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Age-related differences in the perception of gap affordances: Impact of standardized action capabilities on road-crossing judgements

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Abstract

Recent road-crossing literature has found that older adults show performance differences between estimation and perception-action tasks suggesting an age-related difficulty in accurately calibrating the information picked up from the surrounding environment to their action capabilities (Lobjois & Cavallo, 2009). The present study investigated whether participants could accurately perceive gap affordances via information that specifies the time-to-arrival of the approaching cars. To ensure the opportunities for action were the same across different age groups, independent of the actor's action capabilities, the action of crossing the road was standardised. A total of 45 participants (15 children, aged 10-12, 15 adults aged 19-39, 15 older adults aged 65+) were asked to judge, by pressing a button in a head-mounted display, whether the gap between oncoming cars afforded crossing. When the participant pressed the button, they moved across the road at a fixed speed. Adherence to a time-based variable (namely tau) explained 85% and 84% of the variance in both the children and adults' choices, respectively. Older adults tuned less into the time-based variable (tau) with it only accounting for 59% of the variance in road-crossing decisions. These findings suggest that, the ability to use tau information which specifies whether a gap affords crossing or not, deteriorates with age.

Keywords: aging, affordances, tau, action capabilities, road-crossing.

Age-related differences in the perception of gap affordances: Impact of standardized action capabilities on road-crossing judgements

Every day we are constantly making decisions about when and how to act; for example, when driving a car, riding a bike or even crossing a road. This type of action-based decision-making requires us to accurately pick up and use information from the surrounding environment to control our subsequent actions. The difficulty is being able to pick up the spatio-temporal information embedded in an unfolding event and use this to decide if an action can be completed in the remaining time. A clear example of this is crossing the road; a complex spatio-temporal task that requires close perception-action coupling between the actor and his/her surrounding environment to ensure that the pedestrian gets across the road safely (Plumert & Kearney, 2014). This complexity is reflected in the national accident statistics, where incidents involving pedestrians make up 25% of all road related fatalities in the UK (Department for Transport, 2017). Indeed, to perform these actions successfully, we need to be able to detect the relevant perceptual information that specifies whether there is enough time to allow the observer to complete their action (i.e. get to the other side of the road before the approaching car arrives) (Lee, 2005).

In order to anticipate and act ahead of time, information must be picked up through the senses in a direct and immediate way. Gibson's (1979) ecological approach to visual perception provided a theoretical framework whereby decision-making could be understood as emerging from the properties of the environment/actor system (EAS) (Lee, Bootsma, Frost, Land, Regan and Gray, 2009), where we move to perceive and perceive to move. Gibson described the information that arises from the EAS as an opportunity for action, or an affordance. Affordances fall into two broad categories: body-scaled (constrained by the physical dimensions of the actor) and action-scaled (constrained by action capabilities e.g., how fast the actor can run) (Pepping & Li, 1997). As a result, the actor scales the environment to their own capabilities for action e.g. a large gap between two cars affords safe crossing providing the actor can move fast enough to cross the road before the gap closes.

These opportunities for action can come and go in an instant. Understanding what information specifies the 'crossability' of a gap is critical given that the stakes of making an error become greater. The affordance for 'crossability' can be perceived directly by tuning into the changing patterns of the optical array (i.e. optic flow), which is generated as the head moves through the environment. To time our actions accurately, our visual system has to interpret the way this patterning of information specific to the observer, picked up by our senses, changes over time (Craig et al., 2009; Watson et al., 2011). Lee (1976) describes how changes in the optic array can provide direct information about the time-to-arrival (TTA) of an object. Tau, an optical variable, captures how the rate of closure of spatial gaps can provide robust temporal information that allows for the prospective control of the actions of an actor without the need for any complex calculations of speed or distance. This variable is defined mathematically as the size of the gap, at any given moment, divided by its rate of closure ($x/\dot{x}$) (Lee, 1998). As a result, tau can be seen as an invariant property that can be used to prospectively guide action, explaining how we can anticipate what is going to happen next so we can act ahead of time. Research has shown that tau can be reliably used to coordinate actions when intercepting or striking a ball but also when reading biological motion (Bootsma & Peper, 1992; Craig, Delay, Grealy, & Lee, 2000; Brault, Bideau, Kulpa, & Craig, 2012). Importantly, for spatio-temporal tasks, tau can specify the time to arrival of an object but can also specify whether an upcoming collision is going to occur if the current course of action is maintained (Bootsma & Craig, 2003; Coull et al, 2008).

For older pedestrians who often experience a decline in both perceptual abilities and physical capabilities (Corso, 1981; Doherty, Vandervoort, & Brown, 1993) tasks such as driving a car or crossing a road can present a particular challenge. Research has shown how older adults alter their decision-making to compensate for this decline. Cesari, Formenti and Olivato (2003) demonstrated how older adults with the same leg length as younger adults significantly differed in their ability to judge which steps afforded climbing or not. The authors attributed these differences in judgement as being due to a decline in leg dexterity. Furthermore, Zivotofksy, Eldror, Mandel and Rosenbloom (2012) showed that knowledge of your own action capabilities appears to falter with age with elderly participants' road-crossing estimations and their actual crossing times differing significantly due to a failure to recognise the decline in walking speed over the lifespan. Additionally, older adults have been shown to be more conservative in their gap selection and adopt strategies such as a quicker initiation when crossing to allow more time to get across the road and compensate for their slower walking speed (Oxley et al., 2005; Lobjois & Cavallo, 2009).

Conversely, children can take advantage of their wider range of action capabilities and have shown an ability to systematically adjust their walking speed when crossing the road if their current walking speed would result in a collision (Morrongiello, Corbett, Milanovic, Pyne, & Vierich, 2015). However, a greater reliance on evasive skills may suggest children are poorer at tuning into the specifying information in the optical array. Wann, Poulter, and Purcell, (2011) show that children under 11 cannot reliably detect the discrete changes in optic flow i.e. optical looming in cars approaching at over 20 mph. Since the rate of looming is vital for the successful use of tau, any lower thresholds for successfully detecting this information should be reflected in a lower adherence to tau when detecting gap affordances. Despite decreased sensitivity to looming and the use of evasive action, recent research adopting virtual reality paradigms demonstrate that children appear to choose similar temporal gaps to adults suggesting both age groups use similar perceptual information when detecting gap affordances (Morrongiello, Corbett, Milanovic, & Beer, 2015; Plumert et al., 2004; Plumert, Kearney, Cremer, Recker, & Strutt, 2011). The present study aims to address the question if children and adults use the same perceptual information to inform decision-making and if the optical variable used directly specifies time remaining until an approaching car arrives (TTA). This research will further our understanding of children's ability to estimate TTA and determine if age is a factor that prevents children from using perceptual information that specifies gap affordances in a road-crossing scenario.

