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► **To cite this version:**

Régis Lobjois, Nicolas Benguigui, Viola Cavallo. The Effects of Age and Traffic Density on Street-Crossing Behavior. *Accident Analysis & Prevention*, 2013, 53, pp.166-175. 10.1016/j.aap.2012.12.028 . hal-00866012

**HAL Id: hal-00866012**

**<https://hal.science/hal-00866012>**

Submitted on 25 Sep 2013

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## Accepted Manuscript

Title: The effects of age and traffic density on street-crossing behavior

Authors: Régis Lobjois, Nicolas Benguigui, Viola Cavallo

PII: S0001-4575(12)00450-2  
DOI: doi:10.1016/j.aap.2012.12.028  
Reference: AAP 2994

To appear in: *Accident Analysis and Prevention*

Received date: 29-6-2011  
Revised date: 26-11-2012  
Accepted date: 20-12-2012

Please cite this article as: Lobjois, R., Benguigui, N., Cavallo, V., The effects of age and traffic density on street-crossing behavior, *Accident Analysis and Prevention* (2010), doi:10.1016/j.aap.2012.12.028

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The Effects of Age and Traffic Density on Street-Crossing Behavior

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## Abstract

Past research has shown that road users accept shorter time gaps when the waiting time/number of vehicles they let pass before attempting to merge into the traffic increases. While elderly pedestrians are known to be an extremely vulnerable group of road users, very few studies dealt with the effect of environmental constraints and crossing complexity on this population's safety. The present study aimed at determining whether or not street-crossing decisions and behavior of younger and older pedestrians were differently affected by a traffic flow. In an interactive street-crossing task, we assessed whether mean time gap and crossing decisions depended on the position of the gap pedestrians selected into the traffic stream. Results revealed that irrespective of their age pedestrians accepted a smaller time gap when they chose the second interval of the traffic compared to the first one. Contrasting with previous hypotheses, this traffic-related behavior was not accompanied by an increase in the decisions risk. The findings also showed that the transition threshold from rejecting to accepting time gaps was shorter when the second interval was selected compared to the first one. This increment in task constraints might help younger and older pedestrians alike to perceive action possibilities more accurately and to be better attuned to traffic conditions by comparing gaps between each other. This opens an interesting perspective in the understanding and the training of the ability of elderly road users to remain accurate in their judgements.

## Keywords

Aging, Pedestrian, Street Crossing, Traffic Density, Virtual Environment

## 1. Introduction

International accident statistics indicate that elderly pedestrians are an extremely vulnerable road-user group (NHTSA, 2001; OECD, 2001). In France, more than half of all pedestrians killed on the road (51%) in 2004 were over 65 years old, whereas this age group represents less than 15% of the population (ONISR, 2005).

Studies which have looked into age-related changes in elderly pedestrians showed that sensorimotor deficits (e.g., Lobjois & Cavallo, 2009; Oxley et al., 2001), cognitive deficits (e.g., Oxley et al., 2001) or changes in the crossing strategies (e.g., Lobjois & Cavallo, 2009; Oxley et al., 1997) have the potential to explain why this age group is over-represented in accidents. Past studies have also dealt with the effects on older pedestrians' crossing behavior of exogenous factors such as oncoming vehicles speed (e.g., Lobjois & Cavallo, 2007, 2009; Oxley et al., 2005) or crossing complexity (e.g., one way versus two-way roads; Oxley et al., 1997). Little is known about the causes of accidents in elderly pedestrians and more importantly about the environmental factors that affect or improve the behaviour of elderly people in street crossing. Research addressing the impact of a traffic stream on crossing behavior of elderly people is still scarce, as most of the research has been conducted with only one or two approaching vehicles (Dommes & Cavallo, 2012; Dommes et al., 2012; Lobjois & Cavallo, 2007, 2009; Oxley et al., 2005; te Velde et al., 2005). Thus the goal of this study was to assess the effect of a traffic stream on gap acceptance and crossing decisions of younger and older pedestrians.

The effect of a traffic stream on decision making has been addressed in natural conditions with studies on gap acceptance for turning maneuvers of motorists when stopped at an intersection. Ashworth and Bottom (1977) showed that the accepted time gap depended on the velocity of the oncoming traffic and on the front-of-queue delay before right-turn movement execution. Time gaps decreased when both the approach speed of the opponent

vehicle and waiting time increased. Similar results were also obtained by Adebisi and Sama (1989), who showed in addition that the drop in the gap size was due to an increase in the traffic flow on the major road the drivers planned to cross or merge into. It is reasonable to think that an increase in traffic flow would lead to decreased gap sizes between approaching vehicles and thus would affect waiting time and accepted time gap. To further explore the origin of the relationship between gap size and waiting time, Kittelson and Vandehey (1991) compared accepted time gap and waiting time between one group of drivers whose accepted gap was longer than all previously rejected gaps and one group of drivers whose accepted gap was shorter than one or more previously rejected gaps. The first group of drivers actually corresponded to one group who took the first affordable gap (all rejected gaps were lower than the one accepted) while the second group first missed crossable gaps before drivers merged into the traffic. Interestingly, results revealed that drivers who took the first affordable gap waited for 9 s in average and accepted a mean time gap of 5.5 to 7 s while the other group accepted a time gap of 3 to 4 s after having waited for 19.5 s.

Alexander et al. (2002) carried out a study using a driving simulator and showed contradictory results. Younger and older participants drove repeatedly around a circuit which included turning-right maneuvers at an unsignalised junction. At this junction, gaps between vehicles in the traffic stream randomly varied between 1 and 14 s. Results revealed that drivers accepted a smaller gap at higher approach velocities but that the mean accepted time gap increased with the number of gaps participants let pass before they executed their turning maneuver (8.3 s for the first gap accepted, 9 s for the fourth or 10 s for the seventh).

