overall perception of TTC and each can potentially change by learning: the accuracy the cues themselves (looming rate, vergence, disparity), the way they are combined and which ones are given priority in order to produce estimates of TTC. Second, large individual differences are found in tasks that involve TTC as a component, such as catching. One of the common findings in studies in perceptual learning is that the variability between participants decreases over time, and that the participants with the lowest initial performance show the largest effects of practice (Fahle & Henke-Fahle, 1996). The variability shown in TTC and catching tasks would suggest that at least some participants would show strong effects of learning.

We have previously shown that learning can take place in an absolute TTC tasks (see chapter 2). One of the reported changes was a decrease in the variable error of the responses. This implies that the TTC became more consistent with training. This change can be caused by two different processes that can't be dissociated due to the nature of the task. Learning could be taking part at a perceptual stage, increasing the participants' sensitivity to TTC and so leading them to finer judgements. On the other hand, learning could be taking place at a later stage, linking the TTC percept to the motor response. In this second case, even if the percept of TTC has not been changed by the training, the participants would be better at translating their estimate into a response and so reduce the variability of the estimates. The absolute TTC task can't tease learning in these two processes apart. When we studied a TTC discrimination task -in which the motor component of the task is almost negligible-, we didn't find evidences for learning (chapter 1). Although this might point towards a lack of perceptual learning in TTC tasks, such a claim has to be further considered. If we compare both tasks, we can see that they have very different requisites. In the absolute TTC task the participant has to time a response based in a single computation of TTC and the feedback gives information about not only the degree of error but on whether TTC was under or over estimated. The discrimination task, instead, requires the participant to remember and compare the TTC of two intervals and the feedback given does not provide any information about the actual TTC of the stimuli, but only whether the correct one was chosen. It is possible that learning does not take place in the discrimination tasks due to the complexity of the task and the less informative feedback.

One other study has reported learning in a somewhat similar task. Smith et al. (2001) found in a collision prediction task that inexperienced participants would show biases in the timing of their responses. These biases suggested that they relied on looming rate, a simple correlate of the approach of the ball, instead of TTC. With training, the timing of the responses tended towards the use of TTC. In their study, the biases are related to the size and speed of the approaching balls -which alters looming rate but not TTC-. It would be reasonable to claim that these biases are of perceptual and not motor origin, and so, that perceptual learning is taking place. However, the task is very unfamiliar to the participants. First, it takes place under monocular viewing, so the participants might be learning to use monocular sources of information that in their daily life only partially contribute to TTC judgements. Second, the task requires the participants give their response by releasing a simulated pendulum positioned a certain distance in front of them. As the period of the pendulum is not known, it is possible that part of the reduction in bias is due to learning the dynamics of the swing of the pendulum. This might exaggerate the biases shown by the participants. None the less, when we trained participants with a binocular TTC estimation task, similar biases towards the use of simple correlates were found (see chapter 2). We argued that these show the use of motion-in-depth (MID) information by the participants. This finding is of relevance for the current experiment, as in the discrimination task we want to measure sensitivity to TTC, and MID has to be controlled in order to not confound them. This was achieved by decorrelating changes in TTC of changes in MID in the task.

In this chapter we present a series of experiments on the transfer of learning from a binocular absolute TTC task to a relative TTC discrimination task. This is done in order to evaluate whether part of the learning shown in absolute TTC tasks is due to an increase in the sensitivity to TTC. Sensitivity to TTC was tested before and after training by the means of a discrimination task. This task involves the participants judging the relative TTC of two intervals. Special care was made to decorrelate TTC from MID. The rationale is as follows. If absolute TTC tasks produce an increase in sensitivity, and not only an improved motor response in the task, the participants should show changes in their performance in a relative TTC discrimination task. On the other hand, if the decrease in variable error is due to improvements in the motor stage we would not expect the performance in the relative TTC discrimination task to change in any consistent fashion. For each experiment we included control groups that did not receive training in the absolute TTC task, in case of the sensitivity to TTC increasing when it is retested. Specifically, we expect that, if perceptual learning is taking place, the use of TTC will increase in the discrimination task following training in the absolute estimation task.

## Methods

*Participants*

A total of 38 participants with an age range between 19 and 29 years took part in the experiments. 21 took part in the first experiment, 12 in the second and 12 in the third. In the first experiment 11 participants were randomly assigned to the experimental group and 10 to the control group. In the second experiment half of the participants were randomly assigned to the experimental group and the other half to the control group. Six additional participants were tested in the third experiment, and the control group of the second experiment was employed as they shared pre and post test with the third experiment. All participants had normal or corrected-to-normal vision. All the participants took part in the study voluntarily and were free to choose which hand they used for responding in the experiments. The observers were naïve to the hypothesis of the study and not experienced in psychophysics.

*Apparatus*

See Chapter 2. As in Chapter 1, a mouse was employed for the discrimination task.

*Absolute time-to-contact task*

See Chapter 2 for the stimuli, design and analysis of this task.

*Time-to-contact discrimination task*

In the time-to-contact discrimination task two intervals were presented. This task is similar to the one presented in Chapter 1. None the less, there are some changes. Instead of presenting two randomized intervals on each trial, one of the intervals was always a standard interval and the other one was a test interval. The order of standard and test was randomised for each trial. The observers were instructed to choose the interval with the shortest time-to-contact. The distance and speed of the standard interval were chosen to match that of the absolute TTC task. The time-to-contact of the standard interval was 560ms and its motion-in-depth (sum of looming rate and change in disparity) was 11.34 degrees/second. Seven different values for time-to-contact and motion-in-depth were orthogonally manipulated to create the test intervals.

| | TTC (ms) | MID (degrees/s) |
|---|---|---|
| Experiment 1 | 400, 466, 509, **560**, 616, 672, 784 | 8.1, 9.45, 10.31, **11.34**, 12.74, 13.61, 15.88 |
| Experiments 2 and 3 | 331, 400, 466, **560**, 672, 784, 1008 | 6.3, 8.1, 9.45, **11.34**, 13.61, 15.88, 20.41 |

Table 1. Ranges of the stimuli for the three experiments. The values of the standard stimulus are shown in bold.

Table 1 shows the values of the stimuli employed in the three experiments of this chapter. For experiment 1, the standard was multiplied and divided by 1.1, 1.2 and 1.4, resulting in a variation of both TTC and MID of 196% between the largest and the smallest value. For experiments 2 and 3 this range increased to 304% for TTC and 323% for MID by multiplying and dividing the standard by 1.2, 1.4 and 1.8. As there is one stimulus for each combination of TTC and MID this results in 49 different test intervals in both cases. Three weightings of looming rate and change in disparity contributions (25% looming rate, equal weighting and 75% looming rate) were used to compute motion-in-depth. This results in a total of 147 different test intervals. Duration of the approach was randomised between 360 and 540ms for each standard and test interval.

*Procedure and design*

All participants took part in two sessions. At the beginning of the first session participants were instructed on both tasks. When introduced for the first time to a task, participants received ten trials of practice without feedback. During these practice trials they could stop at any moment to ask questions. For the first experiment the first session was comprised of one TTC discrimination task (range was 1.4 times the standard) and three blocks of absolute TTC with feedback. For the second and third experiment the first session was equivalent but with an extended range in the discrimination task (range was 1.8 times the standard). In the second session the order of the tasks was reversed: first absolute TTC with feedback and then TTC discrimination. In the first and second experiment three blocks of absolute TTC were administered in this second session, while in the third experiment only one block was given. For the first and second experiment control groups were tested as well. These control groups performed the TTC discrimination tasks but did not receive any training in the absolute TTC task.

*Analysis of the TTC discrimination task*

Performance in the discrimination task was assessed on the basis of the psychometric response surface relating responses to MID and TTC. This surface is shown in Figure 1. To construct it, we first averaged the responses within each of the 49 cells of response matrix. This is similar to the analysis employed by Regan & Hamstra (1993) that is described in the General Introduction. We chose to represent the responses as the proportion of times that the test interval was chosen over the standard interval. Each cell therefore takes on a value between zero, and both a value of TTC and MID associated to it. This results in a response surface such as the one presented in figure 1. It can be seen that the responses of the participant vary in a predictable fashion, from not choosing the test interval when it had a low TTC and MID to consistently choosing it when both TTC and MID were high.

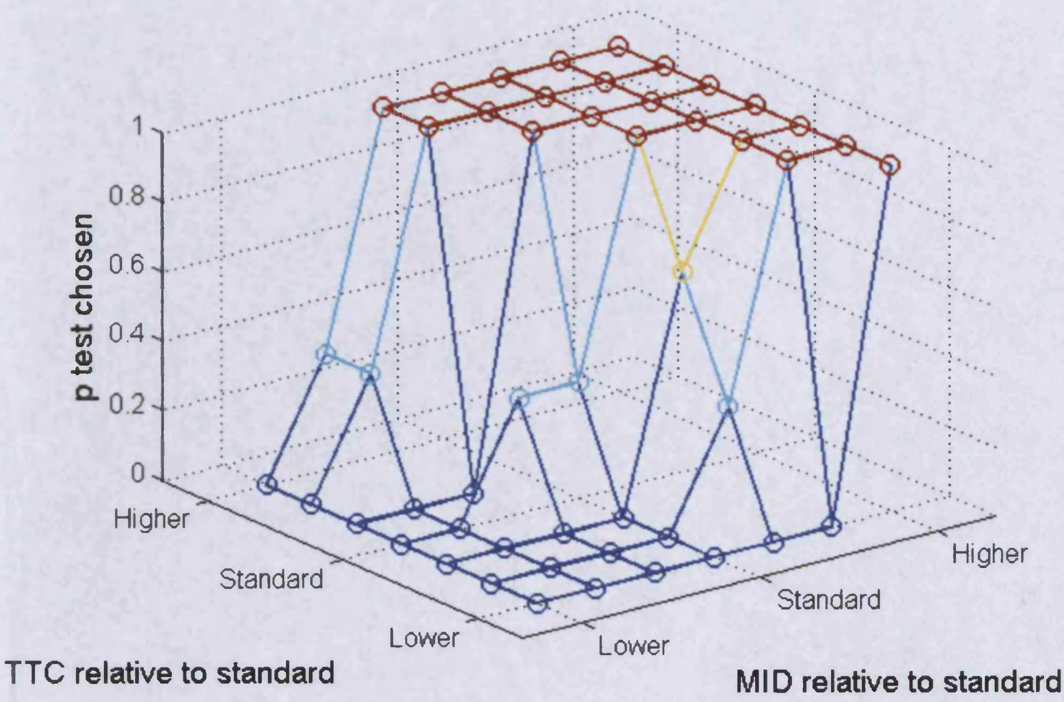


Figure 1. Response surface for a participant of experiment 1. The x and y axes show the TTC and MID. The z axis shows the proportion of times that the test interval was chosen over the standard interval.

We simulated what response surfaces would look like if only TTC or MID were discriminated. For this purpose we simulated observers that only responded to variations in a given variable. They were presented a test interval and a standard interval, and always chose the one with the lowest value of TTC in one case or the highest value of MID in the other. We added Gaussian noise to both of the signals in order to simulate human performance. This produces response surfaces as those presented in figure 2.

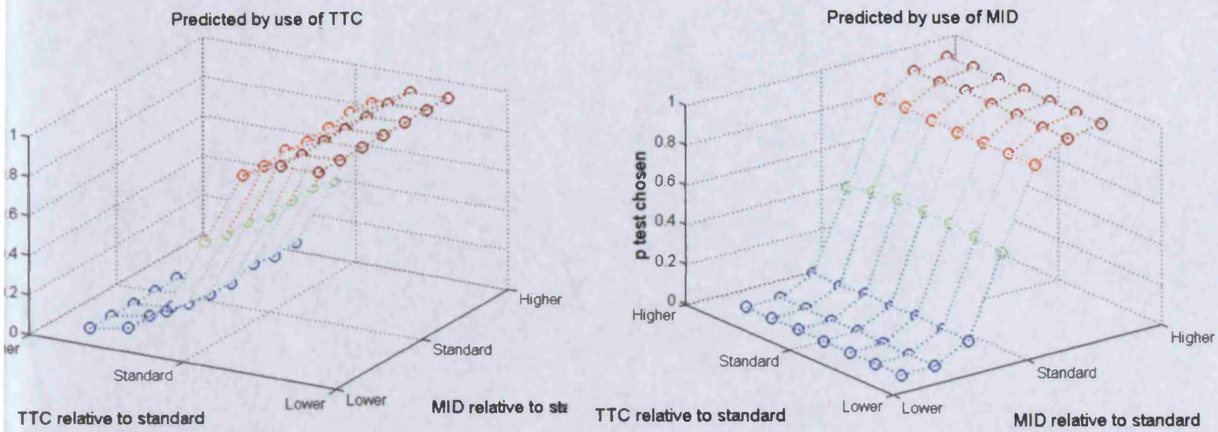


Figure 2. Response surfaces predicted by the use of TTC and the use of MID.