As older adult's movements lack flexibility and speed, the elderly cannot simply take evasive action whenever they have misjudged the TTA of an approaching object. This places a greater importance on the visual system's ability to accurately detect action-relevant information, with inaccurate judgements potentially having serious implications for safe road crossing. Research has shown that time-to-arrival estimates appear to be less accurate in older adults who underestimate the time it takes a moving object to arrive significantly more than young adults (Scialfa et al., 1991). Older adults appear to compensate for this decline in estimation accuracy by adopting simplifying heuristics e.g. 'the further the car is from me, the safer the gap' (Oxley et al., 2005). This results in the conclusion of a heavy reliance on their distance from the object rather than a specifying variable such as TTA (Oxley et al., 2005; Lobjois & Cavallo, 2007; Dommes, Cavallo, Dubuisson, Tournier, & Vienne, 2014). Petzoldt (2014) suggested that a more reasonable explanation was that instead of using heuristics based on physical distance, older adult's gap selection was more likely a result of distorted time-to-arrival estimates. When these factors are considered, it is understandable why older adults are more conservative in their gap selection and make more unsafe decisions when crossing a road (Oxley et al., 2005; Butler, Lord, & Fitzpatrick, 2016).

Many of the original studies investigating the impact of age on making decisions about whether the road is safe to cross or not, have used methodologies that capture behavioural responses by asking participants to press a button or give verbal responses when viewing stimuli on two-dimensional screens or simulated live scenarios (e.g. Oxley et al., 2005; Lee, Young, & McLaughlin, 1984). Some have questioned the lack of ecological validity of some of these methods, with more recent studies turning to immersive, interactive virtual reality environments such as a CAVE or head mounted displays to present an egocentric viewpoint of the approaching cars and offer participants the ability to act more realistically (e.g. Tzanavari, Matsentidou, Christou, & Poullis, 2014; Azam, Choi, & Chung, 2017). Lobjois and Cavallo (2009) compared gap selection of older adults in an estimation task (perception only) and an interactive task that required actual crossing (perception coupled to action). As expected, young adults adopted a different strategy in the actual crossing task, as they were able to calibrate their actions and adjust their walking speed according to the perceptual information specifying the time to arrival of the approaching car. However, no significant differences were found between estimation and actual crossing tasks in the older adults' group. This age-related difference observed in tasks when perception and action are coupled could be attributed to the poorer action capabilities in the adult group. A potential error that is worsened by incorrect estimations of their own road crossing times (Zivotofsky et al., 2012). Alternatively, these findings could be the result of older adults using non-specifying perceptual variables to estimate time to arrival and consequentially are unable to adjust their actions correctly as the perceptual information they are using is unreliable (non-specifying).

The present study was conducted to further investigate how age affects the accuracy of road-crossing judgements. As noted, in tasks where the perception-action loop is maintained, older adults have been shown to be poorer at calibrating their own movements to those required to interact effectively with what is happening in the surrounding environment. Children, on the other hand, have been found to take evasive action (e.g. speeding up or even running) to ensure task success and avoid a collision with a car (Lobjois & Cavallo, 2009; Morrongiello et al., 2015). A two-lane virtual reality scenario will be used where participants cross the road at a fixed speed and therefore, controls for potential differences in action capabilities between participants. This will allow the experimenters to evaluate how participants of different ages (children, young adults and older adults) are able to calibrate their perception of the crossability of the gaps between cars to the standardised road-crossing speed imposed by the virtual reality simulation. The approach of the cars has been controlled in such a way that tau specifies the TTA of the approaching cars. Our analysis will see how well participants tune into and use this information. The present experiment aims to answer the following questions:

(i) How well can each age group judge the ‘crossability’ of gaps between oncoming traffic in a road-crossing task when action capabilities are standardised (fixed movement speed)?
(ii) How does age impact on the ability of participants to use specifying information (tau) to inform road crossing decisions?

Our experiment will allow us to conclude whether there are age differences in detecting the ‘crossability’ of a road (perceptual judgements) when the physical task of crossing the road (action) is standardized for all participants. By standardising the time to cross the road (action response), the ‘crossability’ of the gap between vehicles specified by tau (the time to arrival of the cars) will be the same for all participants. This means variability in action capabilities will not impact on task success and enables us to conclude if performance differences across age groups is due to poorer detection of the perceptual information that specifies the ‘crossability’ of the gap between cars.

Method

Participants.

A total of 45 participants were recruited for the study. This included 15 children (5 boys, 10 girls) aged between 10-12 (*M* = 11 yrs, *SD* = 0.85), 15 adults (8 men, 7 women) aged between 18-39 (*M = 23.5 yrs*, *SD* = 4.1) and 15 older adults (5 men, 10 women) aged between 65–91 (*M = 73.5, SD = 8.9*). Older adults were recruited from local fitness classes and were required to be able to walk for an extended period without an aid. The International Physical Activity Questionnaire (IPAQ) was used to assess older adult's weekly levels of physical activity (Tomioka, Iwamoto, Saeki, & Okamoto, 2011). Participant's own action capabilities were assessed by physically walking across a road 3 times with a large temporal gap between cars (8.9s) while wearing a head-mounted display with a motion tracker from which average walking speeds were extracted (see table 1). This allowed the experimenters to assess walking speed under naturalistic road-crossing conditions. Ethical approval was granted by the University ethics committee.

****INSERT TABLE 1****

Apparatus.

The immersive, interactive virtual road-crossing environment was presented in an Oculus Rift DK2 stereoscopic head-mounted display (see figure 1a). The HMD had a resolution of 1920x1080 with a refresh rate of 100 frames per second with a diagonal field of view of 100 degrees. A head mounted display was preferred to a CAVE system as it allowed for active perception and has been found to produce more accurate judgements when judging gaps in previous studies (e.g. Mallaro, Rahimian, O'Neal, Plumert, & Kearney, 2017). To allow precise updating of head orientation in real-time while navigating through the virtual environment, the ultrasonic Intersense IS-900 motion tracking system was used to track a participant's movement through the environment. Crossing was initiated when a participant pressed the 'A' button on an Xbox One controller.

****INSERT FIGURE 1****

Design.