In a virtual environment, Plumert and her colleagues (2007a, 2007b and 2011) examined gap choices in traffic-filled intersections while participants cycled an interactive simulator. Participants first encountered a set of four intersections, in which randomly ordered gaps ranged from 1.5 to 5 s (in 0.5-s increment). Participants then had to cross a new set of

intersections, in which uncrossable gaps (1.5 and 2 s) were followed by alternating sets of two same-size crossable gaps (3 to 4 s in 0.5-s increment) and four uncrossable gaps. Results showed that participants were willing to accept much smaller gaps when they had to wait for a long time before they could merge into the traffic (mean time gap of 4.8 and 3 s for the first and second set of intersections, respectively).

In the only pedestrian behavior study, by Simpson et al. (2003), participants had to choose the most appropriate gap and cross a virtual road while facing a traffic stream of 10 vehicles. Gap sizes between vehicles randomly varied between 4 and 10 s, in 2-s increment. Results showed that the greater the number of gaps prior to crossing, the shorter the gap chosen to cross in. This confirmed that pedestrians accept smaller gaps after waiting to cross (7.1, 6.1 and 5.8 s for 0, 1 and 2 or more gaps rejected before crossing, respectively).

In sum, previous research indicates that pedestrians (Simpson et al., 2003), cyclists (Plumert et al., 2007a) and motorists (Adebisi & Sama, 1989; Ashworth & Bottom, 1977; but see also Alexander et al. 2002, for opposite patterns) accept shorter time gaps when they let pass time/vehicles before attempting to cross the road. Different hypotheses have been put forward. Assailly (1993) proposed that time wasting might contribute to impatience and increased risk taking. For Hamed (2001), when waiting time increases, pedestrians are more likely to accept higher risk by forcing approaching vehicles to brake. According to Kittelson and Vandehey (1991), the size of the accepted gap decreases particularly when a crossable gap is previously missed. Another explanation could be that the waiting time gives a possibility of viewing several gaps before crossing and is used to improve the attunement of the crossing behaviour to choose shorter gaps. This attunement would correspond to a better calibration of the crossing action in reference to the available time.

Thus the purpose of our study was to examine the effect of a traffic stream on gap acceptance, road-crossing decisions and behavior of younger and older pedestrians. While the

density of the traffic stream clearly impacts the behavior of road users, it is important to investigate this effect on elderly people, especially given that the elderly have been shown to be particularly affected in their perception and decision-making when the environmental constraints increase. For instance, Oxley et al. (1997) showed that older pedestrians adopted less safe road crossing strategies on two-way undivided roads than on one-way roads. In similar vein, older pedestrians were more impaired than younger ones when the speed of approaching vehicles was systematically varied, as they consistently accepted shorter and shorter gaps as speed increased (Lobjois & Cavallo, 2007, 2009; Oxley et al. 2005). This turned into unsafe crossing decisions at high speeds and missed crossing opportunities when car speeds were low.

The present investigation carried out in a simulated interactive road-crossing situation was aimed at determining whether older pedestrians were more or less influenced than younger ones by a traffic stream in the choice of the gap to cross a road. Our second goal was to determine whether the expected drop in the second gap size was the result of a risky behavior or a better attunement-calibration of the crossing behavior.

## 2. Method

### 2.1. Participants

Sixty seven participants took part in the study and were divided into three age groups : 20-30 years old (11 women,  $M_{Age} = 27.1$  years,  $SD = 3.2$  years, and 11 men,  $M_{Age} = 28.1$  years,  $SD = 3.3$  years), 60-70 years old (11 women,  $M_{Age} = 67$  years,  $SD = 2.5$  years, and 11 men,  $M_{Age} = 67.1$  ans,  $SD = 2.4$ ), 70-80 years old (13 women,  $M_{Age} = 75.4$  years,  $SD = 3.3$  years, and 10 men,  $M_{Age} = 75.8$  years,  $SD = 3.3$  years). The elderly participants were retired individuals living on their own. They were recruited with the assistance of the Health Department of the surrounding cities and through advertisements. All participants underwent a medical examination whose purpose was to check certain criteria (i.e., walking perimeter



greater than half an hour without a cane or crutch, ability to easily read 90° to the left through the combined rotation of the head and trunk, horizontal gaze direction when standing at rest, corrected visual acuity of at least 6/10, and absence of major cardiac, neurological, or visual disorders and diseases). Because of the interactive situation and the need for crossing a distance of several meters corresponding to the virtual road, the participants with mobility and other health problems were screened out. This resulted in a healthy sample of older participants in comparison to the actual older population at risk. All signed an informed consent form before participating in the experiment; the study was approved by the local ethics committee.

## 2.2. Experimental Setup

Until recently, much of the research examining gap acceptance was based on estimation tasks, either in children (e.g., Connelly et al. 1996, 1998; Pitcairn and Edlmann, 2000) or elderly pedestrians (e.g., Lobjois and Cavallo, 2007; Oxley et al., 2005). Estimation tasks require participants to give a verbal response or to press a button to indicate whether they would cross the road in front of oncoming traffic. Although estimation tasks provide the advantage of having no physical risk and no need to simulate a portion of the road, their ecological validity has been criticized (e.g., Simpson et al., 2003). It has been showed that the interactive modality of the road-crossing situation improves the perception of crossing possibilities in comparison with button-press or verbal responses (e.g., Lobjois & Cavallo, 2009 ; te Velde et al., 2005). Such interactive design provides a better possibility to couple perception and action and increases the ecological validity of the task (Burkhardt et al., 2003; Morice et al., 2008 ; Stoffregen et al., 2003). Moreover the walk-across-the-road task allows to investigate whether pedestrians adjust their crossing behavior to the traffic conditions, and to study crossing strategies, such as early initiation, modulation of the walking speed and anticipation in crossing by moving forward on the road in order to shorten the crossing

distance. Consequently we used a simulated interactive road-crossing situation, in which participants had to cross a road when they thought it was safe to do so.