We could regard the response surface predicted by the use of TTC as a series of seven psychometric functions. These could be again averaged and the single resulting function be fitted with a probit function (Finney, 1971). However, the case of our example human observer in figure 1 is not as clear cut. Regan & Hamstra (1993) chose to average the response matrix over each of the axes and present two psychometric functions, one for each variable. This doesn't provide always a straightforward interpretation as averaging over one of the axes and fitting a single probit function ignores the interaction between the two variables. Here we chose a different approach, namely, producing probit plane fits. For doing so, we followed the procedure of fitting a probit function but instead of fitting a line we fitted a plane. First, the axes were transformed into their common logarithm. Second, the probit values of the responses were computed. Then, a plane was fitted on the resulting surface. The probit values of the points that comprise the plane could be then transformed back to proportions. The resulting surface is plotted over the responses of the participant in figure 3.

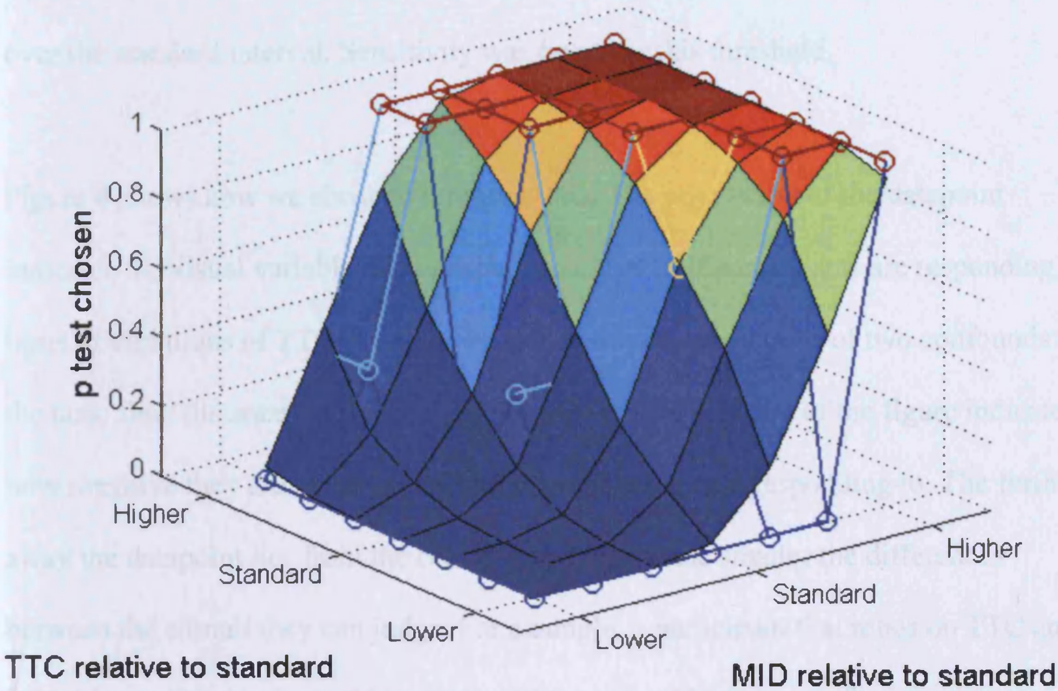


Figure 3. Probit plane fitted over the responses of the participant. The circles connected by blue lines represent the responses of the participant and the mesh the fitted probit plane.

We found that by following this procedure, the responses of the participants in the task could be described using simply two parameters. The first parameter was the orientation of the plane fit. The orientation shows to what variations in the test interval were the participants sensitive. Participants that would rely on only one of the two variables while ignoring variations in the other variable should produce functions that resemble those of figure 2. On the other hand, if the two variables are consistently interacting, other orientations will be found. The second parameter that we used to describe these probit surfaces was the steepness of the surface. This is a measure of how sensitive the participants were to the variable (or combination of variables) that they were responding to. Specifically, we used the steepness of the surface to measure the threshold at which the participant would choose the test interval 75% of the times over the standard interval. Sensitivity was one over this threshold.

Figure 4 shows how we chose to represent this. The orientation of the datapoint indicates the visual variable that is being used, that is, if participants are responding in basis of variations of TTC or MID. We also show the predictions of two confounds in the task: final distance and speed. The distance from the centre of the figure indicates how sensitive they are to variations in the variable they are responding to. The further away the datapoint lies from the centre of the figure, the smaller the differences between the stimuli they can judge. For example, a participant that relies on TTC and is highly sensitive to it would lie on the TTC axis and be far away from the centre of the figure. A participant that relies on MID but is not very sensitive to it would lie on the MID axis and be closer to the centre of the figure.

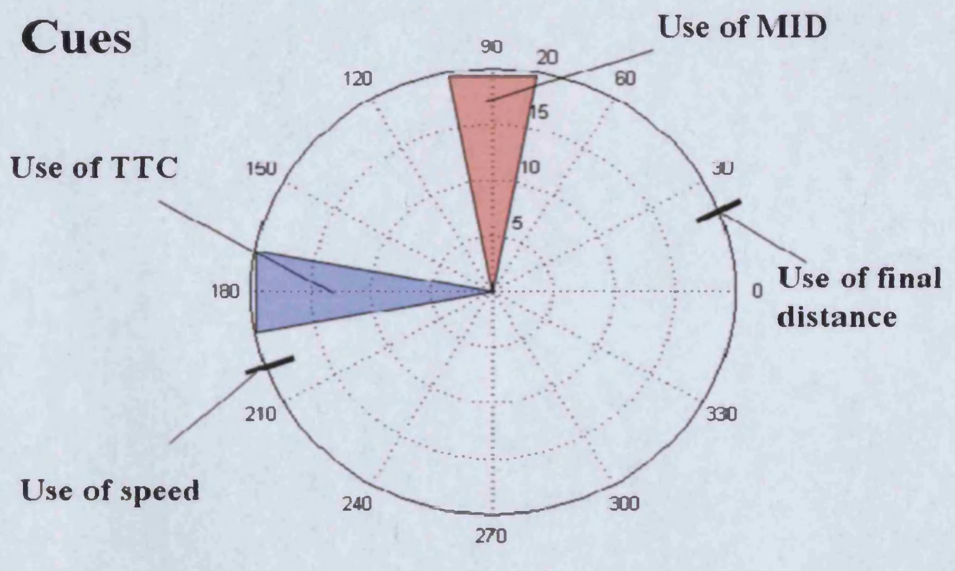


Figure 4. Polar plot for the presentation of the relative TTC discrimination measures. Orientation of the datapoints in the plot show what cue is being used. Distance from the centre, sensitivity to that cue.

## Results

*Overview*

Table 2 summarises the conditions of the three experiments. The only change from Experiment 1 to Experiment 2 is an increase in the range of the discrimination task. The only change from Experiment 2 to Experiment 3 is a decrease in the number of blocks of training that was given to the participants in the absolute estimation task.

| | Number of participants | Discrimination task range | Blocks of training in the 1st and 2nd sessions |
|---|---|---|---|
| Experiment 1 | 11 experimental, 10 control | Variation of 196% | 3, 3 |
| Experiment 2 | 6 experimental, 6 control | Variation of 304% | 3, 3 |
| Experiment 3 | 6 experimental | Variation of 304% | 3, 1 |

Table 2. Summary of the conditions of Experiments 1-3.

Figure 5 shows the prediction that is common to all the three experiments of this chapter. We expect that in the post-test the participants will rely more on TTC and have a higher sensitivity to it. This would appear as a drift of the datapoints towards the TTC axis and away from the centre of the figure.

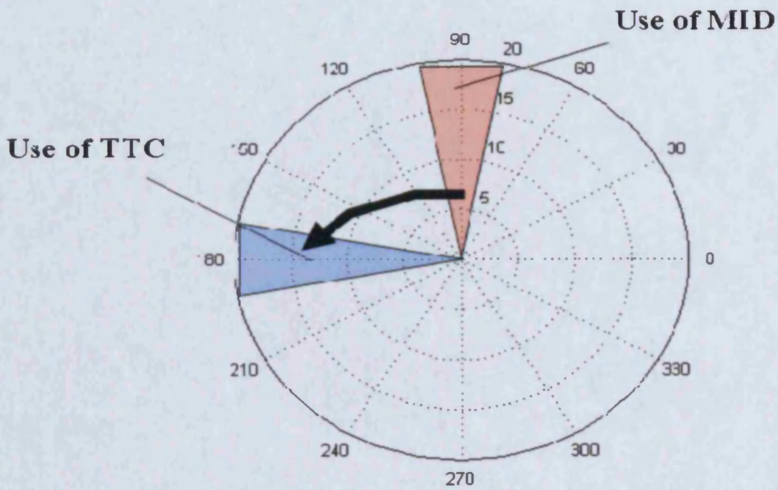


Figure 5. Prediction in the task. Participants are expected to show higher use of TTC in the post test. They are also expected to show a higher sensitivity.

*Experiment 1*

Sensitivity to TTC was tested in a relative TTC discrimination task before and after training in absolute TTC task with feedback. The training consisted of six blocks, which we have previously found that is enough for increasing the precision of the participants' estimates of TTC. In experiment 1 the test intervals contained the TTC and MID of the standard or 10%, 20% or 40% below and above the standard. In the overview we argued that if an increase in sensitivity to TTC follows the training, the participants' datapoints would drift towards the TTC axis and away from the centre of the figure. In figure 6 the blue points show the performance in the pre-test and red points show the performance in the post-test. The points for the same participants are linked by arrows. No particular trend towards and increase in the use of TTC can be seen in this figure. None the less, it must be noted that most participants show a reasonable performance in the task. That is, they are relying on TTC, MID or a combination of both, instead of responding against either of them. The performance of a control group that was not trained with the absolute TTC task is fairly similar (see figure 7). This suggests that the small changes between pre and post test are not related to the training in the absolute TTC task.

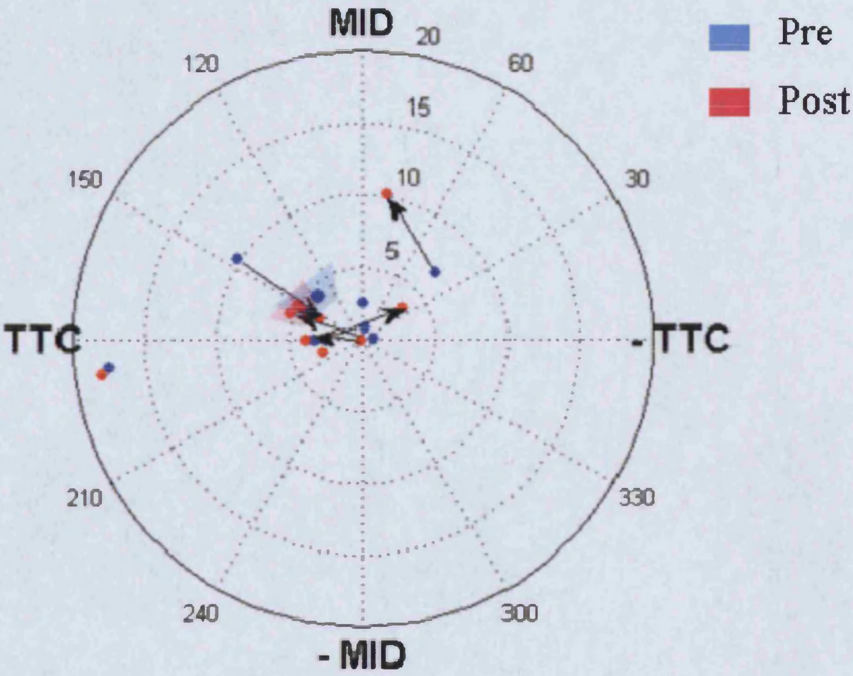


Figure 6. Time to contact discrimination before and after six blocks of training for 11 participants. The range of the task was 40% above and below the standard. The orientation in the polar plot shows what cue are participants responding to, and the distance from the centre shows with what sensitivity they respond to it. Blue dots show the performance before the training and red dots show the performance after the training. The larger circles and their surrounding shaded area is the mean of each condition and the related error surface. The largest changes are indicated with arrows.