The virtual environment consisted of a two-way street, six-metres wide from sidewalk-to-sidewalk (see figure 1b). Each lane of traffic was mirrored to ensure only one gap was presented to the participant in each trial. The task consisted of mirrored bi-directional traffic moving at three constant speeds (32, 48 & 64 KPH (20, 30 & 40 MPH)). The distance between the cars that afforded crossing varied between six distances (30m, 40m, 50m, 60m, 70m, & 80m). The varying speed and distances were combined to give 18 different time gaps (time-to-arrival) to cross the road. The movement speed of the participant was fixed at 1.42 m/s based on an average adult's walking speed (Mohler, Thompson, Creem-Regehr, Pick, & Warren, 2007). Given the width of the road (six-metres) the time to cross the road was fixed at 4.2 seconds. The combination of walking speed and the TTA of the cars meant that in 50% of the trials the gaps between the cars afforded crossing and 50% of the time they did not.

Coding and Measures.

For analysis purposes, if the participants had crossed the road by the time the far lane of traffic arrived it was considered a successful cross. Collisions were recorded if the participant was 'hit' by any of the virtual cars. Safe errors were documented when a participant did not choose to cross even though the duration of the gap exceeded the time it would take to cross the road. Response time was defined as the duration in seconds from when the rear bumper of the lead car passed in front of the participant to the moment the participant pressed the button to initiate a cross.

Procedure.

Consent was given prior to experimentation and assent was received from the parents of the children's group who were present at the time of testing. The experimenter placed the

HMD on the participant’s head. A familiarisation period was conducted, where participants were encouraged to look around and get used to the feeling of being immersed in the virtual road-crossing environment. Next, participants were asked to press the button on the controller to cross the road for without traffic. Participants were seated in a chair and were handed the Xbox One controller and instructed as to which button to press to make a decision. Once they were familiar with the controller, the experimenter placed the HMD on the participant’s head. A familiarisation period was conducted, where participants were encouraged to look around and get used to the feeling of being immersed in the virtual road-crossing environment. Next, participants were asked to press the button on the controller to cross the road for without traffic. When participants pressed the button, they were automatically translated (similar to that of being pushed in a wheelchair) through the environment at a fixed speed of 1.422 m/s taking a total of 4.2 seconds to cross the six-metre road. **Video 1** illustrates the speed and type of movement the participants experienced in the virtual environment (Stafford, 2019). This familiarisation period allowed the participants to experience how fast they would move through the environment when crossing the virtual road. Participants experienced this virtual translation through the environment for five trials.

****INSERT VIDEO 1****

Video 1. Video demonstrating what simulated fixed movement speed was like visually inside the virtual environment.

A calibration period followed which consisted of 18 trials with randomised rates of gap closure between the cars that were not included in the main analysis. This provided participants with an opportunity to calibrate their perception of the TTA of the approaching cars to the timing of the pressing of the button to trigger the standardised movement to cross the road. This exploration was deemed an important means of enabling rapid calibration of perception to action capabilities by establishing action boundaries that specify what is and is not possible (see van Andel, Cole, & Pepping, 2017, for a review).

During the calibration phase, when a trial began, a stream of 11 vehicles in two lanes (travelling at the same speed and equal distances) approached the participant. Embedded within the traffic was a discernible gap between two cars that the participant was instructed to decide whether it allowed enough time to safely cross or not. If the participant accepted a gap that did not afford safe crossing (TTA less than 4.2 seconds), the virtual cars would pass through the participant providing feedback that a collision occurred. Each trial ranged between 13 and 18 seconds. The responses from the 18 trials recorded in this training period were not included in the main analysis but were used in an analysis to determine how quickly participants adapted to the imposed walking speed.

When the participants completed the calibration phase, the main experiment began. This consisted of 54 pseudo-randomised trials representing 18 different time-to-arrival conditions repeated three times. The participant observed the approach of the cars and was instructed that if they felt the gap between the cars was sufficient to cross the road then they should press the button. If they felt it was not then they should not press the button and wait for the trial to end. Although participants were informed that they could take a break at any point, a compulsory break was imposed half way through the experiment. During the breaks, the HMD was removed, and the participant was offered refreshments. The time of the button press along with the coordinates of the participant’s head movements and that of the cars were recorded 100 times per second. These data were used to measure the timing of the decisions with respect to the movement of the cars.

Results

Impact of age on behavioural responses & outcomes

Firstly, the relative success of the participants in the different age groups in the road-crossing study was assessed. Table 2 presents the mean percentage of crosses, collisions, safe errors and response times (with and without collisions).

*****INSERT TABLE 2************

Correct decisions were calculated as a percentage of the total number of trials in which the participant accurately judged the 'crossability' of the gap. A decision was deemed correct if the participant rejected a cross that was too short to afford safe crossing and pressed the button to cross a gap that was long enough to afford safe crossing. Adults performed best in the task overall (*M* = 79.9%, *SD* = 6.8) with children following in second (*M* = 71.7%, *SD* = 7.2) and older adults recording the lowest number of correct decisions (*M* = 66.3%, *SD* = 8). An ANOVA revealed a significant main effect of age on the percentage of correct decisions (*F* (2, 44) = 13.023, *p* <.001). Post hoc tests with Bonferroni correction showed significantly higher percentages of correct decisions for adults compared to children (*p* = .011) and for adults compared to older adults (*p* = <.001). However, no significant differences were found between children and older adults (*p* = .147) highlighting how age impacts on task success.

To assess if there were significant differences between age group's walk speeds, a one-way between-groups ANOVA was conducted. It revealed no main effect of age on walking speed, (*F*(2,44) = .484, *p* = .620) suggesting no particular age group was placed at a disadvantage by adopting a fixed walking speed. Following this, to determine if participant's were scaling the gaps according to the fixed walking speed and not their own action capabilities i.e. accepting/rejecting gaps based on their own walking speed, a simple linear regression was calculated for all 3 groups. If participant's were basing judgements on their own walking speed, participant's with the lowest magnitude of difference between real and imposed action capabilities should be the most successful due to similar gap affordances being presented. The walk duration differential (calculated as 4.22 s (time taken to cross the road in the present experiment) subtracted from the average physical crossing time for each participant) was used to predict the percentage of successful decisions (see table 1). The negative differential values were converted to positive to assess if there was a linear relationship between the magnitude of the differential and success rate. The walk speed differential was not a statistically significant predictor in any age group including children (p = .895), adults (p = .262) and older adults (p = .234). This suggests that participants were not scaling gap affordances to their own action capabilities but rather the fixed walking speed imposed in the present experiment.