The street-crossing simulation device was based on the Sim<sup>2</sup> driving simulator (Espie, 1999) and was adapted to reproduce the demands of a street-crossing task as described above. The device included a portion of experimental road (4.2-m wide, indicated by continuous white markings on the floor), an image-generation, three-screen projection (with each screen 2.70 m wide and 1.90 m high), and 3D sound-rendition system, and a recording system (Figure 1). The setup provided the pedestrian with a horizontal visual field between 90° (at the starting point of the crossing) and 140° (in the middle), and a vertical visual field of 40°. The images (refreshed at 30 Hz) were calculated and projected at the participant's eye height, and the simulated viewing angle was aimed to the vanishing point of the simulated street. The visual scene displayed was dependent on the pedestrian's displacement: the scene, which changed according to the pedestrian's position, was updated interactively by a movement-tracking system that recorded the pedestrian's motion (30 Hz) by means of an unwinding cable attached to the participant's waist.

The visual scenes represented a one-way street 4.20 m wide sidewalk-to-sidewalk. Traffic consisted in a motorcycle followed by cars ( $n = 14$ , generating 13 different gaps) moving at a constant speed from left to right (in reference to the pedestrian standing on the sidewalk). The motorcycle followed a path located 1.10 m from the sidewalk where the pedestrian was standing, and the cars followed a path 2.09 m from the same sidewalk (kept constant throughout the experiments). At the beginning of each scene, the motorcycle was 1.5 s away from the pedestrian and the first vehicle was 1 s away from the motorcycle.

### 2.3. Experimental Task and Design

Participants were asked to stand at the edge of the sidewalk, facing the experimental road. They had to look left at the visual scene, paying attention to the approaching vehicles,

and to walk to the other side of the street at any walking pace (i.e., not running) when they thought it was safe to do so. They were also told that they did not have time to cross in front of the motorcycle or between the motorcycle and the first vehicle.

When participants crossed the experimental road, the visual scene was stopped when the rear end of the next oncoming vehicle passed their crossing line. They then returned to the original position. Between trials, the visual scene was replaced by a blue screen that was displayed until participants were ready for the next trial.

Vehicle speed (40 and 60 km/hr) and time gap between pairs of vehicles were manipulated. Time gap varied between 1 and 7 s, with a 1-s increment, for the first interval (i.e., between the first and the second vehicle of the traffic stream), between 1 and 7 s, with a 1-s increment, for the second interval (between the second and third car), and was increasing from 3 to 8 s with a 0.5-s increment for the remaining intervals. This procedure for the remaining intervals was used so that participants had to determine the smallest gap acceptable for crossing when provided with progressively larger temporal gaps. The time gaps were chosen so that young and old alike would be confronted with both unfavorable and favorable situations.

Gap size for the first two intervals was manipulated in order that each possible combination was presented once (e.g., 1-1, 1-2, and so on until 7-7). This resulted in 49 time-gap conditions (i.e., 7 time-gap conditions for the first interval by 7 time-gap conditions for the second one), repeated two times (i.e., at 40 and 60 km/h).

#### 2.4. Procedure

After having been explained the basic principle of the experiment, participants performed some practice trials (vehicle speeds: 50 km/h; time gaps for the first two intervals: 1.5, 3.5, 5.5 and 7.5 s, the other time gaps increasing with a 1-s increment from 3 to 8 s) until they confirmed that they fully understood the task. The 98 trials (49 gap sequences x 2

speeds) were randomly distributed into two blocks of 25 trials and two blocks of 24 trials which were randomized across participants. The complete session lasted approximately 45 min.

## 2.5. Data analysis

The participants' crossing behavior was recorded on each trial. Several variables were also calculated for each participant, each speed and each of the first two intervals.

### 2.5.1. Mean Accepted Time Gap

In a data set where gaps could be either rejected or accepted by the road users, the variable that is of major interest is often referred to the critical gap (Alexander et al., 2002). As the response variable of such a data set is binary, the conventional regression analysis, either linear or nonlinear, is not appropriate (Al-Ghamdi, 2002). Many different methods for the estimation of gap acceptance parameters have been used (for a review, see Brilon et al., 1999). To estimate the critical gap from an S-shape cumulative Gaussian distribution of gaps accepted, logistic regression determine the coefficients that make the observed outcome most likely using the maximum-likelihood technique (Al-Ghamdi, 2002) which is one of the procedures that can be recommended for practical application (Brilon et al, 1999). The logistic function, of the form:  $F(x) = \frac{1}{1 + e^{-\left(\frac{x-\alpha}{\beta}\right)}}$ , with  $x$  the time gap,  $\beta$  the slope of the logistic

curve at point  $\alpha$ , was then used to compute the mean accepted time gap and the transition threshold from the raw data, i.e., the percentage of accepted crossings at each time gap (see Figure 2). The mean accepted time gap corresponds to the transition point between the decision not to cross and the decision to cross (argument  $\alpha$  of the function which corresponds to the mean time gap at which participants decided to cross 50% of the time). The transition threshold (argument  $\beta$  which corresponds to half the difference between the arguments for function values of 0.25 and 0.75) indicates the abruptness of the transition from rejecting to

accepting time gaps, and whether the perception of action possibilities is accurate. The more the behavior is finely tuned to time gaps, the more this transition will be abrupt (Oudejans et al., 1996).

### 2.5.2. Crossing behavior

In regard to the pedestrian's motion (his/her position on the experimental road at each point in time and the respective positions of each vehicle on the virtual road), initiation strategies, exposure time and safety margin were computed for each participant and each accepted crossing. Initiation strategies were tracked through initiation time and distance of anticipation. Initiation time was equal to the time between the moments when the rear end of the lead vehicle of the gap passed in front of the pedestrian and when the participant started to walk. Initiation time was negative when the participant anticipated his crossing and started walking before the (rear end of the) lead car of the gap passed his/her crossing line and positive after that. Distance of anticipation corresponded to the distance the participants walked on the experimental road before the lead car has passed. This distance was computed only when the initiation time was negative. When the initiation time was positive, the distance of anticipation was 0. Exposure time corresponded to the time during which the participants were directly exposed to the approaching vehicle, in front of which they chose to cross. It was equal to the time between the moments when the rear end of the lead car of the interval passed the pedestrian crossing and when the participant was completely over the curb of the opposite sidewalk. This method made it possible to compare behavior between intervals as it did not depend on the interval chosen in the traffic stream (contrary to the crossing time, which has usually been used; e.g., Lobjois & Cavallo, 2009; te Velde et al., 2005). The safety margin was equal to the time between the moments when the pedestrian reached the other curb and when the front end of the oncoming vehicle has reached the pedestrian crossing.