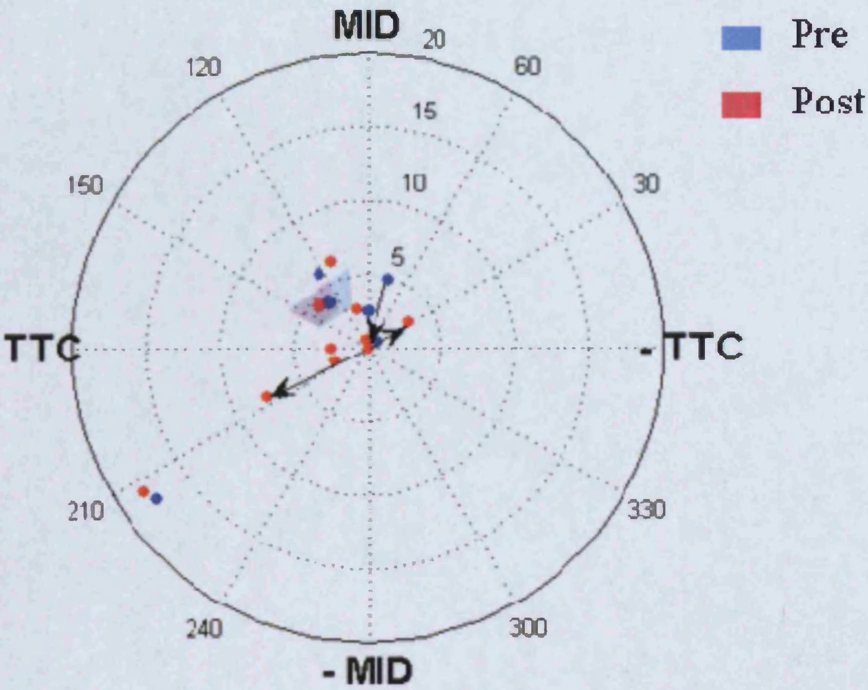


Figure 7. Time to contact discrimination data for the control group of 10 participants. The range of the task was 40% above and below the standard. The orientation in the polar plot shows what cue are participants responding to, and the distance from the centre shows with what sensitivity they respond to it. Blue dots show the performance before the training and red dots show the performance after the training. The larger circles and their surrounding shaded area is the mean of each condition and the related error surface. The largest changes are indicated with arrows.

*Experiment 2*

In experiment 2 we increased the range of the discrimination task. This was due to the previous range deemed as too narrow to measure effectively the performance of naïve participants. In experiment 2 we increased the range of the task in order to increase the difference between the test intervals and the standard intervals. This would make it easier for naïve participants to provide correct responses. The test intervals had TTC and MID same as the standard or 20, 40 or 80% above or below it. As in experiment 1, the participants were trained with six blocks of the absolute TTC judgement task with feedback. Although there were changes for the individual observers, no tendency for an increased use of TTC or an increase in sensitivity was found (see figure 8). The same can be said for the control group, which did not have any training in the absolute TTC task (see figure 9). As in experiment 1, the participants made reliable judgements during the task. If they had responded at random during the task, their sensitivity would be 0, and if they had misunderstood the instructions, they would have responded against the task relevant variables. This doesn't seem to be the case. That is, they responded as predicted by the use of the two main variables that we assessed (TTC and MID).

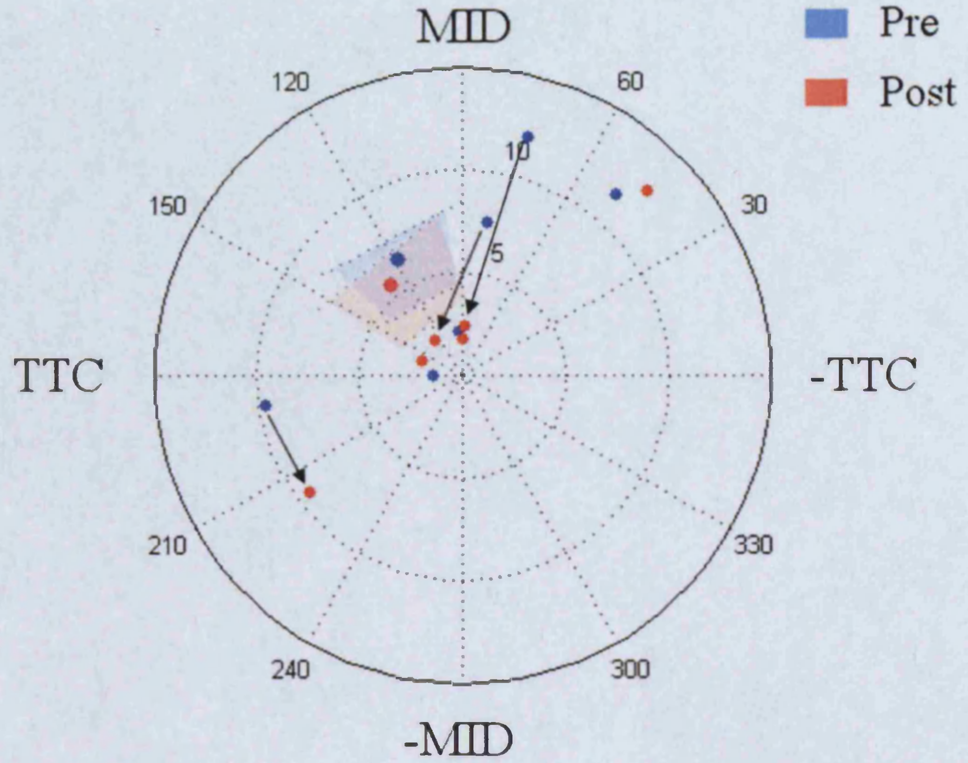


Figure 8. Time to contact discrimination before and after six blocks of training for six participants. The range of the task was 80% above and below the standard. The orientation in the polar plot shows what cue are participants responding to, and the distance from the centre shows with what sensitivity they respond to it. Blue dots show the performance before the training and red dots show the performance after the training. The larger circles and their surrounding shaded area is the mean of each condition and the related error surface. The largest changes are indicated with arrows.

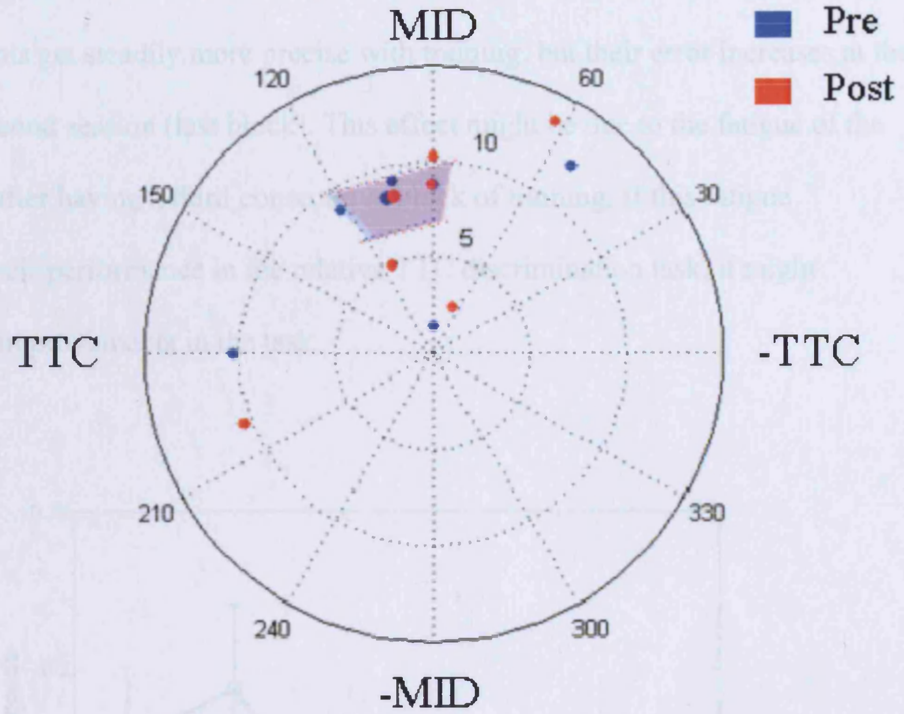


Figure 9. Time to contact discrimination data for the six participants of the control group. The range of the task was 80% above and below the standard. The orientation in the polar plot shows what cue are participants responding to, and the distance from the centre shows with what sensitivity they respond to it. Blue dots show the performance before the training and red dots show the performance after the training. The larger circles and their surrounding shaded area is the mean of each condition and the related error surface. The largest changes are indicated with arrows.

*Experiment 3*

Although we took care in providing an easier task for the participants in experiment 2, we did not find changes on relative TTC judgements following training. When we further analysed the data of experiment 2, we found that the performance of the participants decreased towards the end of training. Figure 10 shows the variable error of the participants across the six blocks. It can be seen that the estimates produced by the participants get steadily more precise with training, but their error increases at the end of the second session (last block). This effect might be due to the fatigue of the participants after having a third consecutive block of training. If this fatigue diminishes their performance in the relative TTC discrimination task, it might overshadow improvements in the task.

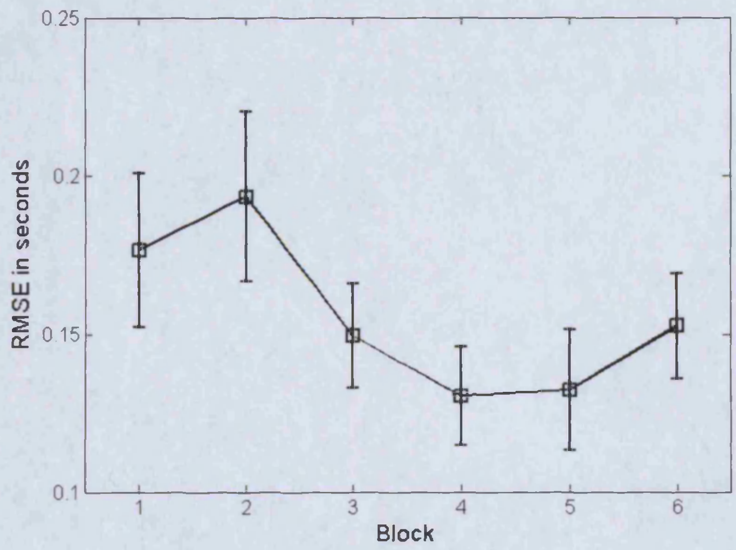


Figure 10. Variable error in the absolute TTC task of experiment 2. The error bars represent the standard error between subjects.

In experiment 3, we shorten the length of training from six blocks to four blocks, in order to reduce possible fatigue before the post test. In order to do so, the first session is composed of a pre test and three blocks of training, and the second session is composed of a block of training followed by the post test. In all other respects this experiment is similar to experiment 2, so the same control group can be employed to compare the performance of the trained group. Again, as in experiments 1 and 2, there was no trend to an increase in use of TTC or increase in sensitivity (figure 11). As previously, the participants made reasonable judgements. In both the pre and post test, the measures seem to have been very similar, with slight changes shown by some participants.

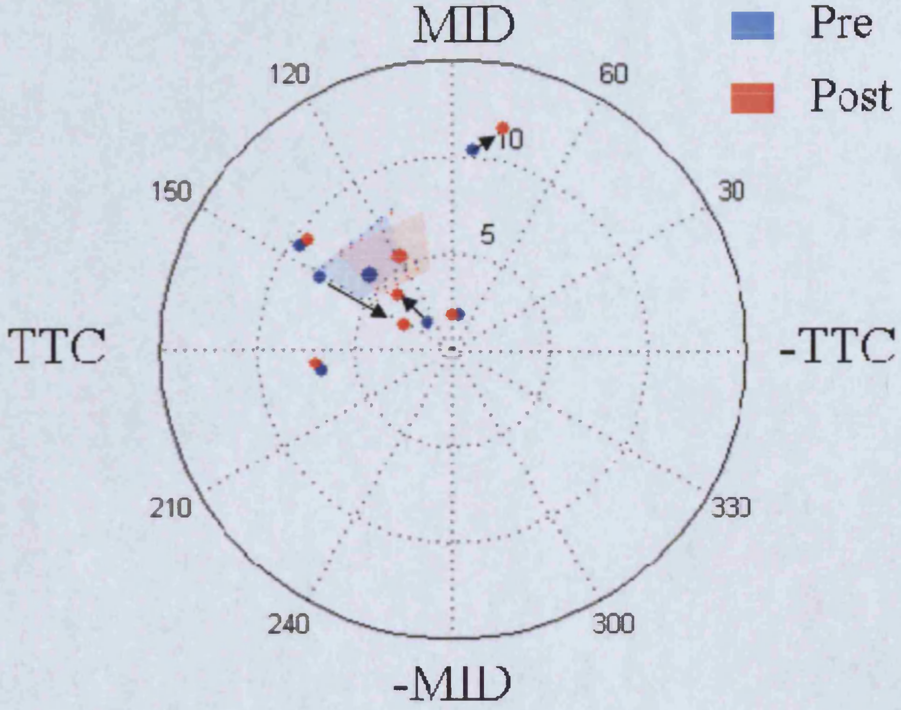


Figure 11. Time to contact discrimination before and after four blocks of training for six participants. The range of the task was 80% above and below the standard. The orientation in the polar plot shows what cue are participants responding to, and the distance from the centre shows with what sensitivity they respond to it. Blue dots show the performance before the training and red dots show the performance after the training. The larger circles and their surrounding shaded area is the mean of each condition and the related error surface. The largest changes are indicated with arrows.