A comparison of practice calibration trials against recorded trials was analysed to assess if the differences between groups in terms of the percentage of correct decisions was impacted by a longer learning/calibration period. The percentage of correct decisions in the initial practice trials was recorded with adults performing the best overall (*M* = 75.4%, *SD* = 7.2), older adults following in second (*M* = 60.3, *SD* = 14.2) and children recording the lowest number of correct decisions (*M* = 55.1, *SD* = 16.38). A repeated measures t-test was used to compare each age group’s practice calibration trials and the main experimental session trials and revealed no significant differences for adults (*p* = .965) or older adults (*p* = .108). However, significant differences were found between children’s practice and recorded trials *t*(18) = 5.28, *p* = .004. This suggests a longer learning period was required for the children to calibrate to the fixed walking speed. This could also be due to children’s greater use of action capabilities to take evasive action when crossing the road compared to other age groups (Morrongiello et al., 2015).

The number of crosses was calculated as a percentage of the total number of trials crossed. As 50% of the trials in the simulation afforded crossing, groups closer to the 50% mark would suggest that participants performed better. Older adults adopted a more cautious approach crossing less frequently (*M* = 40%, *SD* = 12.8) than the children's group (*M* = 53.7%, *SD* = 11.5) (see table 2). Although children were closer to the 50% mark, they accepted more crosses than the simulation afforded suggesting a more risky approach resulting in more collisions with the cars. An ANOVA revealed a significant main effect of age on the percentage of gaps accepted as 'crossable' F (2, 44) = 4.807, *p* =.03. Post hoc tests with Bonferroni correction revealed children crossed significantly more times than older adults suggesting developmental differences in how many gaps were perceived to afford crossing (*p* = .01). However, no significant differences were found between children and adults (*p* = .494) or adults and older adults (*p* = .300).

Collisions were defined as the car reaching the participant before the cross was completed and were calculated as a percentage of the total number of crosses accepted. Interestingly, although older adults crossed fewer times than the other participant groups, Table 2 shows how older adults performed worse than the other age groups registering a high percentage of collisions (*M* = 34.9%, *SD* = 12.8). Children also performed poorly with over a quarter of their crosses resulting in collisions (*M* = 28.1, *SD* = 11). Adults were substantially more accurate in their performance recording the lowest collision rate of 17.6% (*SD* = 11.3). An ANOVA revealed a significant main effect of age on the percentage of collisions registered in crosses accepted *F* (2, 44) = 6.192, *p* =.001. Post hoc tests with Bonferroni correction confirmed adults had significantly fewer collisions than older adults (*p* = .001) suggesting the aging process has a significant impact on the accuracy of judgements. Although there were no significant differences between older adults and children (*p* = .368), the differences between children and adults did approach significance (*p* = .056).

Safe errors were categorised as the percentage of rejected crosses where the gap between cars would have afforded crossing. Consistent with the crossing data, older adults were more conservative in their gap selection with 30.2% (*SD* = 9) of rejected gaps affording crossing.

An ANOVA again revealed a significant main effect of age on the percentage of safe errors (*F* (2, 44) = 6.192, *p* =.004). As expected, post hoc tests with Bonferroni correction showed that older adults make significantly more safe errors than adults (*p* = .003) suggesting that adults were much more confident in accepting gaps that afforded crossing. However, no significant differences were found between children and adults (*p* = .315) nor older adults and children (*p* = .209).

Furthermore, when participants did decide to cross, response time was calculated as the time (in seconds) it took to press the button (begin crossing) once the rear of the car closing the gap passed the participant. Table 2 shows a large difference in mean response times between older adults when they collided with the cars (*M* = 1.1s) than when they crossed safely (*M*= 0.75s). An ANOVA revealed a significant main effect of age on response times (*F* (2, 44) = 8.671, *p* <.001). Post hoc tests with Bonferroni correction showed that older adults hesitated significantly more than adults (*p* = .032) and children (*p* = .001) with no significant differences being found between children and older adults (*p* = .481).

To investigate if response time contributed to the number of collisions in each age group, a Two-Way Between Subjects ANOVA examined the effects of both age group and collision (yes or no) on response times. As every participant recorded at least one collision, this analysis compared the average response time when the participant collided with the car (coded as 1) to trials with no collision (coded as 0) across the three age groups. The results revealed a significant interaction between age and collision and response time *F* (1,88) = 5.393, *p* = .023). Furthermore, significant main effects were found for both collision *F* (2,88) = 3.819, *p* = .026) and age F (2,88)=23.303, *p* = <.001). Bonferroni post hoc tests showed a significant difference in response times with older adults waiting significantly longer to make a decision than children (*p* = <.001) and adults (*p* = <.001). However, no significant differences were found between children and adults (*p* = .317). This shows that a slower response time was a major contributing factor in older adults failing to cross safely but not for children and adults (see figure 2).

****INSERT FIGURE 2****

Modelling participant's responses according to tau differentials

The present experiment aimed to understand if age affected the ability to judge whether a gap between cars afforded crossing or not. Previous research has shown that tau is a variable that blends space and time and can provide reliable information that specifies the rate of closure of the motion gaps at its current closure rate between cars. As this information is directly available to the observer through the optic flow, we wanted to see how well participants 'tuned' into or used this information to inform their decisions to cross. The gap between cars is considered as opening as soon as the rear bumper of the leading car passes the participant and closed as soon as the front bumper of the closing car reaches the participant (see figure 1b). A tau value was calculated by taking the current size of the gap divided by its current rate of closure, mathematically represented as:

$$\tau_X = x/\dot{x}$$

This tau value is negative until it reaches zero when it is closed. As the velocity of the participant and cars in the present paradigm is constant, this can be summarised as:

If the value of the tau of gap Z (between the participant and the other side of the road) is greater than the value of the tau of gap X (between the oncoming car and the participant), i.e. $| \tau \text{ (Z)} > \tau \text{ (X)}|$ then the gap affords safe crossing. This means that the Z gap will close before the X gap.

If however, the value of tau of gap Z (cars and the participant) is less than the value of the tau of the gap X (participant and the other side of the road), i.e.$| \tau \text{ (Z)} < \tau \text{ (X)}|$ then the gap does not afford safe crossing as the gap between the oncoming car and the participant will close before they can cross the road.

Subtracting tauX from tauZ for all the different experimental conditions gives 18 unique tau differential values that specify the ‘crossability’ of the road gap. This information allows the actor to assess whether the gap between cars affords crossing or not and creates a continuous scale on which accepted and rejected crossing decisions can be plotted (Watson et al., 2011) (see table 2). As the movement speed of both the cars and the participant is fixed, and therefore both gaps close at a constant rate, the difference in tau values will not change as the trial unfolds. A negative tau differential value denotes an unsafe opportunity for crossing as the gap between cars would close before the gap between the participant and the opposite sidewalk is closed. If the value is greater than zero this would afford a safe opportunity to cross provided the participant pressed the button in time. Note that the greater the tau differential is above zero then the more time the participant has to cross and the easier the decision. The same is true for tau differential values that are more negative. Tau differentials around zero will be more difficult to judge.