### 2.5.3. Categorizing the decisions

For the accepted crossings, a close call occurred if the participant was still on the road when the car passed the crossing line but was not “hit” by the vehicle. Note that the safety margin for this type of decision was negative (although the pedestrian was not “hit” by the vehicle), which is a common criterion for categorizing decisions as unsafe (e.g., Simpson et al., 2003). A tight fit corresponded to crossing with a safety margin between 0 and 1.5 s.

For rejected crossings, a missed opportunity corresponded to trials in which the individual’s mean exposure time was shorter than the approaching car’s time gap.

These values were then expressed as percentages of the number of accepted crossings for the first two categories, and of the number of rejected crossings for the third category. This method was used to determine the respective percentages of each decision category independently of the number of accepted or rejected crossings, since our previous studies showed that the elderly have fewer opportunities than the younger adults (Lobjois & Cavallo, 2007; 2009; Lobjois et al., 2008).

All variables were input into analyses of variance (ANOVA) with age and gender as between-participant factors, and vehicle speed and selected interval as within-participant factors. The significance level was set at 0.05 for all statistical analyses. The effect size ( $\eta^2$ ) was also computed. Significant effects were further examined using Newman–Keuls post hoc test.

### 3. Results

The participants’ responses are plotted in Figure 2 as a function of age, vehicle speed, and time gap for the first two intervals of the traffic stream. The percentages of accepted crossings as a function of age, speed and position of the gap in the traffic stream are given for information in Figure 3.

#### 3.1. Mean accepted time gap and transition threshold

The Age<sub>3</sub> x Gender<sub>2</sub> x Speed<sub>2</sub> x Interval<sub>2</sub> ANOVA on the mean accepted time gap revealed a main effect of age,  $F(2,61) = 3.53, p < .05, \eta^2 = .10$ , vehicle speed,  $F(1,61) = 93.16, p < .0001, \eta^2 = .60$ , interval,  $F(1,61) = 4.03, p < .05, \eta^2 = .06$ , as well as an interaction between age and speed,  $F(2,61) = 9.97, p < .001, \eta^2 = .27$ . The mean time gap was significantly lower for the 20-30 year-olds ( $M = 3.12$  s) than for the 60-70 ( $M = 3.64$  s) and 70-80 year-olds ( $M = 3.52$  s) who did not differ from each other. The time gap was lower at 60 ( $M = 3.19$  s) than at 40 km/h ( $M = 3.66$  s), and for the second interval ( $M = 3.38$  s) in comparison with the first one ( $M = 3.47$  s). The post hoc test on the interaction between age and speed showed that the young group selected a similar average time gap at all vehicle speeds, whereas this gap dropped as speed increased for the two older groups (Table 1).

The ANOVA on the transition threshold (Table 1) revealed a main effect of interval,  $F(1,61) = 4.16, p < .05, \eta^2 = .06$ , and vehicle speed,  $F(1,61) = 7.71, p < .01, \eta^2 = .11$ . Transition threshold was shorter when the second interval was selected ( $M = 0.08$  s) in comparison with the first one ( $M = 0.12$  s); it was also shorter at 60 ( $M = 0.07$  s) than at 40 km/h ( $M = 0.12$  s).

## 3.2. Crossing behavior

### 3.2.1. Initiation strategies

The ANOVA on the mean initiation time (Table 2) revealed a main effect of gender,  $F(1,61) = 5.16, p < .05, \eta^2 = .08$ , interval,  $F(1,61) = 24.94, p < .0001, \eta^2 = .29$ , and speed,  $F(1,61) = 283.3, p < .0001, \eta^2 = .82$ . Women ( $M = -1.35$  s) initiated their crossings sooner than men ( $M = -1.0$  s), and participants started to cross sooner when they selected the second interval ( $M = -1.34$  s) in comparison with the first one ( $M = -1.01$  s), and at 40 ( $M = -1.32$  s) than at 60 km/h ( $M = -1.03$  s). The ANOVA also revealed interactions between age and interval,  $F(2,61) = 4.92, p < .05, \eta^2 = .14$ , gender and speed,  $F(1,61) = 8.87, p < .01, \eta^2 = .13$ , and speed and interval,  $F(1,61) = 13.04, p < .0001, \eta^2 = .18$ . Post hoc test on the interaction

between age and interval showed the same interval effect as above in the younger ( $M = -0.94$  and  $-1.52$  s, for the 1<sup>st</sup> and 2<sup>nd</sup> interval, respectively) and older-old groups ( $M = -1.13$  and  $-1.49$  s, for each interval, respectively), but there was no difference for the younger-old adults ( $M = -0.98$  and  $-1.04$  s, for the first two intervals, respectively). The post hoc test on the gender-by-speed interaction revealed a significant difference between speeds for the women ( $M = -1.53$  and  $-1.18$  s at 40 and 60 km/h, respectively) as well as for the men ( $M = -1.12$  and  $-0.88$  s at 40 and 60 km/h, respectively). Note that there were no group differences at any given speed. The post hoc test on the interaction between speed and interval showed that initiation time was shorter at 60 than at 40 km/h either for the first interval or for the second. Furthermore, participants initiated their crossings sooner when they selected the second interval than when they accepted the first one, and this was true whatever the speed.

Based on the results involving the interval, it could be hypothesized that crossings were initiated sooner at the second interval simply because the lead vehicle of the gap had an arrival time greater than the lead car of the first gap. One way to disambiguate this result was to determine whether participants took advantages of this initiation strategy in moving forward on the road in order to shorten the crossing distance. According to this logic, the distance of anticipation should be all the more high since the crossing initiation was soon. In other words, if the sooner initiation time at the second interval was not only due to the higher arrival time of the lead vehicle, the distance of anticipation should differ according to the selected interval and be higher for the second one.