## Discussion

We report three experiments on the transfer of learning between absolute TTC judgements and relative TTC judgements. Although the amount of training given to the participants and the difficulty of the relative TTC discrimination task were varied, in all three cases we failed to find transfer between the two tasks. If transfer of learning had been found it would have indicated that part of the increases in performance that are found during training in absolute TTC estimation are due to an increase of the observer's sensitivity to TTC. We did not find this to be the case. Instead of increased sensitivity to TTC, we suggest that most of the learning taking place in absolute TTC tasks is due to improvements in the motor response and calibration of the TTC estimates. Next we describe both processes and why learning in either process does not transfer to relative TTC judgements.

The first process is an increase in the precision of the motor response that translates the perceptual estimate into a timed action. In our task, once the arrival time of the object has been estimated, a well timed button press has to be performed. The suggested motor learning would be equivalent to reducing the temporal variability of this button press. Although our laboratory setting might seem unrealistic, it is reasonable to think that motor learning takes place in actions such as catching or hitting over long periods of time. On the relative TTC discrimination task the responses of the participants do not have time constraints and they do not require well timed actions. In this sense, we can't expect any motor learning to transfer, or maybe even take place, in the discrimination task. The second process that we suggest that undertakes learning in the absolute TTC task is a calibration of the TTC estimates. By this we refer to the bias of the observer to over or under estimate a certain perceived TTC. We have previously shown that TTC estimates can be modified by trial to trial feedback (see Chapter 3). This suggests that feedback is continuously monitored in order to produce well timed responses. In our relative TTC discrimination task, information about the actual TTC of the interval is not needed for responding in the task and it is not available through feedback. In other experiments information about the TTC and properly calibrated estimates are needed. For example, in the single interval task employed by Regan & Hamstra (1993), in which, participants had to compare the test interval with the average of the set. A stimulus for the average of the set was never presented, and instead it was expected to be acquired by presenting all the stimuli that comprised the task. Such a single interval task could present response biases that can be reduced with feedback. Another task that requires the participants to estimate the TTC of the approaching objects, and potentially calibrate it, is identifying objects as having short or long TTC (Oberfeld & Hecht, 2008). We have previously shown that absolute TTC tasks show such a calibration process, in which the TTC estimates of the participants approach those given by the feedback as training progresses (see Chapters 2 and 3). Our relative TTC discrimination task would not be affected by changes in calibration, as both the test and the standard interval would undergo them.

Taken together, these results suggest that increasing the sensitivity to TTC is not a priority of the visual system, as other sources of error are more noticeable and easier to tackle. It might yet be the case that under certain conditions such increases in sensitivity are found, such as during very prolonged training in a task that has been mastered in all its other aspects. Even so, in most studies, the learning that has been found is compatible with simpler explanations. For example, Smith et al. (2001) provided evidence of a change from a simple strategy (looming rate) to a more complex strategy (TTC) in a collision prediction task. However, in their study the task given to the participants was highly unfamiliar, and given that it was presented monocularly, they might have spent a fair deal of effort in learning a novel strategy they might not use in daily life, when binocular vision is available. Also, in a catching task, Jacobs & Michaels (2006) report learning compatible with calibration to the visual variable preferred by each participant. In their data, the fit between the timing pattern of the responses and several correlated visual variables increases with training. This suggests that maybe the catches themselves are being more consistent, and so, their timing is better correlated with the visual variables. In summary, the more unfamiliar to the participant a timing task, the more learning takes place. However, there seems to be no evidence for changes in perceptual sensitivity taking place in such tasks.

# Chapter 5 – Relationship between the perception of TTC and interception

## Abstract

Previous research has assumed interception to rely on the perception of TTC, but no empirical research has been carried out to substantiate this relationship. In this chapter we relate two measures of TTC perception to ball hitting skill in a large group of participants. In the first task, relative TTC discrimination, we found that those participants who demonstrated sensitivity to TTC hit significantly more balls than those that didn't. In the second task, absolute TTC estimation, we found that the more precise participants hit more balls in the hitting task than the less precise participants. Together, these results suggest that accurate perception of the arrival time of an approaching object plays a central role in interception.

## Introduction

It is an implicit assumption of the previous chapters, and the literature on TTC (see the General Introduction), that experiments assessing TTC estimation are tapping a process that is central to catching or hitting a ball. Is this assumption correct? Do the laboratory measures of TTC have external validity?

In this chapter, we explored the assumption of TTC perception underlying interceptive timing. Specifically we asked, does the performance in laboratory based relative TTC discrimination and absolute TTC estimation tasks predict performance on a natural interception task?

## Methods

*Participants*

54 participants with an age range between 19 and 29 years took part in the experiments. Each participant took part in the study voluntarily and was given 9 pounds as payment for their participation. The experiment took a total of an hour and half. All participants had normal or corrected-to-normal vision. The participants were naïve to the hypothesis of the study and not experienced in psychophysics.

*Apparatus and stimuli*

Apparatus and stimuli for the relative discrimination task and the absolute estimation task were the same as in Chapter 4. The range of parameters of the discrimination task was of 10%, 20% and 40% below and above the standard for both TTC and MID. This is the same range that was employed in Experiment 1 of Chapter 4.

In the hitting task the participant had to sit behind a perspex shield that allowed for the arm to be placed in front of the face. Two fixed length pendulums were released from three different positions each to create a total of six different trial types. The balls were standard squash balls attached to a piece of transparent fishing line. The pendulums were attached to the metallic railing of the ceiling by small magnets.

*Tasks*

*Relative and absolute TTC tasks*

The absolute TTC estimation task was identical to the one described in Chapter 2. The relative TTC discrimination task was identical to the one described in the first experiment of Chapter 4.

*Ball hitting task*

In this task the participants were instructed to hit an approaching ball off to the side with two fingers. The participants sat on the floor behind a protective shield made of perspex placed in front of them. The shield was transparent and allowed for unobstructed lateral motion of the arm used in the task. A circuit made out of a laser beam and a photodiode was used to recording the speed of the ball in each trial. This circuit was placed so that the laser beam would be interrupted by the ball midway its trajectory. By knowing the size of the ball and the time that the laser was interrupted, the speed of the ball at that point could be calculated. Each trial was also recorded using a video camera. Two pendulums of different lengths (151cm and 197cm) were used to create two different arrival times (1.23s and 1.40s). These pendulums were released from three different distances from the participant in order to produce three different speeds (two, three and four m/s) at a point placed 40cm in front of the surface of the shield (see figure 1).

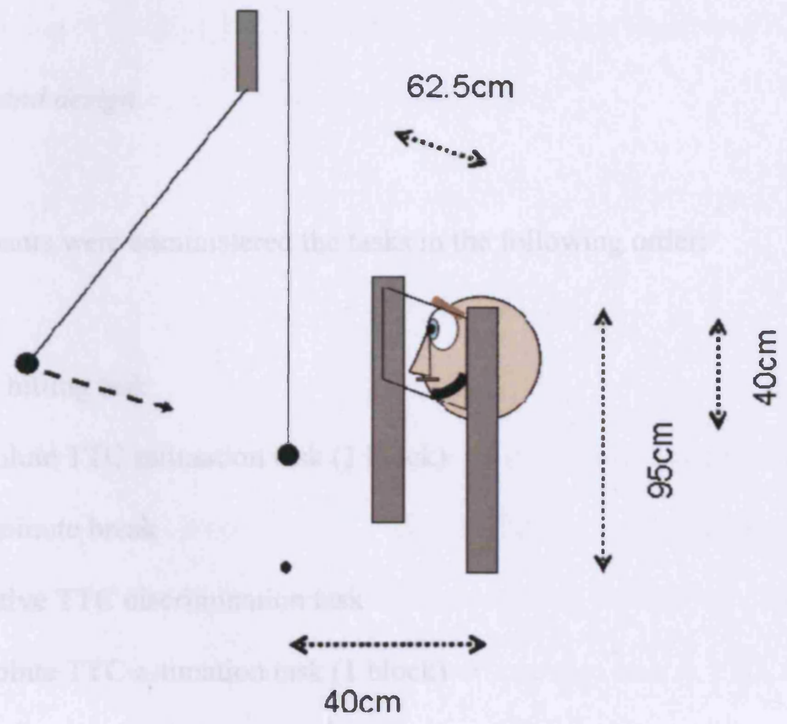


Figure 1. Depiction of the ball hitting task setup. The participant sits behind the protective shield and is free to move his arm in front of it. The balls are released so they approach the participant without any lateral motion component.

Four practice trials were administered before starting the task. On these trials two balls with the shorter arrival time and two balls with the longer arrival time were released from positions not used in the actual task. Participants were instructed to hit the ball by extending the index and middle finger of a hand of their choice. During the task each of the possible combinations of arrival time and speed was presented four times in order to produce 24 trials. The order of presentation of these trials was randomized in each session. The performance of the participant was coded (from the video record) as *hits* (the ball is clearly displaced to one side by the hit), *misses* (the participant doesn't hit the ball or does so but not moving his arm laterally) and *touches* (when the ball is hit but not displaced or when the trial doesn't clearly fall in one of the two previous categories).

*Procedure and design*

All participants were administered the tasks in the following order:

- ball hitting task
- absolute TTC estimation task (1 block)
- 10 minute break
- relative TTC discrimination task
- absolute TTC estimation task (1 block)

We kept this order for two reasons. First, we assumed that the hitting task would be easier to understand and so give us the highest chances of the participants not being confused in the later tasks. Secondly, we wanted to administer the absolute TTC task twice as a measure of fatigue. In other experiments we had noted that in long sessions performance deteriorates in this task towards the end of the session. (In actuality, in this study we found no differences in variable or constant error between the first and the second test in the task.) For each of the tasks separate instructions were provided in the form of written instructions and each participant took part in some practice trials that were not recorded.

*Analysis*

Details of the analysis of the relative TTC discrimination task can be found in the Methods section of Chapter 4. Details on the analysis of the absolute TTC estimation task can be found in the Methods section of Chapter 2.

## Results

All the following results are based on comparing the results in relative and absolute TTC tasks with a natural hitting task in a large sample of 54 participants. As will be recalled from Chapter 4, cue use can be understood using a polar plot. This plot shows whether participants were responding in the discrimination task to TTC, MID or any intermediate combination between the two. Figure 2 shows hitting skill as function of cue use. For this plot, distance from the centre indicates a larger proportion of balls being hit. It can be seen that the proportion of balls hit in the axis that indicates use of TTC is higher (about 0.6) than on the axis that indicates use of MID (over 0.4). In further analysis, we will refer to those participants that are in the area within 45 degrees of using TTC as TTC users. It can be seen from figure 2 that these TTC users comprise almost half of the sample. The sensitivity that the participants showed in the discrimination task was also assessed. In the plot in the top left of figure 3 we show the hitting skill of the sample in function of sensitivity. The relationship was not significant ($F(1, 53) = 1.23, p = 0.27$).

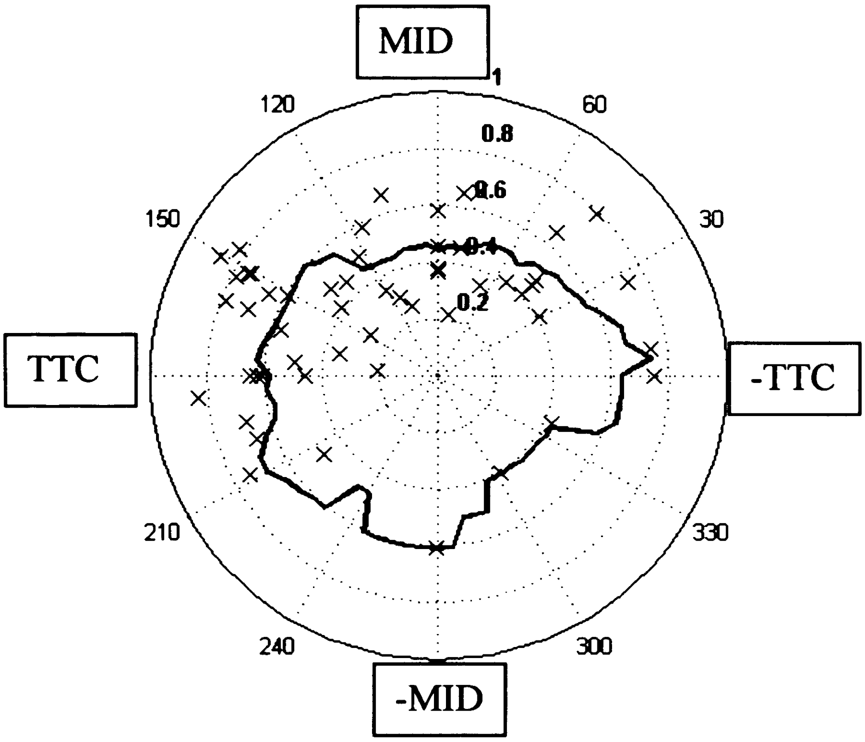


Figure 2. Proportion of balls hit plotted in function of cue use. The crosses indicate the data of the individual participants. The continuous line shows the proportion of balls hit for a moving average. The moving average had a window of 25 degrees.