INSERT TABLE 3 “*

Impact of age on gap selection

By plotting each age group’s average percentage of accepted crosses against the tau differentials, we are able to see how well this informational variable can explain the variability obtained in the results for each group and will show if age impacts on the ability to use this information to make judgements about whether the gaps between the two cars affords crossing. If participants are tuning into the tau differential information and using it to inform their decisions, we would expect a strong relationship between the two variables. The more negative the tau differential then the closer the number of crosses should be to 0% and the more positive the tau differential then the closer the number of crosses should be to 100% giving an ‘S-Shaped’ curve. When the tau differentials become close to the ‘critical value’ of 0 and the motion gaps close around the same time, responses should be around 50% reflecting the difficulty in accurately detecting an opportunity to cross.

To measure how accurately participants used tau, a logistic function was fitted against the data. The R^2 values represent how closely the response data fits the ‘S’ shaped curve. This will reflect the extent to which tau is used. The logistic equations were also used to calculate the Critical Value (CV) or threshold points where participants’ cross rates exceeded 50%. As tau provides temporal information, critical values should provide an indication of how accurately participants perceived when the motion gaps of the cars would close faster than the participant could get across the road. Therefore, critical values at 50% response rate that are closer to a tau differential of 0 suggest a greater sensitivity to tau information. The following equation was used to calculate the critical value where u is the upper bound, β0 and β1 are constants and X is the variable in question:

$$X = -log\left(\frac{\beta 0}{\frac{1}{50}-\frac{1}{u}}\right)/log(\beta 1)$$

Figure 3a shows that 85.1% of the variance in the children’s data could be explained by adherence to tau information when judging whether the gap between cars afforded crossing. Furthermore, the children’s group’s critical value was very close to 0 (-0.04) showing that they began to switch to accept gaps when it was still unsafe to cross (the car-participant gap would have closed before the participant-sidewalk gap). The slope of the curve between 25% and 75% was also calculated. This indicates how rapid the switch between the rejected crosses and the accepted crosses was for the tau differentials. A steeper gradient suggests the participant’s switched more rapidly between accepting gaps that didn’t afford safe crossing to those that did. Conversely a flatter gradient suggests a more gradual switch indicating less certainty in crossing judgements. Children recorded a slope value of 0.392 indicating a strong discrimination between affordances of the gaps based on tau differentials.

Similar to the results for the children, figure 3b demonstrates that adults predominantly use tau when deciding to cross the road with 83.6% of the variance in the data being explained by the tau differential. The adults' critical value was also close to zero (0.14), indicating that adults tended to cross when the motion gaps of the cars were larger, indicating safer crossing decisions. This adherence to tau is reflected in the slope value of 0.313 with adults switching rapidly from rejected to accepted crosses when the tau differential goes above zero.

Interestingly, older adults did not appear to use the tau differential when crossing the road when compared to the other two age groups. Figure 3c shows the tau differential only explained 59.1% of the variance in the decision response data. The critical value for the tau differential was also much higher (0.41) suggesting that older adults crossed only when the motion gaps of the cars were considerably longer than the gap required to safely cross, indicating a greater degree of cautiousness in their decision-making. As older adults do not utilise tau as effectively, the group's slope value is higher (0.612) indicating a more gradual switch between rejecting gaps that did not afford crossing and accepting gaps that did. This suggests older adults were less certain of when to switch judgements from 'no' to 'yes' and vice-versa.

****INSERT FIGURE 3****

Are participants using other non-specifying informational variables?

In order to establish whether participants were tuning into other sources of perceptual information to decide whether the road afforded crossing or not, a logistic function was fitted to other non-specifying informational variables that included differentials of the event duration and distance.

Event duration is classified as the time between the trial starting and the gap closing. This does not reliably predict safe crossing as a small gap with slow cars can take longer to close than a large gap with fast cars. The distance differential states how far the car would be away from the participant after the crossing duration. However, this fails to account for how the gap dynamically changes over time. Similar to the tau differential, the R^2 values will reflect how closely the response data fits the 'S' shaped curve. Event duration accounted for 63% of the variance in crossing decisions for children, 65% in adults and 25% in older adults. Conversely, distance differentials accounted for 72% of the variance in children, 71% in adults and 48% in older adults. These variables could act as a heuristic for predicting crossing decisions. For instance, a gap takes a long time to close from the start of the trial is likely to afford crossing, but adherence to the information provided by these variables alone is not enough to produce accurate results. Therefore, it is not surprising that the specifying tau differentials explain most of the variance in all age groups.

Discussion

In the present experiment, we aimed to see whether there are age differences in ability to detect whether a gap is perceived as being sufficient to cross a road when road crossing speed is standardized for all participants. By controlling for the action capabilities of the participant, any age-related differences in the perception of affordances can be attributed to poorer detection of information that specifies the time-to-arrival of the approaching cars, rather than an ability to regulate action as an event unfolds. The analysis focused on two questions: (i) How well can each age group judge the 'crossability' of gaps between oncoming traffic in a road-crossing task when action capabilities are standardised (fixed movement speed)?, and,

ii) How does age impact on the ability of participants to use specifying information (tau) to inform road crossing decisions?

Concerning the impact of age on task performance, the results demonstrated that older adults performed the worst overall making significantly fewer correct decisions when compared to both the groups of adults and children. When these results were broken down, older adults made more unsafe errors (colliding with cars while crossing) and safe errors (rejecting a gap that was safe to cross). This was despite older adults crossing the least number of times compared to the other two groups. These results are in line with previous estimation studies that examined age-related differences in road-crossing performance. In these studies older adults selected gaps that were insufficiently large to safely cross the road but also missed many more crossable opportunities (Oxley et al., 2005; Lobjois & Cavallo, 2007). It could be argued that these original findings were due to the utilisation of a methodology that did not preserve the integrity of the perception-action loop and as a result led to the activation of different neural pathways (van der Kamp, Rivas, van Doorn, & Savelsbergh, 2008). However, studies that did maintain the perception-action loop have also found that older adults made similar unsafe errors (Lobjois & Cavallo, 2009; Dommes et al., 2014). A failure of older adults to perform well in the present experiment suggests that the poorer performance across estimation and perception-action tasks is not solely down to age-related motor decline. This idea is consistent with a body of literature that investigated developmental differences in terms of the perception of action capabilities, with older adults being as good at determining their maximal height for stair climbing as younger adults (Konczak, Meeuwsen, & Cress, 1992)