The ANOVA on the mean distance of anticipation (Table 2) revealed a main effect of speed,  $F(1,61) = 362.7, p < .0001, \eta^2 = .86$ , and interactions between age and interval,  $F(2,61) = 5.77, p < .01, \eta^2 = .16$ , age and speed,  $F(2,61) = 3.82, p < .05, \eta^2 = .11$ , gender and speed,  $F(1,61) = 6.77, p < .05, \eta^2 = .10$ , and speed and interval,  $F(1,61) = 4.44, p < .05, \eta^2 = .07$ . Distance of anticipation was shorter at high speed ( $M = 0.36$  m) than at low speed ( $M = 0.54$



m). Post hoc test on the interaction between age and interval revealed that younger participants walked further ahead on the road when they selected the second interval ( $M = 0.47$  m) in comparison with the first one ( $M = 0.40$  m). There was no interval difference in both older groups ( $M = 0.45$  and  $0.43$  m in the younger-old group, and  $0.51$  and  $0.47$  m in the older-old group, for the first and second interval, respectively). The post hoc tests on the age-by-speed, gender-by-speed and speed-by-interval interactions showed the same speed effect as above in the three age groups, the two gender groups and the two intervals.

### 3.2.2. Exposure time

The ANOVA on the mean exposure time (Table 2) revealed a main effect of speed,  $F(1,61) = 418.3, p < .0001, \eta^2 = .87$ , and an interaction between age and speed,  $F(2,61) = 14.1, p < .0001, \eta^2 = .32$ . Exposure time was shorter at 40 ( $M = 3.25$  s) than at 60 km/h ( $M = 3.5$  s). Post hoc test on the age-by-speed interaction showed that the exposure time of each age group increased significantly with speed (Table 2), but this increase tended to be higher in elderly ( $M = 0.33$  s) than younger ( $M = 0.17$  s) pedestrians.

### 3.2.3. Safety margin

The ANOVA on the mean safety margin (Table 2) revealed a main effect of speed,  $F(1,61) = 349.8, p < .0001, \eta^2 = .85$ , and an interaction between age and speed,  $F(2,61) = 24.07, p < .01, \eta^2 = .44$ . Safety margin was shorter at 60 ( $M = 1.81$  s) than at 40 km/h ( $M = 2.29$  s). Post hoc comparisons on the age-by-speed interaction showed that the safety margin of each age group decreased significantly with the speed increase (Table 2), but the decrease tended to be higher in elderly ( $M = 0.66$  s) than younger ( $M = 0.24$  s) pedestrians.

### 3.3. Decisions

Results revealed that the mean time gap was influenced by the selected interval indicating that participants accepted a lower gap for the second interval. This result was accompanied by a similar effect on transition threshold, suggesting that participants' crossing

decisions were much more finely tuned to time gaps for the second interval. Decisions analysis was then dedicated to examining the origin of the lower gap at the second interval.

First of all, previous studies interested in the gap accepted when faced with a traffic stream suggested that this particular behavior was associated with greater risk taking. To explore this hypothesis, the percentages of close calls and tight fits were analyzed as a function of the interval accepted in the traffic stream. Except for the robust main effect of speed (on close calls,  $F(1,61) = 16.18, p < .0001, \eta^2 = .21$ , and tight fits,  $F(1,61) = 102.6, p < .0001, \eta^2 = .63$ , participants had more close calls and tight fits at 60 than at 40 km/h) and the interaction between age and speed (on tight fits,  $F(2,61) = 6.70, p < .01, \eta^2 = .18$ , the three age groups showed the same speed effect as above), the interval did not yield any significant effects neither as a main effect nor through interaction (Table 3). Note that the previous analysis on the safety margin did not reveal any effect of this factor either.

A second hypothesis examined the proposal of Kittelson and Vandehey (1991) according to which participants took more risk at the second interval because they first missed an opportunity. To test this hypothesis, we computed the percentage of close calls and tight fits at interval 2 for each participant who had missed an opportunity at interval 1 ( $n = 43^1$ ). The results revealed no close calls at the second interval in this particular condition. The percentage of tight fits at interval 2 following a missed opportunity was compared to the overall percentage of tight fits (i.e., independently of what happened at interval 1) as a function of age, gender and speed. Among the results of interest, the percentage of tight fits at interval 2 following a missed opportunity ( $M = 7.9\%$ ) was significantly lower than the overall percentage ( $M = 25.2\%$ ),  $F(1,37) = 45.77, p < .0001, \eta^2 = .55$ .

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<sup>1</sup> We also compared the mean time gap accepted at intervals 1 and 2 by participants who missed an opportunity at interval 1 and those who did not. Similarly to Kittelson and Vandehey (1991), this analysis was aimed at determining whether participants who first missed an opportunity accepted a lower gap at interval 2 by comparison with interval 1. Of the results of interest, the interaction between groups and interval was not significant. Participants who missed an opportunity at interval 1 crossed the road with a mean time gap of 3.79 and 3.66s at interval 1 and 2, respectively, and the other participants did so with a mean time gap of 2.9 and 2.91s at interval 1 and 2, respectively.

#### 4. Discussion

The present study aimed at examining the effect of a traffic stream on gap acceptance, crossing decisions and behavior of younger and older pedestrians. Based on previous research showing that road users accepted shorter and shorter gaps as waiting time/number of vehicles they let pass increased, our first goal was to determine whether this particular behavior was observed in the older pedestrians. Our second goal was to assess whether this drop in the gap size increased risk taking or could correspond to a better attunement with the possibility of road crossing. In an attempt to explore the origin of this drop, we also tested the proposal of Kittelson and Vandehey (1991), according to which the gap drop comes from the acceptance of gaps shorter than one or more previously rejected gaps, which is suitable to explain the higher risk in the older pedestrians as they miss more opportunities than younger pedestrians.