The relationship between the three measures from the absolute TTC task and hitting skill was also investigated. In figure 3, hitting skill is plotted against the variable error of the estimates, the constant error of the estimates, and the slope of the estimates (a measure of compression). We found that the constant error and the slope of the TTC estimates was not related to hitting skill ($F(1, 53) = 0.51, p = 0.475$.; $F(1, 53) = 0.06$, $p = 0.812$). This suggests that biases that the participants might have in their TTC estimates in the absolute TTC task did not affect their success in hitting a ball. The relationship between variable error and hitting skill marginally reached significance ($F(1, 53) = 3.96, p < 0.1$). The slope of the fit between variable error and hitting skill was of -0.93. In our task, this translates every 100ms of variable error reducing the number of balls hit by about two.

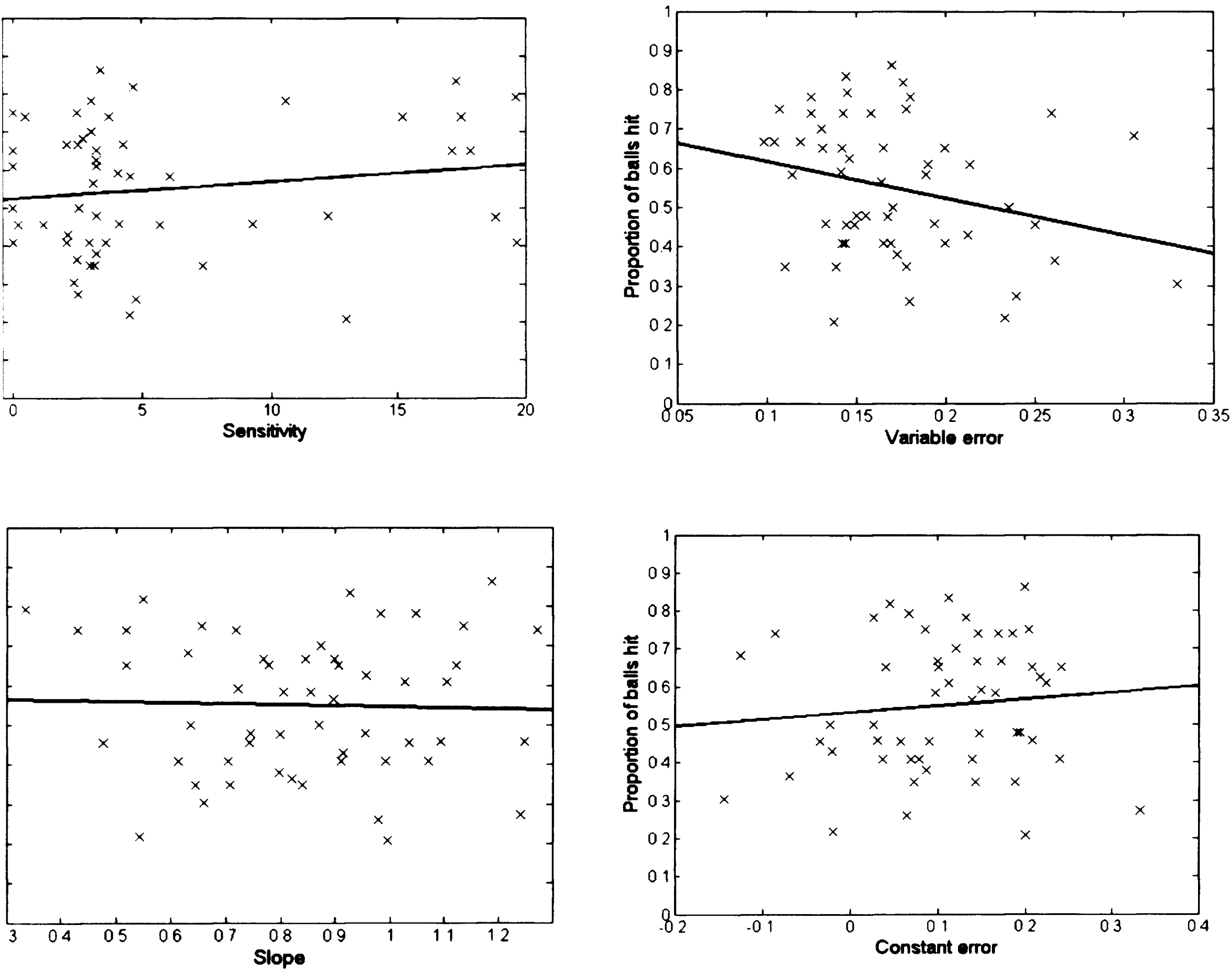


Figure 3. Relationship between proportion of balls hit and the other variables. Clockwise from top left: sensitivity, variable error, constant error and slope. The crosses indicate the data of the individual participants and the continuous lines the result of a linear regression on the data.

For the purpose of statistical analysis we split the observers into two groups, those that respond to TTC (within 45 degrees of the predicted by TTC) and those that do not (all the rest of the participants). The left hand side in figure 4 compares the number of balls hit by the participants that used TTC and those that did not in the discrimination task. Participants relying on TTC hit on average 13.84 balls while those not relying on TTC hit on average 11.41 balls. This difference between the number of balls hit in the two groups was significant ($t(52) = -2.249$, $p = 0.029$). When the participants that did not employ either TTC nor MID were discarded this relationship grew stronger. The participants employing TTC hit more balls than those employing MID ($t(44) = 2.575$, $p = 0.013$), with the TTC users hitting on average 13.84 balls and the MID users hitting on average 10.86 balls.

The relationship between variable error and hitting skill shown in Figure 3 was marginally significant. We performed a median split on this variable to divide our sample in a group with high variable error and a group with low variable error. We found that the low variable error group hit more balls during the hitting task (right hand side in figure 4). The group with lower variable error hit 13.63 balls on average, while the group with higher variable error hit 11.44 balls ($t(52) = -2.013$, $p = 0.049$).

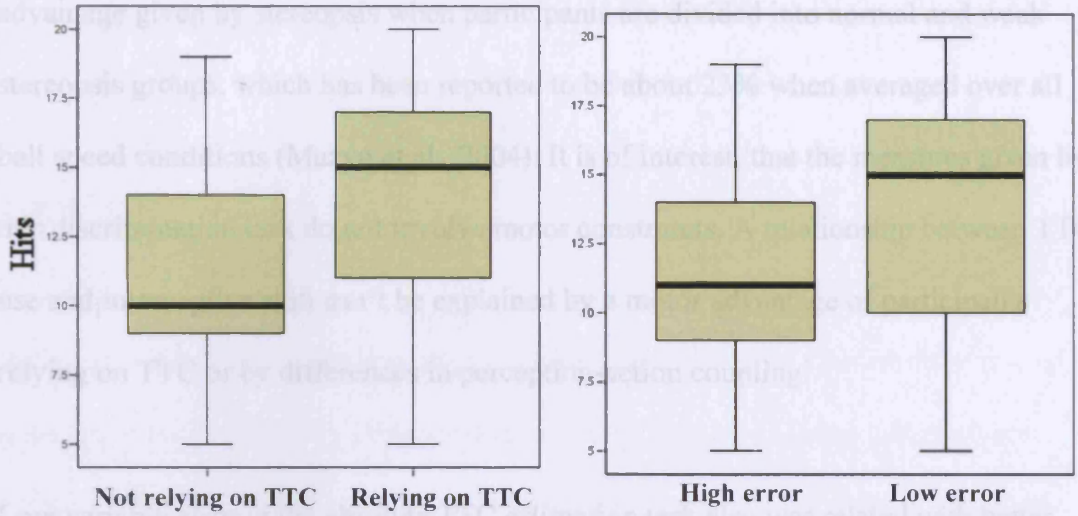


Figure 4. Number of balls hit in the hitting task for the participants relying on TTC and for those not relying on TTC.

## Discussion

Our data suggests that there is a link between the perception of TTC as measured by laboratory tasks and the success of interceptive actions. Different models of interception rely on the observer being able to compute TTC in order to produce a well timed action (Lee, 1976; Peper et al., 1994). Although correlates of TTC could be employed as controlling variables to guide a hitting or grasping movement, it seems to be that the intrinsic accuracy of the variable employed does have an impact on the success of the action.

Participants relying on TTC -as measured in a relative discrimination task- seem to hit about 25% more balls than those not relying on TTC. This is equivalent to the advantage given by stereopsis when participants are divided into normal and weak stereopsis groups, which has been reported to be about 23% when averaged over all ball speed conditions (Mazyn et al., 2004). It is of interest, that the measures given by this discrimination task do not involve motor constraints. A relationship between TTC use and interceptive skill can't be explained by a motor advantage of participants relying on TTC or by differences in perception-action coupling.

Low variable error in the absolute TTC estimation task also was related with better performance in the ball hitting task. This is less surprising than the relationship between use of TTC and ball hitting as the measure of variable error does involve motor components. We have previously suggested that the decrease of variable error in TTC estimates is related to improvements in the perception-action coupling and the accuracy of the motor response (see chapters 2 and 4). If participants with lower variable error have also a more accurate or faster perception-action coupling we would expect them to be more skilled at an interception task (see for example Le Runigo, Benguigui & Bardy, 2005). However, a relationship between the precision of absolute TTC estimates and interceptive skill gives some weight to the possibility that the findings of chapters 2 and 3 hold on for natural interceptive actions.

# General Discussion

## *Summary*

In the previous chapters we presented a number of studies that examined the role of learning in the perception of time-to-contact. A number of different designs were employed that shed light on different aspects of these learning processes. Relative discrimination judgements were used to measure sensitivity to TTC and other available cues that might have been employed to judge arrival time. These discrimination judgements allowed for most cues to be tightly controlled, and were deemed to produce results that tapped on the perceptual mechanisms with little influence of motor mechanisms. On the other hand, these judgements were not very realistic and issues about the efficiency of feedback were raised. Absolute estimation judgements were used to measure the accuracy of TTC perception. Unlike discrimination measures, the absolute measures allowed us to relate the perceived TTC magnitudes to the actual TTC magnitudes, matching one to the other. The downside of these judgements is their reliance in well timed motor responses. Finally, a real interceptive task was implemented. This allowed us to relate our two laboratory tasks to an ecologically valid task in which predicting timing was needed. The following by summarises the findings.

In Chapter 1 we were interested in the role of learning in a relative TTC discrimination task. Regan & Hamstra (1993) reported that under monocular viewing expert observers can discriminate stimuli in basis of their TTC while ignoring variations in other variables that correlate with it. However, in situations where no feedback is given, inexperienced participants might be biased when judging the relative TTC of two stimuli (DeLucia, 1991; DeLucia, 2005). These participants seem to rely on correlates of the approach of the object, cues that have an imperfect relationship with the actual TTC. One of such correlates that has been proposed as a method to guide interceptive actions, and to estimate TTC is the looming rate of the approaching object (Michaels et al., 2001; Smith et al., 2001; Lopez-Moliner et al., 2007). Smith et al., (2001) studied the effects of training in a task that involved timing the release of a pendulum in order to knock an approaching ball. They found that early in the task, looming rate would be employed for timing these actions and that with training a pattern of responses resembling more that predicted by the use of TTC would appear. This led us to ask if the differences between discrimination tasks that favoured the use of looming rate and those that favoured the use of TTC might be due to learning taking place in the task.

We addressed this question by designing a new relative TTC discrimination task. First, we wanted to compare the use of looming rate and TTC during the training. This was done by choosing a parameter range in which 25% of the trials would predict opposite responses depending on whether the participants relied on looming rate or TTC. We called these conflicting trials. Without such conflicting trials, it would not be possible to tell which variable was being used in the task. Second, although Regan & Hamstra (1993) employed a single interval method, we chose to use a two interval forced choice discrimination. Rationale for this choice is further discussed in Chapter 1 And third, the task was presented binocularly, which allows the participants access to more sources of information (Laurent et al., 1996).

We did not find any effects of training in this task. Moreover, the participants did not rely on TTC before or after training. Instead, participants relied in looming rate or motion-in-depth (MID). These results might be due to the MID being more salient than TTC in this task. It has been suggested that on discrimination tasks participants rely on any cues that allow them to discriminate the two sequences (Tresilian, 1995, 1999), and the high success rate given by MID might have encouraged such behaviour. Reasons for the lack of learning in this task are discussed further on.