If the older adult group still performs worse in a task where action capabilities are standardised, this suggests that the older adult group is tuning into, and subsequently using to make their decisions, perceptual information that does not reliably specify whether a gap between cars affords crossing or not. To investigate to what extent age related changes may influence an individual's ability to use specifying information; the present road-crossing scenario was modelled as the relative rate of closure of two gaps, i) the gap between cars (perception) and ii) the gap between the participant and the other side of the road (action). By comparing the relative time to closure of these gaps, information about whether the gap between cars affords safe crossing can be picked up and used to guide the action based decision (i.e. press the button to cross the road). In terms of the present experiment, the use of tau as a prospective variable to decide if the gap affords crossing is critical as once the participant presses the button they are committed to crossing and are unable to adjust their movements online as a function of the approach of the oncoming cars. Mapping responses using an S-shaped logistic function allowed us to test how a differential variable such as tau, could explain the variance in the decisions made by the participants. The high percentage of the variance in the data explained by this function for both children and adults (85% and 84%, respectively) suggested they were using this variable to inform decisions about whether to cross the road or not. The finding that children are effectively able to tune into a variable based on optical expansion of the approaching cars is not consistent with previous literature showing children aged 10-11 have a significantly lower perceptual threshold for looming (Wann et al., 2011). This reduced sensitivity would result in an increased difficulty to effectively tune into tau, information that is dependent on the change in optical size of an approaching object. Instead, these results are more in line with previous literature investigating children's road-crossing behaviour in virtual reality showing children and adults choose the same temporal gaps indicating no discernible difference in the ability to perceive TTA information (Morrongiello, Corbett, Milanovic, & Beer, 2015; Plumert et al., 2004; Plumert et al., 2011). The findings of the present study are novel in that they demonstrate how children are deciding whether the temporal gaps between cars affords crossing based on specifying information (tau). This is consistent with other empirical findings of children's road-crossing decisions (e.g. Lee et al, 1984).

However, it is important to note that the critical point where the children were deciding when they would cross was below zero (criticial value (CV) = -0.04) meaning that children were deciding to cross when the gap of the approaching cars would close before the gap to cross the road would close, resulting in a collision with a car. In contrast, the group of adults were deciding to cross when the critical value was above zero (CV = 0.14) meaning that the road-crossing gap would close before the cars arrived. This suggests that adults preferred were better calibrated to the information and made decisions when the road was safe to cross, a strategy which was not present in the group of children. This finding is consistent with previous literature that examined age-related threshold points where children perceived the switch from an unsafe gap to a safe gap sooner than adults (Azam, Choi, & Chung, 2017).

In contrast, older adults appeared to be tuning into less reliable and non-specifying information with the tau differential accounting for only 59% of the variance (CV = 0.41). As older adults were not always effectively using information that specifies the TTA of the cars, it is not surprising that older adults performed worse in the task. To establish if older adults were using simpler non-specifying information that would be consistent with heuristics, event duration and distance differentials were included in the analysis. Neither of these variables explained as much of the variance in crossing decisions as tau (25% & 48% respectively compared to 59%). This provides support for the Petzoldt (2014) hypothesis that older adults are still using TTA to inform decisions but this information is more prone to distortion.

In addition, when older adults made an unsafe decision to cross and ended up 'colliding' with the cars, their response time for the next trial was significantly higher. Previous studies that have examined response times in older adults have found earlier initiation times to compensate for a slower walking speed (Oxley et al., 1997; Lobjois & Cavallo, 2009). Researchers theorised that an increase in response time was due to the altered action capabilities afforded by the fixed walking speed and as a result, older adults did not feel a need to compensate by initiating early. However, this appeared to be detrimental to performance as the longer it took participants to initiate crossing, the sooner the gap between cars would close and the less safe the choice. This response time can be attributed to the poorer use of information specifying the TTA of cars as older adults took longer to identify optically if the gap afforded safe crossing. Similar findings have been documented in older drivers who have been found to have a reduced sensitivity to visual looming leading to a 50% reduction in the time available to take evasive action (Poulter & Wann, 2013). Conversely, children and adult response times did not significantly differ. This finding is not consistent with previous literature which indicated that children hesitate significantly more than adults in road-crossing tasks (Plumert, Kearney, & Cremer, 2004). This was attributed to the fixed movement speed, as children were not able to regulate their movement and adopt evasive action meaning they cannot afford to wait longer, which has been shown to be a common strategy adopted in this age group (Morrongiello, Corbett, Milanovic, Pyne, & Vierich, 2015).

Our findings show that children's perceptual judgements of the crossability of gaps via TTA information is similar to that of adults when action capabilities are standardised. Children's poorer performance in road-crossing scenarios appears to be reflected in the failure to adopt an effective strategy that coordinates self-movement with the approaching car (Morrongiello, Corbett, Milanovic, & Beer, 2015). Plumert et al. (2011), for example, found children quickly entered a tight gap by incorrectly judging their maximum achievable time-to-cross to be less than the approaching car's TTA. This type of miscalculation suggests children fail to regulate their crossing actions based on information in the optic flow that specifies whether the gap between cars affords crossing at its current rate of crossing, a strategy termed affordance-based control (Fajen, 2007).

Conversely, older adult's judgements of gap affordances are poor when action capabilities are standardised due to less adherence to specifying information. This has important implications for road-safety interventions in identifying what to train in each age group. Children appear to be able to effectively tune into tau to inform their decision-making but potentially are unable to effectively regulate their movement using tau as an optical variable. Further research should establish if children can effectively adopt an information-movement coupling strategy when crossing the road. This will help us understand if regulation of self-movement with respect to object-movement is a major constraint limiting children's road-crossing ability. Older adults, however, need assistance to help them re-learn how to tune into and use the correct information (i.e. tau). This could be achieved by training older adults to rely less on informational variables that only weakly correlate with TTA e.g. distance of approaching car when the gap opens and rely more on useful, specifying variables (i.e. tau), a process called education of attention or attunement (Jacob & Michaels, 2007). Recent research has identified that training in a full-scale simulation device that requires participants to physically cross the road enables older adults to become more sensitive to vehicle speed (Maillot, Dommes, Dang, & Vienne, 2017). This suggests that feedback provided in environments that afford a calibration between perception and action, can aid older adults shift from non-specifying variables to information that encapsulates both speed and distance information.