Concerning the effects of age, the results showed that the 60-70 and 70-80 age groups selected a greater time gap for crossing than the younger group. This result is in line with what could be expected in the light of the age-related decrease in walking speed (fastest as well as self-paced) observed in prior work (Carmeli et al., 2000; Lobjois and Cavallo, 2007; Oxley et al., 2005) and indicates that in this simple street-crossing situation (single lane, one-way traffic) older adults were able, to a certain extent, to take their changing sensory and motor abilities into account when making a decision. The efficiency of this compensatory behavior was demonstrated by the similar safety margins and unsafe-decision rates found here for the three populations of pedestrians. These findings are comparable to observations of real-life crossing behavior by Oxley et al. (1997), who showed that the crossing behavior of older pedestrians was safer, and similar to that of younger pedestrians, on a one-way than on a two-way road.

Our gender results contrast with Holland and Hill (2010) who showed that crossing decisions of men and women differed. As Holland and Hill (2010) accounted for this

difference by a reduced mobility, the absence of gender differences in our study could be explained by the fact that our participants were scrutinized for mobility measures and cardiac, neurological and visual disorders resulting in our population sampling dropping out people with mobility and other health problems. This is attested, for example, by the lack of gender and age difference on the exposure time.

This last result is interesting in that the most recent studies (Holland & Hill, 2010; Lobjois & Cavallo, 2007; Oxley et al., 2005) used crossing time compared to the available time to estimate the safety margin and the percentage of unsafe decisions in button-press tasks. However, the current study found a significant age difference on crossing time<sup>2</sup> but not on exposure time. This suggests that safety margin may be underestimated and unsafe decisions overestimated when computed from the crossing time and that crossing behavior should be studied in an interactive road-crossing situation in order to collect relevant indicators of crossing behavior (for empirical evidence, see Lobjois & Cavallo, 2009, and te Velde et al., 2005 who showed differences in unsafe decisions between an estimation task and an interactive one).

Confirming previous studies, our results yielded a strong effect of speed on crossing decisions and behavior, as shown previously in pedestrians (Lobjois and Cavallo, 2007, 2009; Oxley et al., 2005; Simpson et al., 2003), but also in driver's left-turn gap acceptance (Alexander et al., 2002; Yan et al., 2007). However, the pattern of results revealed differences depending on age. Younger adults selected a similar time gap at both speeds, but had more and more close-calls and tight fits as speed increased. Older adults selected a shorter time gap, had more close-calls, tight fits and less missed opportunities as speed increased. This figure of gap acceptance according to age and speed is hypothesized to depend on the sensory components of the crossing. Concerning the perceptual decision component of the crossing, it

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<sup>2</sup> The ANOVA on the mean crossing time revealed a main effect of age,  $F(2,61) = 6.19, p < .01, \eta^2 = .17$ , with a significant difference between the 70-80 year-olds ( $M = 4.65$  s) and both other groups ( $M = 4.18$  and  $4.35$  s for the 20-30 and 60-70 year-old groups, respectively).

has been suggested that older participants operate in a mixed mode by founding their decisions on time gap but also on distance-based heuristics (e.g., Lobjois & Cavallo, 2007; Oxley et al., 2005). This was confirmed by the fact that younger adults crossing decisions were much more finely tuned to the time gap than those of older adults (Lobjois & Cavallo, 2009) and that the respective weight of time and distance in the decision process changes from time in the young group to time and distance in the older adults (Lobjois et al., 2005). Concerning the motor component of the crossing, participants at all ages were more conservative at slow than at fast speeds (higher time gap, sooner initiation, greater distance of anticipation and shorter exposure time). This particular behavior could come from the greater angular size subtended by the oncoming vehicle from the observer's perspective at slow speeds than at fast speeds. This may have induced a feeling of being unsafe, thus leading participants to anticipate their crossings and to shorten their exposure time at 40 comparatively to 60 km/h.

In line with previous studies on gap acceptance (Adebisi & Sama, 1989; Ashworth & Bottom, 1977; Kittelson & Vandehey, 1991; Plumert et al., 2011; Simpson, et al., 2003), our results confirmed that the accepted time gap decreased when the waiting time/number of vehicles pedestrians let pass increased. This result is similarly present in older pedestrians. Second, all of the studies reported above have implicitly suggested that the decrease of the mean time gap was associated with an increase in risk taking. Analysis of the decisions did not confirm this view as the percentage of close-calls and tight fits did not change as a function of the selected interval. Third, our results did not support the assumption of Kittelson and Vandehey (1991), according to which the gap drop does not result only from the waiting time but also from an acceptance of gaps shorter than one or more than one previously rejected gaps (i.e., after an opportunity was missed). On the one hand, participants who first missed an opportunity did not take more risk at interval 2. On the other hand, their mean time

gap did not differ as a function of the selected interval: those who missed an opportunity at interval 1 did not select a shorter gap at interval 2.

At last, our results revealed that the transition threshold was lower at interval 2 in comparison to the first one. This suggests a different origin and interpretation of the effect of the selected interval on the gap size, which is in line with a better attunement of the responses and a calibration hypothesis. The abruptness of the transition from rejecting to accepting time gaps suggests that the perception of action possibilities (i.e., whether a gap is affordable or not) and the calibration between perception and action are improved when participants choose the second interval. We assume that rejecting the first available gap could have increased the safety of the crossings. Pedestrians could estimate more accurately the approach of the oncoming vehicle and its arrival time by comparing the second gap to the first one. They could also calibrate more accurately their perception and action to determine whether the gap is crossable or not. Lastly, they could anticipate their crossings by moving forward on the road and shortening the crossing distance.

While Virtual Reality (VR) tools have many advantages to study human behavior (risk completely removed, experimental control), some issues related to the evaluation of simulations have to be discussed. Stoffregen et al. (2003) argued “that in the strict sense of duplication, simulation is essentially impossible” as “sensory stimulation in a simulator cannot be identical to sensory stimulation that is available in the system being simulated” (p. 111). Simulation cannot capture all of the conditions, information, sensations, and factors associated with crossing decisions. These differences provide information to the participants about the nature of the road-crossing simulation, as such. For these reasons, we have to acknowledge that our VR tool has a limited physical validity. The question that arises is whether a limited physical validity jeopardizes the “psychological validity” (Pinto et al., 2008) or “action fidelity” (Burkhardt et al., 2003; Stoffregen et al., 2003). First, Pinto et al.