In Chapter 2 we assessed effects of practice on a binocular absolute TTC estimation task. When estimating TTC with a timed action, several sources of error are available. Error is related to the variable that is employed, how much noise this variable has, how biased or inaccurate the variable is and the variability of the timing of the motor response. It has been reported that when binocular cues are available, TTC estimates have less variability and they are less biased relative to the actual TTC (Gray & Regan, 1998). However, it is not known if learning takes place in these tasks as it does in monocular absolute TTC estimation (Smith et al., 2001). Our results from chapter 1 suggest that under binocular presentation, little or no learning takes place in TTC judgement tasks. In the absolute TTC judgement task a single ball was presented approaching the observer and then made to disappear before arrival. Accurate feedback was presented to coincide with the time the ball would have actually arrived at the observer and participants responded by trying to press a button at this time. We found that the timing of estimates improved with practice. The variability of the responses decreased gradually, and so did the tendency of the participants to overestimate TTC. This rendered the responses of the participants more accurate once they had undergone practice than before it. On the other hand, we found that the looming rate of the stimuli had an effect on the TTC estimates. This effect did not diminish with practice.

The results of Chapter 2 point towards training not producing a change in the visual variables used in the task. Namely, the timing biases due to looming rate did not decrease, which would have indicated that the strategy that participants were relying on was changing. Instead, two changes seem to account for the learning that we found: a calibration of the timing and a reduction of noise. First, the initial timing biases are corrected by comparing the time of the responses with the TTC estimates provided by the feedback. This allows the range of the estimates to approach the range of the actual TTC, and so provide a timing that is more accurate. It is unclear whether this change is due to a calibration of the perceptual variable or if motor components are involved, such as a correction of the mapping from the perceptual estimate of TTC to the timing of the action. Second, the decline of the variability of the responses is compatible with a reduction of noise. This renders the estimates more precise. As with the calibration of the timing, this change can take place either at a perceptual level (an increase in sensitivity) or at a further motor stage. As before, the fact that the perceptual estimates of TTC are better translated into a motor response by changes in the quality of the perception-action coupling is a plausible alternative. Chapter 3 pursued this idea by exploring the effect of feedback on the calibration of the TTC estimates. Chapter 4 studied whether perceptual sensitivity was increased.

Chapter 3 focused further on how feedback is used to set the timing of responses in an absolute TTC task. In Chapter 2 we suggested that one of the roles of feedback is to calibrate TTC estimates in a trial-by-trial fashion. This was based on the observation that participants early on in the task tended to overestimate TTC, and gradually reduced this bias with practice. It follows that the timing of TTC responses could be manipulated by biasing the feedback. We tested this by training a group with feedback that was presented consistently early and a group with feedback that was presented consistently late. It was found that compared to a control group with accurate feedback, both these groups biased the timing of their responses in the expected direction. This suggests that feedback is used to calibrate TTC estimates. The change in timing took place gradually but quickly, in the first 30 to 45 trials of the experiment.

In chapter 3 we studied whether the learning in the absolute TTC task of Chapter 2 was driven by changes in perceptual sensitivity. As previously discussed, the changes in variability in Chapter 2 could be due to higher perceptual sensitivity or due to an improvement in matching the perceptual estimate with a motor response. In Chapter 4, we took advantage of the fact that relative discrimination tasks (e.g. Chapter 1) measure the perceived TTC with little influences from the motor system. By placing relative discrimination tasks before and after training the participants with an absolute TTC task, we were able to measure whether changes in sensitivity took place during the training. In three experiments in which we varied the parameters of the relative discrimination task, we did not find any reliable changes in sensitivity. This suggests that increases of perceptual sensitivity are not the main process leading to reduced variable error in absolute TTC estimates.

That no increases in sensitivity are found due to practice in an absolute TTC estimation task suggest that the reduced response variability shown in these tasks was due either to changes in the perception-action coupling or the motor response. A change in the perception-action coupling is also compatible with the changes in timing reported in Chapters 2 and 3. It might be the case that the priorities of the visual system in order to reduce its error when intercepting an approaching object are to bias the matching of percepts into actions and to reduce the noise associated with this transformation, instead of trying to focus into more effective perceptual sources of information or increase its sensitivity to them. As our experiments were performed in naïve participants in tasks novel for them, it remains the case that over very extended practice, these perceptual changes are still possible. Anyhow, we suggest that perceptual changes are not necessary for reducing a large amount of timing error in these tasks.

Several authors have suggested that some approximation of TTC -such as the monocular variable tau- is perceived in order to appropriately time a catch, hit or avoidance (Lee, 1976; Peper et al., 1994). In Chapter 5 we tested the assumption that the perception of TTC underlies the timing of interceptions. We did so by assessing the perception of TTC in relative discrimination tasks and absolute estimation tasks, and relating it to hitting skill in a large sample of participants. We found that those participants that relied on TTC in the discrimination task, and those participants that showed less variability in their estimates in the absolute TTC task, were more successful in the ball hitting task. This suggests that accurate TTC perception provides an advantage when intercepting a moving object. At the same time, it does provide support for the fact that our previously employed tasks relate to the timing of interceptive actions.

*Perceptual or perceptuo-motor learning?*

One of the recurrent topics of this thesis is whether perceptual learning is taking place. This is due to the fact that we did not find increases in perceptual sensitivity following training (Chapters 1 and 4), although we found learning in absolute TTC estimation tasks (see Chapters 2 and 3). The main difference between the two tasks is that although the absolute estimation task depends on the perceptual estimate, it also includes the precision of the motor action in its measures. This confounds perceptual and motor learning in the task. On the other hand, if learning had been found in the relative discrimination task, this could have been attributed to perceptual changes.

We addressed whether perceptual learning was taking place in the absolute TTC estimation task in two different ways. First, in Chapter 2, we analysed the effects of variations in looming rate on the constant error of the TTC estimates. We found that as looming rate was increased, the participants estimated the ball to reach them earlier. Smith et al. (2001) found that with training, this effect of looming rate on the timing of the responses decreased. This seems like genuine perceptual learning, as looming rate is a visual variable that affects the TTC estimate. In our experiment, we did not find the effect of looming rate on constant error to decrease with training. Instead, the two main changes we reported were a decrease of variable error (the estimates were more consistent) and a decrease of constant error (the estimates were closer to the veridical TTC). Neither of these two effects discards the possibility of learning taking place at a further, motor phase. The second way we investigated perceptual learning in the absolute TTC estimation task was by measuring its effects on a relative TTC discrimination task (see Chapter 4). This directly addresses whether the decrease in variable error in Chapter 2 is due to an increase in perceptual sensitivity. In three different experiments we found that training in absolute estimation did not increase the perceptual sensitivity to TTC. This, again, suggests that the learning we are finding is not taking place at a perceptual stage.

We have suggested in this thesis that learning could be taking place when the perceptual estimate is transformed into the motor system. At some point, the estimated TTC has to provide predictive information for an action enough time in advance for allowing for planning. Le Runigo et al. (2005) showed that expert and novice tennis players differed in the speed of their perceptuo-motor link. This allows the expert players to make use of visual information when there is less time left for the hit, and so correct their actions to achieve better performance. Our suggestion here is that this link does not only get faster, but also more precise with training.

In Chapter 3 we showed that manipulating the timing of the feedback relative to the TTC of the ball biased the estimates of the participants. In this thesis we did not study whether this calibration process takes place at a perceptual level. This could be done by studying the transfer of these biases to perceptual tasks. There are three previously employed tasks that do not require actions to be performed and that seem like good candidates for measuring the transfer of calibration: a single interval discrimination task in which the test is compared with the average of the set (McKee, 1981; Regan & Hamstra, 1993); an absolute TTC estimation task based on a staircase procedure, in which the stimulus is matched to a tone or flash of lights (Gray & Regan, 1998); and an identification task in which participants have to classify stimuli as having a short or long TTC (Oberfeld & Hecht, 2008). After training with biased feedback in an absolute TTC estimation task (or other interceptive tasks) we could expect the bias of the estimated TTC to change in these tasks if the calibration process is of perceptual nature.

*Feedback for judgements and feedback for actions*

The nature of relative discrimination and absolute estimation tasks also leads to differences on the feedback that is available for each. As we have previously discussed, the response in the discrimination task is a choice between the two presented intervals. The feedback that is given on this choice is whether the response was correct or not. Let's suppose that two intervals with the same ball travelling at the same speed are presented, with one of them being closer to the participant than the other. This would lead to this closer ball to have a shorter TTC, a higher looming rate, a higher rate of change in disparity and a larger image size. If the participant -correctly- chooses this interval, this would reinforce his use of any of the previously mentioned cues in order to perform successfully in the task. In order to switch from one cue to another, disagreements between the cues need to be introduced. After all, computing TTC is not necessary if a simple variable as the expansion or the size of the image allow you to behave optimally. In our experiments, we introduced disagreements between the different sources of information. In Chapter 1, the TTC and looming rate of the stimuli predicted opposing responses in 25% of the cases. In

Chapters 4 and 5, both TTC and MID predicted a larger number (50%). These experiments cannot be directly compared due to a number of differences in the methods and design. However, we found that when the correlation between TTC and other sources of information was high (Chapter 1), participants relied on these alternative sources of information, namely MID. When the correlation between TTC and MID was lower, such as in the orthogonal manipulations of Chapters 4 and 5, we found a number of participants relied on TTC.

We did not find learning in any of the discrimination tasks, neither when this correlation between cues was high (Chapter 1) or low (Chapter 4). However, in Chapter 4, the participants did not receive feedback during the discrimination task, and were instead trained on the absolute estimation task. It would be of interest to explicitly manipulate the correlation between the cues to test if learning takes place when this correlation is low. Under such conditions, TTC would allow for notably more successful performance than its correlates.

The absolute TTC estimation task forces participants to produce an explicit estimate of TTC. The feedback given on this response is also of absolute nature. As discussed in Chapter 2, this opens new possibilities in the processes that can undergo learning. The main difference with the discrimination task is that if there is a timing mismatch with the feedback, the bias of the estimates can be calibrated to decrease this mismatch. This process can take place with any cue that the participants might be using in the task. Our data suggested that participants did not rely on TTC. If they relied on MID, learning could be taking place in the form of improving the mapping between the perceived MID and the TTC signalled by the feedback. This would lead to an increase in performance.

Others have shown that feedback is more effective for actions than for perceptual judgements (Gray et al., 2006). One of the reasons for this difference might be the kind of information that the two tasks are relying on. On their perceptual discrimination task, feedback signalled whether the response was correct or incorrect. On their simulated catching task, feedback signalled whether the response was accurate, whether it was an underreach or whether it was an overreach. The information on the catching task might be richer, and initial calibration of the motor system might lead to larger effects of learning.

*Why are biases so easily acquired?*

In Chapter 3 we showed that participants trained with biased feedback calibrated their TTC estimates in the direction signalled by the feedback. This bias was acquired rapidly, in the first 30 or 45 trials of training in the task. Why would the visual system be biased so easily by feedback if the stimuli carry accurate information about TTC?

It might be the case that the constant calibration of TTC estimates is advantageous for successful performance in a number of tasks. In a number of sensoriomotor tasks it has been found that the mapping of perception to actions has to be calibrated in order to show optimal performance and adapt to changes of the organism (Bedford, 1999; Hernandez, Levitan, Banks & Schor, 2008). Calibrating perceived TTC to the catch or hit might be part of a similar process. In the discussion of Chapter 3, we used the example of hitting a shuttlecock during a game of badminton. Compared to a tennis ball, a shuttlecock will fall slowly because of the increased air resistance. TTC estimates are based on first order information, and so don't take acceleration in account (Benguigui et al., 2003). If we tried to hit a falling shuttlecock with the same timing that we would hit a falling tennis ball, this would lead us to hit too early. This is the sort of scenario in which we would need to calibrate our TTC estimate in order to delay our hit. It has been suggested elsewhere (Baures et al., 2007) that hitting and catching accelerating objects relies on 'shortcuts' instead of making use of information about the acceleration of the object. Acquired biases for different scenarios could be taken as an example of such shortcuts.

It has also been recently suggested that the known size of a ball is combined with information about its looming rate in order to produce accurate TTC estimates (Lopez-Moliner et al., 2007). Increasing the size of the ball will increase looming rate, and if this is the variable guiding the catch, it will produce an earlier catch. Knowledge about the fact that the ball is accelerating and knowledge about its size can be seen as two forms of prior knowledge that could produce more accurate interceptions. Here we suggest an alternative way to Lopez-Moliner et al. (2007) of using knowledge about ball size. Employing looming rate or MID as a controlling variable for the interception, knowledge about object size could be used to compensate the estimate. For example, if the ball size is increased which would lead to earlier action, a bias to time the action earlier could be added that is proportional to the increase in size of the ball. This would allow the same process to explain both the interception of accelerating balls and the role of object size.

It remains to be seen whether biases can be acquired independently for two different tasks, and whether they can be combined. For example, let's suppose that in a single task we present identifiable shuttlecocks and tennis balls. It would be necessary for the participant to acquire a bias to respond late, but only in those trials in which a shuttlecock is presented. Is this the case and independent biases can be stored, or is the bias rapidly calibrated to the task at hand? In this second case, our responses would always be calibrated to the last task that we performed, and practice with a new task would always be required in order to perform successfully.