Although this study aimed to address the age-related differences between perception-action and estimation, more research is needed to understand how older adults behave when action capabilities are standardised. As the experiment de-coupled perception and action, participants were not able to regularly assess the environment and alter their decisions, thus breaking the reciprocal relationship between individual and environment. For example, in perception-action tasks, participants could regularly assess the rate of closure of the gap between cars against how fast they were crossing the road to maintain a safety margin and ensure they safely crossed before the gap between cars closed (see Lee, 1998 for an explanation). As there was no ability to regulate behaviour as a function of the approaching cars, this may explain the high number of collisions across all groups suggesting calibrating movement to your own action capabilities is vital for successful road-crossing. It could be argued that this places children at a disadvantage who have been shown to utilize their action capabilities when coordinating self-movement with an external object (Ceari et al., 2003; Chihak et al., 2010; Morrongiello et al., 2015). As a result, children's perception of temporal information which specifies affordances in dynamic scenarios may not be as finely tuned as adults but are able to rely on their movement adaptability to ensure task doesn't go beyond the limits of their action capabilities. For example, Chihak et al. (2010) found when attempting to synchronize movements with an approaching car to intercept a moving gap, children often mistimed their approach speed and slowed down more than necessary. This resulted in a reliance in their action capabilities to produce enough acceleration in the closing seconds to prevent a missed opportunity for action or collision with the vehicle. However, the results in the present study are not consistent with this suggestion with children showing greater adherence to the optical variable tau to inform gap judgements compared to older adults. This showed children were able to recognize the task-demands, placing a greater reliance on tuning into reliable perceptual information as the constraint of a fixed walking speed prevented habitually adopting evasive action. In contrast, older adults who in real-life contexts have comparatively higher task demands due to the decline in action capabilities associated with age, were unable to increase their sensitivity to specifying information when the action component of crossing was standardized (Larsson, Grimby, & Karlsson, 1979; Öberg, Karsznia, & Öberg, 1993).

Additionally, these age group difference in performance could also be down to the choice of technology and how it was utilised. Children and adults may have had more exposure to virtual environments and this age-related unfamiliarity could have influenced older adult's decision-making to be more cautious or risky than in a natural road-crossing context. Furthermore, while virtual reality is a useful methodological tool for safely studying road-crossing, research has found a consistent underestimation of distance when wearing HMDs (Willemsen, Colton, Creem-Regehr, & Thompson, 2009). The way to negate these distance effects is for active exploration of the virtual environment in the HMD (Richardson & Waller, 2007). It is not clear if the exploration via translation through the environment in this experiment by a button press was enough to avoid the technology impacting TTA estimations. However, the amount of variance explained in detecting gap affordances by tau in adults (85%) and children (84%) suggest that the environment provided enough information in the optic flow to perceive TTA.

In conclusion, the present paper demonstrates that age-related calibration is not simply due to older adults not being able to act upon the information but rather it may be that they are picking up and using non-specifying perceptual information to make their decisions. This may explain why older adults were not able to regulate their movement as accurately as children and adults who use a specifying perceptual variable such as tau.

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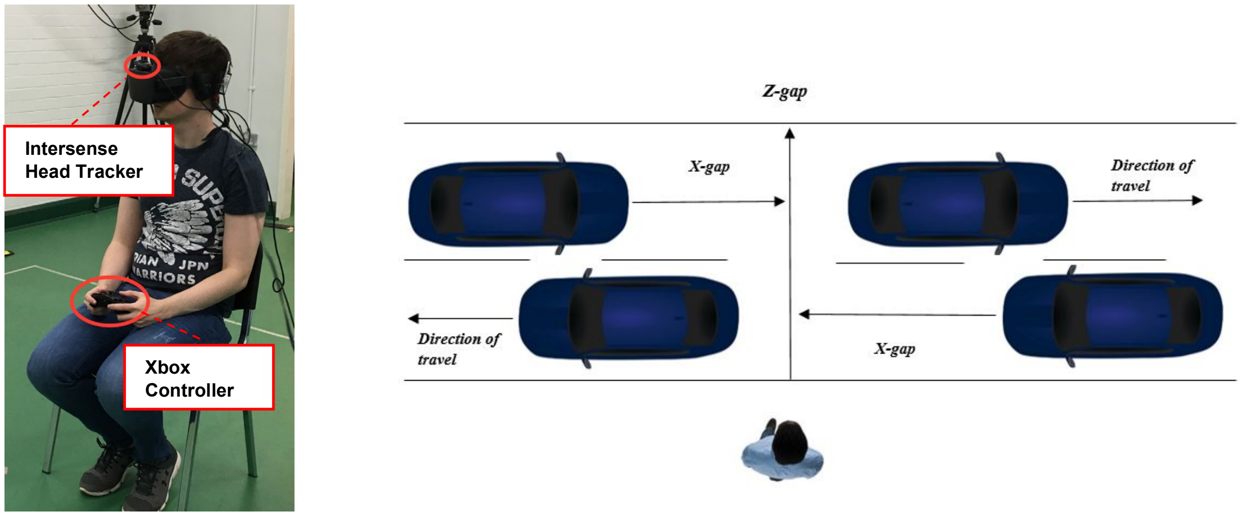

(a) (b)

Figure 1. (a) A photograph of a participant wearing the Oculus HMD with an Intersense head tracker attached to update the viewpoint in the virtual world in real time. The participant is holding the Xbox controller in his hand to record his responses. (b) A schematic diagram showing the axes of movement of the two lanes of cars and the gaps between them. The participant has to close the gap in the Z-axis before the gap in the X-axis closes (i.e. before the trailing car in the far lane crosses the z axis).

Table 1

Summary of means for each age group's average walk speed (SD) including its, max, min, range and differential between actual and imposed walk speed (SD).

Age Group	Walk Speed (m/s)	Max	Min	Range	Walk Speed Differential (m/s)
Children	1.39 (0.23)	1.98	1.14	0.85	-0.03 (0.23)
Adults	1.44 (0.17)	1.82	1.15	0.66	0.02 (0.17)
Older Adults	1.41 (0.16)	1.61	1.09	0.52	-0.01 (0.16)

Table 2

Summary of means (SD) for each age group including percentage of correct decisions, accepted crosses, collisions resulting from crosses and safe errors (rejected opportunity). In addition, mean response time(s) with and without collision is summarised.