(2008) suggested that a high level of physical fidelity is not always required to achieve good levels of psychological validity. A small discrepancy can be tolerated due to limitations inherent in information intake and processing (e.g., Hochberg, 1986). Second, some of our results do not support the statement that a limited physical validity jeopardizes the psychological validity. Lobjois and Cavallo (2009) showed in a previous study that with a similar visual and auditory stimulation, the interactive road-crossing situation improves the perception of action possibility when compared to a non-interactive task. This result suggests that the interactive component of the task contributes to the sameness of the psychological processes underlying the activity and to the psychological validity of our VR tool. Due to the limited physical fidelity, one can assume that participants might have behaved differently than if actual traffic and potential real injuries might occur. In combination with the absence of risk, this could turn into a high number of collisions (i.e., a greater risk taking behavior in the safe virtual environment). This is at least not supported by the number of collision which was particularly low (no collision in the younger group, 2 in the 60-70 year-old group, and 5 collisions in the 70-80 year-old group). Finally, these data mirrored published accident statistics as well as developmental differences between younger and older adults, suggesting that the VR tool was valid to examine crossing skills and strategies. While some of our results supported a relatively good psychological validity of the VR situation, direct comparisons between VR simulations and road-crossing behavior in a natural environment are still needed (e.g., Schwebel et al., 2008).

## 5. Conclusion

The present study was undertaken to address the effect of a traffic stream on road-crossing decisions in younger and older adults. Our findings showed that healthy older adults were aware of their reduced action capabilities and were able to take their changing sensory and motor abilities into account when making a decision in a single lane, one-way traffic

street-crossing situation. This confirmed that older adults were not more impaired than younger ones by a one-way traffic stream. This interpretation is supported by observations of real-life crossing behaviour by Oxley et al. (1997), who showed that the crossing behaviour of older pedestrians was safer, and similar to that of younger pedestrians, on a one-way than on a two-way road.

The second important result relied on the traffic stream effect. Similarly to previous research in driving (Adebisi & Sama, 1989; Ashworth & Bottom, 1977; Kittelson & Vandehey, 1991) and bicycling (Plumert et al., 2011), a drop in the gap size occurred when the waiting time/number of vehicles pedestrians let pass increased. The interesting new result came from the observation that the decrease in the gap size was not accompanied by an increased risk taking as suggested by previous research. This figure of crossing decisions in traffic-filled situation was originated from a better selection of crossable gaps. Younger as well as older adults' decisions were better attuned to the traffic flow when they selected the second interval. The flow of vehicles might help them to compare gaps between each others and judge the crossability of the gap. This opens an interesting perspective to improve the ability of elderly road users to remain accurate in their judgements.

From the present and previous studies, several paths for improving older pedestrians' road safety can be put forward. First of all, the robust effect of the approaching vehicle speed on the crossing decisions and safety even after training (e.g., Dommes & Cavallo, 2012; Dommes et al., 2012) argues for the introduction of appropriate speed limits in urban areas. Second, other important issues for the crossing safety like choice of crossing location (Holland & Hill, 2010) and two-way roads (Oxley et al., 1997) are still understudied. Finally, a third way to improve street-crossing safety in the elderly relies on training/rehabilitation programs. While our findings suggest that crossing behaviour was better attuned to the traffic flow when the participants selected the second interval, it could be valuable to design training



programs using a traffic stream instead of one or a couple of vehicles (e.g., Dommes & Cavallo, 2012; Dommes et al., 2012). A repeated practice in a traffic-filled situation could potentially help older adults make better use of the approaching vehicles' speed. At last, the screening out of participants with mobility and other health problems resulted in a sample of healthy older participants in comparison to the actual older population at risk. These healthy older participants were shown to be able to take into account their changing sensory and motor processes and to maintain well attuned behaviour to the traffic stream. While recent results revealed that athletes outperformed non-athletes in a virtual street-crossing task (Chaddock et al., 2011), and that most rehabilitation programs were targeted toward visual and cognitive processes, these programs could also target the effects of physical activity/fitness on cognitive and motor skills to determine whether an active lifestyle could help older adults in everyday activity such as crossing a road.

## Acknowledgments

This research was supported by a grant from the Fondation Mutuelle d'Assurance des Instituteurs de France to the Laboratory of Driver Psychology (Viola Cavallo).

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Table 1

Mean Accepted Time Gap as a Function of Age, Gender, Vehicle Speed and Traffic Conditions.

Age	Gender	Accepted Time Gap (s)				Transition Threshold (s)			
		1st Interval		2nd Interval		1st Interval		2nd Interval	
		40 km/h	60 km/h	40 km/h	60 km/h	40 km/h	60 km/h	40 km/h	60 km/h
20-30	Women	3.30	3.09	3.12	2.98	0.167	0.099	0.067	0.014
	Men	3.25	3.17	3.13	2.90	0.156	0.031	0.016	0.015
60-70	Women	3.97	3.39	3.96	3.28	0.116	0.114	0.210	0.060
	Men	3.94	3.32	3.88	3.39	0.090	0.109	0.105	0.049
70-80	Women	3.88	3.17	3.81	3.12	0.225	0.106	0.115	0.070
	Men	3.88	3.30	3.87	3.20	0.114	0.079	0.115	0.071

Table 2

Mean initiation time, distance of anticipation, exposure time and safety margin as a function of age, gender, interval and vehicle speed.