*Learning in TTC estimation: a sketch of what's going on*

On this section we will try to put together our results to sketch a diagram of what is possibly going on in the visual system when it is being trained in interceptive actions. Our findings suggest that simple cues are combined in a fashion that produces TTC estimates. These estimates are biased according to the nature of the stimuli. For example, if motion-in-depth is relied on, it will lead to estimates of TTC that are influenced by the size and the speed of the approaching object. We found that in tasks that in relative TTC judgement tasks participants discriminated the arrival time of approaching balls based in variations in their motion-in-depth (see Chapter 1). We found absolute TTC estimation also to be biased. For two balls with the same TTC, a participant would respond consistently earlier to the one with the higher looming rate (see Chapter 2). It is not possible that these biases appear in the action stage of the absolute TTC estimation task. Instead, they seem to be produced by the visual variables used in guiding the action.

Our data suggests that training did not influence this perceptual stage in which cues about the approach of the object are combined into a TTC estimate. There are a number of ways in which learning could take place at this stage. First, cues that provide a better estimate of TTC could be identified and employed in the task. We did not find this to be the case in neither relative discrimination tasks nor absolute estimation tasks, although it has been claimed elsewhere (Smith et al., 2001). Second, the noise associated with the cues employed could be reduced; this would lead to finer estimates of TTC to be extracted from them. We did not find sensitivity to any visual variables to increase following training (see Chapters 1 and 4). However, in further stages of the interceptive action, learning does seem to take place. We identified two changes that follow training in absolute TTC estimation in Chapter 2. The first one is an increase in the consistency of the responses. This could follow either a reduction in noise in the perceptual or the motor stage of the interception. In Chapter 4 we suggest that this change does not seem to take place at the perceptual stage. The second change we found was that the responses could be calibrated by using feedback. That is, the bias of the estimates could be changed in order to match closer the feedback that was provided (Chapter 3). For example, if a participant was consistently overestimating TTC and given feedback on it, they would tend to respond earlier and reduce this overestimation. It is not clear where this process takes place. Taken together, it seems to be the case that early perceptual stages are fairly much fixed, but once the TTC estimates have been generated, the actions that are based in them can be adaptively changed.

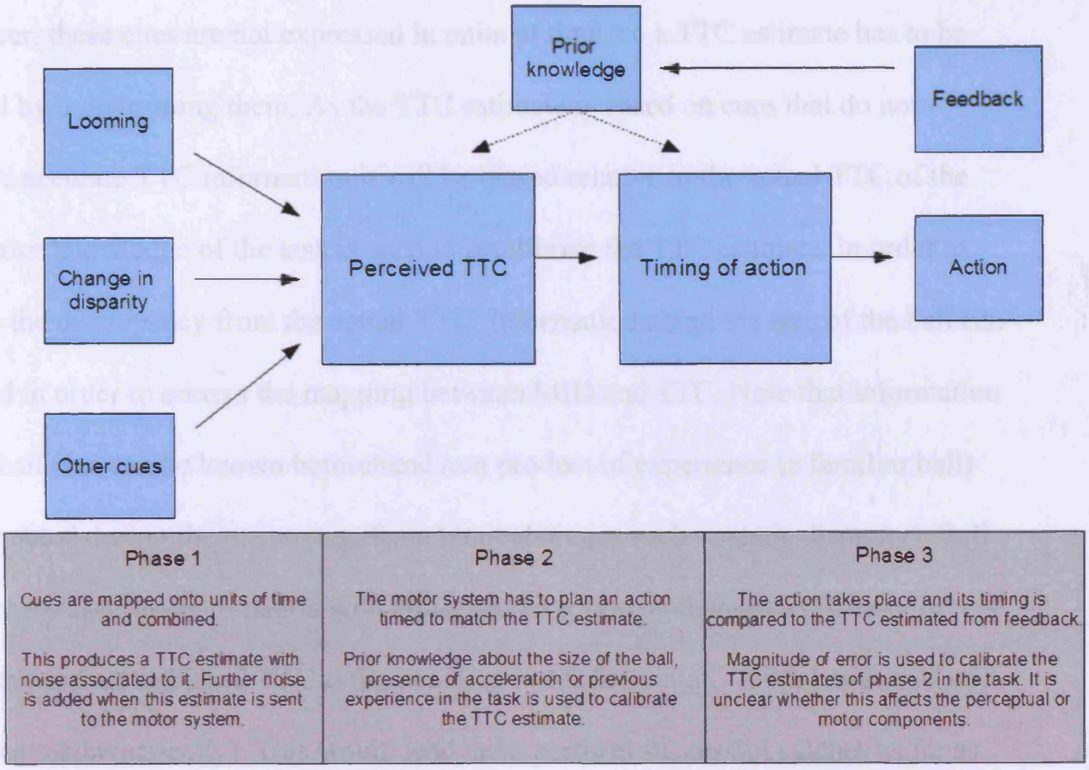


Figure 1. Diagram showing influence of learning in the timing of interceptive actions.

Figure 1 sketches some of these ideas (it might be of interest for the reader to compare this diagram with the proposal of Tresilian, 1994). In this diagram, the process of intercepting a ball has been divided into three phases. The first phase is perceptual, and consists of the generation of a TTC estimate from available cues. In the second phase, this TTC estimate is sent to the motor system that times an action to it. In the third phase the action takes place and feedback is generated from the outcome in order to increase the success of future actions. Let's follow what happens when a ball has to be caught.

First, the different cues to the approach of the object are perceived. Looming rate and the change in disparity, and their combination MID are examples of such cues. However, these cues are not expressed in units of time, so a TTC estimate has to be formed by transforming them. As the TTC estimate is based on cues that do not provide accurate TTC information it will be biased relative to the actual TTC of the ball. Prior knowledge of the task is used to recalibrate the TTC estimate, in order to reduce the discrepancy from the actual TTC. Information about the size of the ball can be used in order to correct the mapping between MID and TTC. Note that information about ball size can be known beforehand as a product of experience (a familiar ball) or computed during the action (e.g. from binocular cues such as static disparity). Ball size can be used in combination with either looming rate or change in disparity in order to produce unbiased TTC estimates (Lopez-Moliner et al., 2007, has formulated this idea mathematically). This would lead us to perform successful catches as far as there is not a great variability in the size of the ball, or 'catch' balls are not present. Notice that in our tasks the uncertainty about ball size is large, as it is varied from trial to trial. At this point the TTC estimate is also calibrated by our previous experience. This feedback loop will be discussed in the following paragraph. After these changes have taken place we will have a TTC estimate that has been calibrated to the requisites of the task.

The TTC estimate produced by the visual system is sent to the motor system and this has to plan an action matching the timing demanded by the TTC estimate. Practice increases the efficiency of this link reducing the amount of noise that is associated to translating the estimated TTC from the visual system into the motor system. Practice has been found also to reduce the time required to plan and execute the action (Le

Runigo et al., 2005). A shorter visuo-motor delay allows for more accurate information to be used in the catch. For example, if the last information we use to time the grasp is extracted 200ms before the arrival of the ball, the TTC estimate that is computed from it will be more reliable than one computed 500ms before the arrival of the ball. Assuming a variability of 5% in TTC estimates, such a shortening of the visuo-motor delay would reduce the possible error from 25ms to 10ms. Finally, when the catch itself takes place, the mismatch between the timing of the grasp and the TTC estimated by feedback is used to calibrate the following grasps. Such feedback is available from a number of sources. For example, we can see whether the ball was arriving early or late in our hand, and we can feel how comfortably the contact was made. If the grasp was performed severely late the ball will bounce from our palm and if early, hit our fingers.

There are a number of unknowns in this model that require further study. First, we don't know if the effect of feedback on calibrating timing of interceptions is affecting the perceptual phase or the motor phase. The previous paragraph assumed this information was used when the TTC estimate was computed, and so the feedback would alter the perception of TTC. But it is maybe more plausible that it takes place in the motor system. After all, when we play badminton after a long time, we feel that we are delaying our actions when the shuttlecock is falling slowly. Second, although the increased efficiency of translating the TTC percept into a motor action is a good suspect for the increase in consistency of TTC estimates in absolute TTC tasks, we only have indirect evidence for this claim. This evidence comes from the lack of increase in sensitivity reported in the experiments of Chapter 4. Third, the stage at which information about ball size is integrated is not known. This could be earlier on than when calibration due to learning takes place, maybe as early as to be considered another cue together to MID and combined with this in order to produce a TTC estimate. Alternatively, feedback might be used to learn a specific calibration that is related to each ball size, case in which it would take place later, even as late as in the motor phase of the action. However, this later option is more parsimonious as it reduces ball size to a cue that triggers a learnt bias, similar to those that we have taught to our participants in chapter 3. Fourth, a formalization of this model has not been produced. It remains to be seen how successful a model based on MID might be at timing the catch of a falling ball if allowed a short visuo-motor delay, information about ball size and a learnt bias to respond early.

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# Appendix

## Chapter 1

### Thresholds for the TTC, looming and MID for all the observers

1st indicates the first session of training and 6th the last session of training. Medians of all the sessions are reported. $Thres_{50}$ indicates to the 50% point of the psychometric function and $thres_{75}$ indicates the 75% point of the psychometric function. The unit is the logarithm of the ratio of the two intervals. A negative $thres_{75}$ shows that the participant was responding in the contrary direction to what was predicted for that variable.

### TTC

Conflict

| Observer | 1st $thres_{50}$ | 6th $thres_{50}$ | Median $thres_{50}$ | 1st $thres_{75}$ | 6th $thres_{75}$ | Median $thres_{75}$ |
|---|---|---|---|---|---|---|
| AE | -0.0097 | -0.1387 | 0.0137 | 0.1148 | -0.1627 | 0.1626 |
| GJ | 0.0089 | -0.2129 | 0.0255 | 0.0309 | -0.1079 | -0.1154 |
| GRE | -0.2136 | 0.0423 | -0.0105 | -0.0969 | -0.2736 | -0.2032 |
| MF | -0.0269 | -0.0882 | -0.0507 | -0.1243 | -0.0217 | -0.0073 |
| PH | 0.727 | -0.6579 | 0.0021 | -0.0821 | 0.3509 | 0.2918 |
| Average | 0.0971 | -0.2111 | -0.0040 | -0.0315 | -0.0430 | 0.0257 |

All trials

| Observer | 1st thres50 | 6th thres50 | Median thres50 | 1st thres75 | 6th thres75 | Median thres75 |
|---|---|---|---|---|---|---|
| AE | 0.0059 | -0.0166 | 0.0020 | 0.1085 | 0.084 | 0.0896 |
| GJ | 0.0014 | -0.0209 | -0.0134 | 0.1406 | 0.1198 | 0.1302 |
| GRE | -0.0362 | 0.0602 | 0.0142 | 0.0664 | 0.1685 | 0.1234 |
| MF | 0.0094 | -0.0325 | -0.0162 | 0.1039 | 0.0396 | 0.0489 |
| PH | -0.0067 | -0.0062 | -0.0056 | 0.0683 | 0.0741 | 0.0762 |
| Average | -0.0052 | -0.0032 | -0.0038 | 0.0975 | 0.0972 | 0.0937 |

**Looming Rate**

Conflict

| Observer | 1st thres50 | 6th thres50 | Median thres50 | 1st thres75 | 6th thres75 | Median thres75 |
|---|---|---|---|---|---|---|
| AE | 0.02474 | -0.1109 | -0.0476 | 0.3861 | 0.1658 | 0.2694 |
| GJ | -0.0165 | -0.0135 | -0.0150 | 0.0786 | 0.1503 | 0.1315 |
| GRE | -0.1641 | 0.0562 | 0.0226 | 0.0331 | 0.2063 | 0.2118 |
| MF | NaN | -3.5865 | -0.0447 | NaN | 0.0236 | 0.0236 |
| PH | -0.2109 | -0.1027 | -0.0121 | 0.1507 | 0.3875 | 0.1663 |
| Average | -0.0917 | -0.7515 | -0.0194 | 0.1621 | 0.1867 | 0.1605 |

Notice that the psychometric function for observer MA did not fit in the first session. This session for this observer was ignored in the analysis presented in chapter 1, and was the only datapoint missing.