Age Group	% Correct	% Crosses	% Collisions	% Safe error	Response time (s)	Response time with collision (s)
Children	72.2 (7.1)	53.7 (11.5)	28.1 (11)	24.3 (8.3)	0.48 (0.2)	0.5 (0.2)
Adults	80.4 (6.7)	46.9 (9.4)	17.6 (11.3)	19 (8.7)	0.57 (0.1)	0.6 (0.2)
Older Adults	67 (7.8)	40 (12.8)	34.9 (12.8)	30.2 (9.1)	0.75 (0.2)	1.1 (0.4)

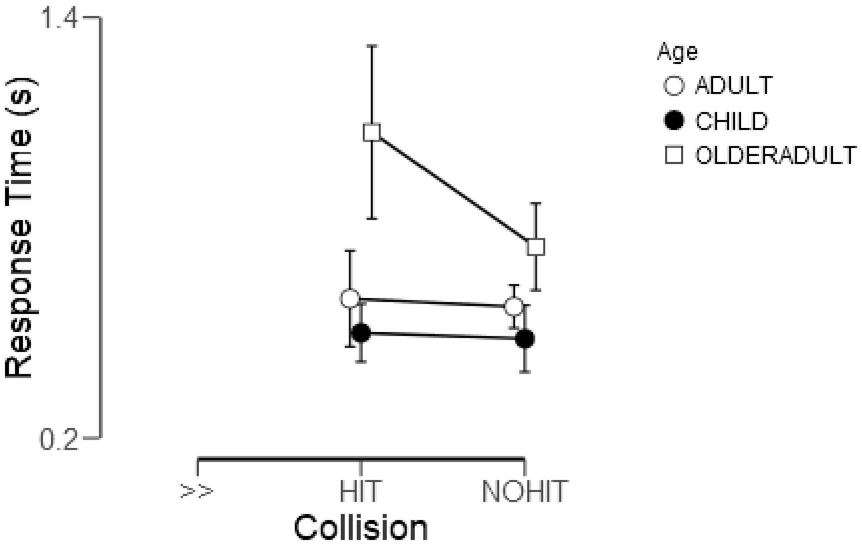

Figure 2. A graph showing the mean response times in seconds with respect to whether a Collision resulted or not (Yes/No) for each age group (Children, Adults, & Older Adults). From the graph it can be seen that older adults showed a greater response time in the trials where they crossed unsuccessfully with a minimal difference for children and adults.

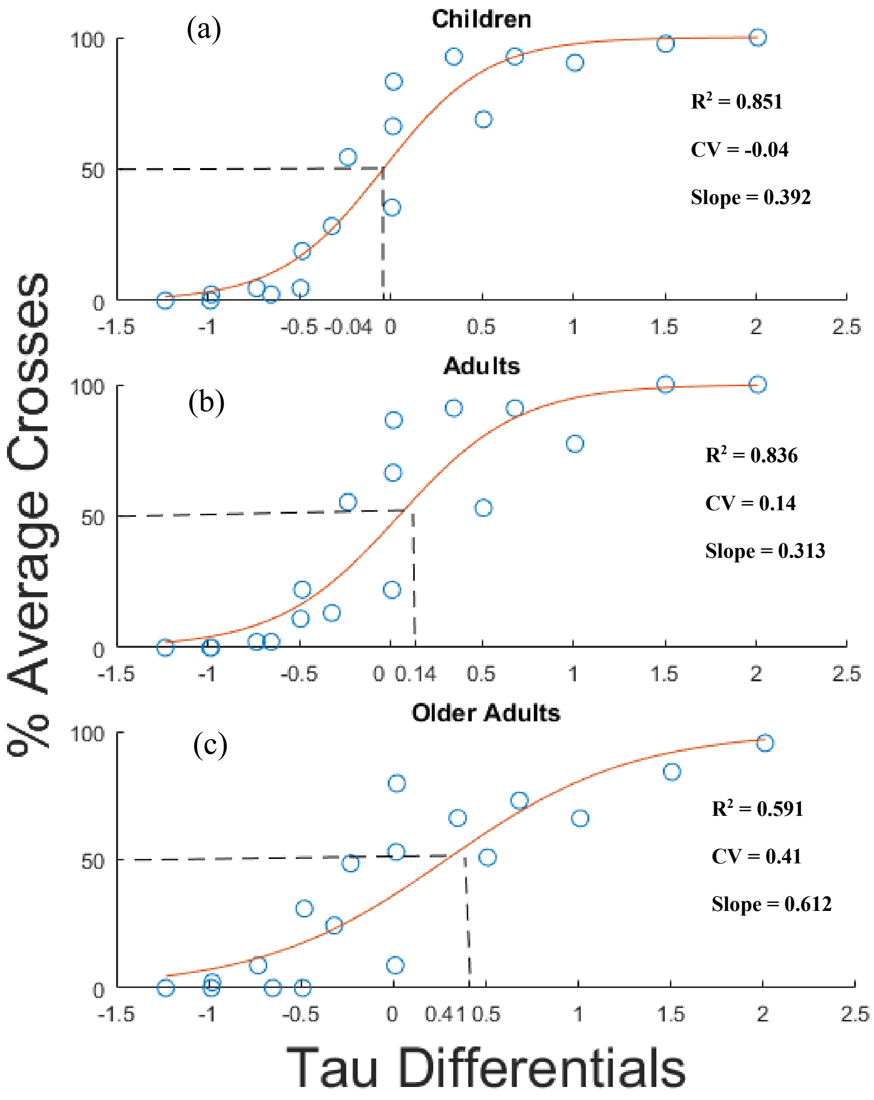

Figure 3. Figures showing the logistic functions for the tau differential (the difference between tauX and tauZ) and the % average cross responses for children (a), adults (b) and older adults (c). The R^2 (percentage of variance explained by the regression line), CV (critical value when the responses switch from collision to no collision) and the slope values for each group are also displayed.

Table 2

Table displaying the speed, distance, the resulting time-to-arrival, the tau differential, the gap with the greater tau value and if crossing was afforded (yes/no).

Speed (KPH)	Distance (M)	Time-to-arrival (Speed/Distance)	Tau Differentials	Greater Tau Value	Cross (Y/N)
32	30	1.69	-1.23133	Z	No
48	30	2.24	-0.98493	Z	No
32	40	2.25	-0.98014	Z	No
32	50	2.81	-0.73156	Z	No
48	40	2.96	-0.65265	Z	No
64	30	3.36	-0.49129	Z	No
32	60	3.37	-0.4819	Z	No
48	50	3.73	-0.3204	Z	No
32	70	3.93	-0.23168	Z	No
64	40	4.47	0.009143	X	Yes
48	60	4.48	0.014513	X	Yes
32	80	4.49	0.017713	X	Yes
48	70	5.22	0.347295	X	Yes
64	50	5.59	0.509402	X	Yes
48	80	5.97	0.680958	X	Yes
64	60	6.71	1.009448	X	Yes
64	70	7.83	1.505605	X	Yes
64	80	8.95	2.009754	X	Yes