All trials

| Observer | 1st $thres_{50}$ | 6th $thres_{50}$ | Median $thres_{50}$ | 1st $thres_{75}$ | 6th $thres_{75}$ | Median $thres_{75}$ |
|---|---|---|---|---|---|---|
| AE | 0.0137 | -0.0279 | -0.0030 | 0.208 | 0.1434 | 0.1935 |
| GJ | -0.0063 | -0.038 | -0.0314 | 0.1963 | 0.1862 | 0.2034 |
| GRE | -0.0701 | 0.0724 | 0.0270 | 0.1106 | 0.2106 | 0.1864 |
| MF | 0.0021 | -0.0516 | -0.0393 | 0.1592 | 0.1091 | 0.1401 |
| PH | -0.033 | -0.0166 | -0.0052 | 0.144 | 0.149 | 0.1461 |
| Average | -0.0187 | -0.0123 | -0.0104 | 0.1636 | 0.1597 | 0.1739 |

**MID**

Conflict

| Observer | 1st $thres_{50}$ | 6th $thres_{50}$ | Median $thres_{50}$ | 1st $thres_{75}$ | 6th $thres_{75}$ | Median $thres_{75}$ |
|---|---|---|---|---|---|---|
| AE | 0.0189 | -0.0712 | 0.0130 | 0.2601 | 0.1101 | 0.1166 |
| GJ | -0.0096 | 0.0023 | -0.0036 | 0.0506 | 0.0866 | 0.0942 |
| GRE | -0.0596 | 0.0183 | 0.0170 | 0.012 | 0.0950 | 0.1218 |
| MF | 0.0401 | -0.1684 | -0.0256 | 0.2161 | -0.0080 | 0.1032 |
| PH | -0.1007 | -0.0354 | -0.0136 | 0.0856 | 0.1361 | 0.0827 |
| Average | -0.0222 | -0.0509 | -0.0026 | 0.1249 | 0.0840 | 0.1037 |

All trials

| Observer | 1st $thres_{50}$ | 6th $thres_{50}$ | Median $thres_{50}$ | 1st $thres_{75}$ | 6th $thres_{75}$ | Median $thres_{75}$ |
|---|---|---|---|---|---|---|
| AE | 0.0137 | -0.0198 | 0.0012 | 0.168 | 0.1076 | 0.1510 |
| GJ | -0.0036 | -0.0292 | -0.0242 | 0.1708 | 0.1528 | 0.1727 |
| GRE | -0.0563 | 0.0623 | 0.0224 | 0.0952 | 0.1846 | 0.1631 |
| MF | 0.0032 | -0.0476 | -0.0299 | 0.1346 | 0.0651 | 0.0911 |
| PH | -0.0174 | -0.0084 | -0.0036 | 0.1093 | 0.1118 | 0.1106 |
| Average | -0.0121 | -0.0085 | -0.0068 | 0.1356 | 0.1244 | 0.1377 |

## Constant error for training and retest

Constant error in seconds, for all the blocks and participants. Only participants JG, JS and MA took part in the retest blocks, which are marked as R1-R6.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AE | 0.125 | 0.181 | 0.225 | 0.181 | 0.178 | 0.124 | 0.104 | 0.198 | 0.115 | 0.116 | 0.121 | 0.120 |
| AH | 0.434 | 0.393 | 0.296 | 0.258 | 0.283 | 0.287 | 0.286 | 0.321 | 0.296 | 0.300 | 0.283 | 0.294 |
| JG | 0.254 | 0.300 | 0.274 | 0.252 | 0.149 | 0.159 | 0.194 | 0.251 | 0.211 | 0.214 | 0.240 | 0.222 |
| JS | 0.111 | 0.089 | 0.089 | 0.053 | 0.186 | 0.150 | 0.091 | 0.181 | 0.150 | 0.154 | 0.133 | 0.126 |
| MA | 0.270 | 0.263 | 0.302 | 0.291 | 0.261 | 0.305 | 0.256 | 0.186 | 0.072 | 0.023 | 0.023 | -0.001 |

| | 13 | 14 | 15 | 16 | R1 | R2 | R3 | R4 | R5 | R6 | R7 | R8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AE | 0.246 | 0.134 | 0.090 | 0.139 | | | | | | | | |
| AH | 0.231 | 0.250 | 0.250 | 0.228 | | | | | | | | |
| JG | 0.210 | 0.212 | 0.247 | 0.232 | 0.175 | 0.141 | 0.126 | 0.144 | 0.136 | 0.157 | 0.120 | 0.152 |
| JS | 0.235 | 0.216 | 0.214 | 0.242 | 0.157 | 0.188 | 0.162 | 0.148 | 0.162 | 0.181 | 0.166 | 0.185 |
| MA | 0.085 | 0.080 | 0.073 | 0.042 | 0.047 | 0.008 | 0.021 | 0.037 | 0.061 | 0.025 | 0.059 | 0.047 |

**Variable error for training and retest**

Variable error as RMSE in seconds, for all the blocks and participants. Only participants JG, JS and MA took part in the retest blocks, which are marked as R1-R6.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AE** | 0.131 | 0.118 | 0.119 | 0.104 | 0.109 | 0.082 | 0.118 | 0.088 | 0.093 | 0.080 | 0.075 | 0.096 |
| **AH** | 0.125 | 0.145 | 0.145 | 0.171 | 0.107 | 0.095 | 0.092 | 0.102 | 0.054 | 0.064 | 0.079 | 0.076 |
| **JG** | 0.097 | 0.071 | 0.085 | 0.086 | 0.073 | 0.071 | 0.069 | 0.100 | 0.060 | 0.068 | 0.065 | 0.077 |
| **JS** | 0.180 | 0.137 | 0.156 | 0.119 | 0.120 | 0.112 | 0.120 | 0.117 | 0.080 | 0.107 | 0.096 | 0.098 |
| **MA** | 0.087 | 0.097 | 0.100 | 0.074 | 0.113 | 0.082 | 0.085 | 0.078 | 0.089 | 0.081 | 0.074 | 0.086 |

| | 13 | 14 | 15 | 16 | R1 | R2 | R3 | R4 | R5 | R6 | R7 | R8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AE** | 0.090 | 0.114 | 0.077 | 0.080 | | | | | | | | |
| **AH** | 0.065 | 0.077 | 0.070 | 0.082 | | | | | | | | |
| **JG** | 0.059 | 0.069 | 0.067 | 0.061 | 0.073 | 0.081 | 0.064 | 0.069 | 0.083 | 0.061 | 0.074 | 0.080 |
| **JS** | 0.104 | 0.090 | 0.093 | 0.076 | 0.080 | 0.078 | 0.075 | 0.089 | 0.071 | 0.086 | 0.086 | 0.092 |
| **MA** | 0.079 | 0.087 | 0.091 | 0.071 | 0.089 | 0.078 | 0.077 | 0.085 | 0.075 | 0.078 | 0.080 | 0.085 |

**Chapter 3**

**Constant error for the three groups**

Constant error for the control group for the eight blocks of training:

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| **Obs1** | 0.064 | 0.181 | 0.172 | 0.123 | 0.095 | 0.112 | 0.109 | 0.142 |
| **Obs2** | -0.022 | 0.067 | 0.036 | -0.002 | -0.066 | -0.080 | -0.075 | -0.092 |
| **Obs 3** | 0.055 | 0.031 | 0.069 | 0.038 | 0.016 | 0.026 | 0.035 | -0.004 |
| **Obs 4** | 0.090 | 0.196 | 0.144 | 0.200 | 0.189 | 0.130 | 0.149 | 0.130 |
| **Obs 5** | 0.267 | 0.233 | 0.284 | 0.339 | 0.230 | 0.244 | 0.230 | 0.246 |
| **Obs 6** | 0.136 | 0.182 | 0.090 | 0.053 | 0.059 | 0.026 | -0.021 | -0.047 |
| **Obs 7** | -0.127 | -0.147 | -0.151 | -0.086 | -0.145 | -0.161 | 0.047 | 0.025 |
| **Average** | 0.066 | 0.106 | 0.092 | 0.095 | 0.054 | 0.042 | 0.068 | 0.057 |

Constant error for the early group for the eight blocks of training:

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| **Obs 1** | -0.029 | 0.033 | 0.027 | 0.050 | -0.040 | -0.037 | -0.004 | 0.025 |
| **Obs 2** | 0.047 | -0.011 | 0.047 | 0.000 | -0.046 | -0.051 | -0.046 | 0.003 |
| **Obs 3** | 0.044 | 0.017 | -0.015 | -0.064 | -0.089 | -0.081 | -0.090 | -0.055 |
| **Obs 4** | 0.158 | 0.078 | 0.092 | 0.122 | 0.065 | 0.104 | 0.119 | 0.130 |
| **Obs 5** | -0.002 | 0.036 | 0.064 | 0.001 | -0.071 | -0.060 | -0.005 | 0.055 |
| **Obs 6** | -0.016 | 0.001 | 0.017 | 0.004 | -0.041 | -0.009 | 0.007 | -0.046 |
| **Obs 7** | -0.021 | -0.017 | 0.047 | -0.024 | -0.064 | -0.002 | -0.138 | -0.115 |
| **Average** | 0.026 | 0.020 | 0.040 | 0.013 | -0.041 | -0.019 | -0.023 | -0.001 |

Constant error for the late group for the eight blocks of training:

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| **Obs 1** | 0.198 | 0.226 | 0.224 | 0.206 | 0.186 | 0.188 | 0.210 | 0.201 |
| **Obs 2** | 0.213 | 0.262 | 0.253 | 0.256 | 0.233 | 0.231 | 0.263 | 0.246 |
| **Obs 3** | 0.075 | 0.092 | 0.073 | 0.027 | 0.011 | 0.054 | 0.100 | 0.063 |
| **Obs 4** | 0.254 | 0.258 | 0.269 | 0.244 | 0.209 | 0.262 | 0.251 | 0.241 |
| **Obs 5** | 0.218 | 0.308 | 0.351 | 0.325 | 0.286 | 0.314 | 0.293 | 0.318 |
| **Obs 6** | 0.022 | -0.025 | 0.064 | 0.073 | 0.137 | 0.144 | 0.050 | 0.085 |
| **Obs 7** | 0.168 | 0.253 | 0.230 | 0.205 | 0.230 | 0.200 | 0.200 | 0.084 |
| **Average** | 0.164 | 0.196 | 0.209 | 0.191 | 0.185 | 0.199 | 0.195 | 0.177 |

**Pre-test and post-test data from experiment 1 for all the participants**

| Experimental group | | | | Control group | | | |
|---|---|---|---|---|---|---|---|
| Orientation | | Sensitivity | | Orientation | | Sensitivity | |
| Pre | Post | Pre | Post | Pre | Post | Pre | Post |
| 180 | 180 | 2.510 | 3.911 | 180.0 | 181.0 | 2.510 | 2.510 |
| 138.5 | 160.2 | 0.000 | 5.310 | 129.5 | 199.6 | 4.189 | 2.349 |
| 147 | 154.5 | 10.308 | 3.316 | 90.1 | 106.9 | 2.514 | 2.716 |
| 73.5 | 153.4 | 0.819 | 4.275 | 211.4 | 205.5 | 0.000 | 7.562 |
| 254.9 | 97.1 | 0.052 | 0.000 | 140.1 | 33.5 | 0.000 | 3.280 |
| 90 | 178.5 | 2.510 | 2.512 | 39.8 | 116.7 | 0.842 | 0.000 |
| 186.4 | 187.6 | 17.582 | 18.164 | 123.0 | 112.9 | 5.983 | 6.443 |
| 42.7 | 80.5 | 6.829 | 10.210 | 90.0 | 106.5 | 2.510 | 0.655 |
| 180.1 | 196.5 | 3.254 | 2.770 | 74.2 | 110.0 | 4.886 | 0.000 |
| 180 | 37.9 | 2.510 | 3.455 | 215.6 | 212.6 | 17.595 | 18.094 |
| 9.5 | 252.6 | 0.795 | 0.000 | | | | |

**Pre-test and post-test data from experiment 2 for all the participants**

| Experimental group | | | | Control group | | | |
|---|---|---|---|---|---|---|---|
| Orientation | | Sensitivity | | Orientation | | Sensitivity | |
| Pre | Post | Pre | Post | Pre | Post | Pre | Post |
| 49.7 | 45.1 | 11.538 | 12.658 | 90 | 67.2 | 1.437 | 2.597 |
| 92.6 | 90 | 2.195 | 1.827 | 122.5 | 114.2 | 8.851 | 5.078 |
| 80.5 | 127.4 | 7.572 | 2.160 | 53.9 | 62.2 | 12.167 | 13.620 |
| 188.5 | 217.3 | 9.697 | 9.395 | 180 | 200 | 10.307 | 10.436 |
| 180 | 159.8 | 1.437 | 2.097 | 103.3 | 90 | 9.211 | 10.307 |
| 74.8 | 90 | 11.583 | 2.193 | 90 | 90.4 | 8.870 | 8.871 |

**Pre-test and post-test data from experiment 3 for all the participants**

| Experimental group | | | |
|---|---|---|---|
| Orientation | | Sensitivity | |
| Pre | Post | Pre | Post |
| 145 | 142 | 9.612 | 9.450 |
| 151 | 150.7 | 7.817 | 2.878 |
| 81 | 90 | 1.850 | 1.827 |
| 189.2 | 185.3 | 6.859 | 7.085 |
| 131.1 | 135 | 1.960 | 4.063 |
| 84.5 | 77.9 | 10.485 | 11.801 |