Age	Gender	Interval	Speed	Initiation time (s)	Distance of anticipation (m)	Exposure time (s)	Safety margin (s)
20-30	Women	First	40 km/h	-1.24	0.48	3.11	2.20
			60 km/h	-0.98	0.34	3.27	1.95
		Second	40 km/h	-1.96	0.56	3.05	2.23
			60 km/h	-1.58	0.39	3.32	1.98
	Men	First	40 km/h	-0.88	0.45	3.20	2.13
			60 km/h	-0.68	0.33	3.31	1.93
		Second	40 km/h	-1.44	0.54	3.14	2.17
			60 km/h	-1.11	0.38	3.26	1.94
60-70	Women	First	40 km/h	-1.21	0.63	3.27	2.41
			60 km/h	-0.97	0.42	3.56	1.82
		Second	40 km/h	-1.39	0.60	3.29	2.35
			60 km/h	-0.96	0.36	3.58	1.76
	Men	First	40 km/h	-0.97	0.45	3.22	2.43
			60 km/h	-0.76	0.30	3.45	1.93
		Second	40 km/h	-1.00	0.45	3.22	2.48
			60 km/h	-0.83	0.29	3.45	1.97
70-80	Women	First	40 km/h	-1.40	0.70	3.34	2.28
			60 km/h	-1.15	0.47	3.67	1.60
		Second	40 km/h	-1.95	0.68	3.33	2.27
			60 km/h	-1.43	0.42	3.69	1.61
	Men	First	40 km/h	-1.07	0.50	3.39	2.26
			60 km/h	-0.81	0.31	3.71	1.66
		Second	40 km/h	-1.37	0.46	3.40	2.30
			60 km/h	-1.08	0.28	3.69	1.62



Table 3

Decision Percentage for each Age, Decision Category, Selected Interval and Vehicle Speed.

Age	Decision Category (%)	First Interval		Second Interval	
		40 km/h	60 km/h	40 km/h	60 km/h
20-30	Accepted Crossings				
	Close Calls	1.4	2.3	2.7	2.9
	Tight Fits	29.3	36.2	27.8	36.2
	Rejected Crossings				
	Missed Opportunities	8.5	4.3	5.9	2.9
60-70	Accepted Crossings				
	Close Calls	0.6	4.4	2	4.2
	Tight Fits	21.7	34.7	21.2	33.6
	Rejected Crossings				
	Missed Opportunities	18.9	7.8	20.5	7.7
70-80	Accepted Crossings				
	Close Calls	2	6.5	1.1	5.4
	Tight Fits	22.9	40.3	21.8	42.8
	Rejected Crossings				
	Missed Opportunities	17.2	2.6	17.3	2.8

## Figure Captions

Figure 1. Top-down schematic view of the experimental setup.

Figure 2. Percentage of accepted crossings for each age group (20–30, 60–70, and 70–80) as a function of vehicle speed, time gap and traffic conditions.

Figure 3. Percentage of accepted crossings as a function of age group, vehicle speed and order of the gap in the heavy traffic condition.

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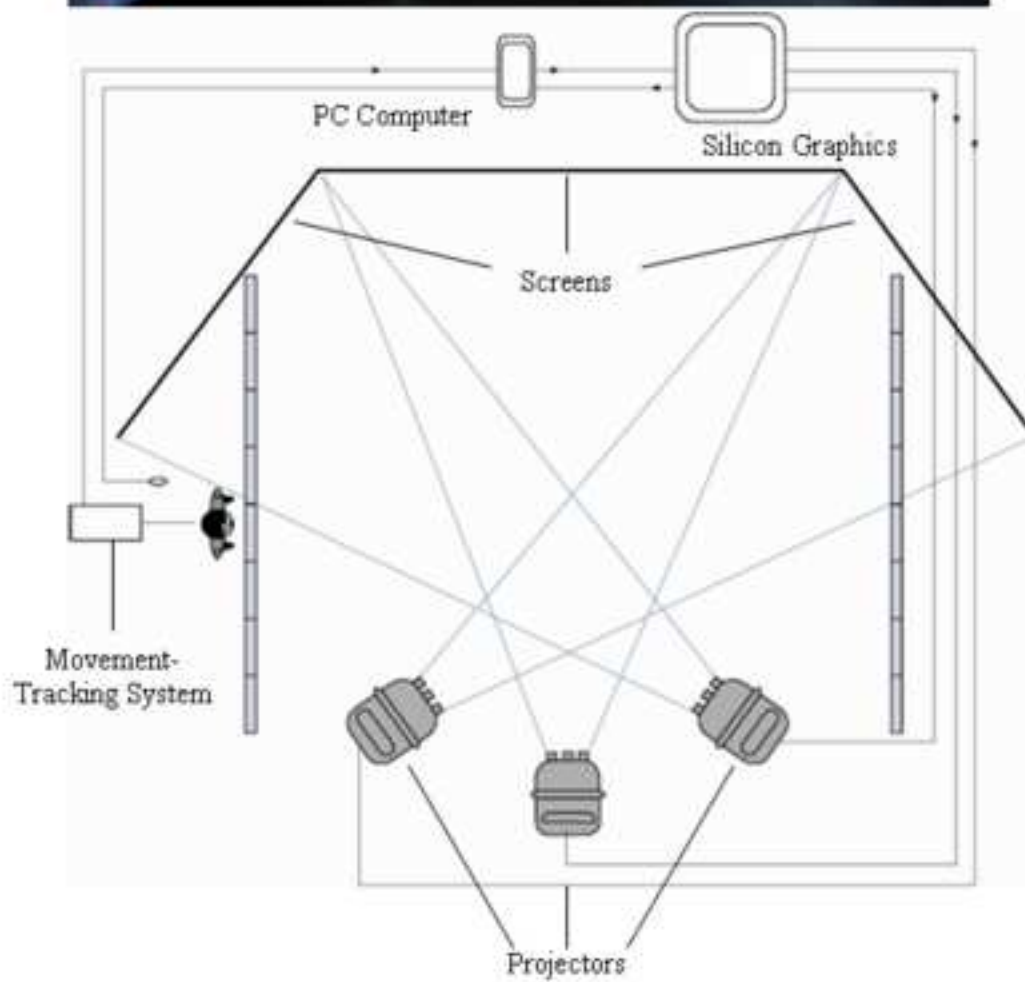
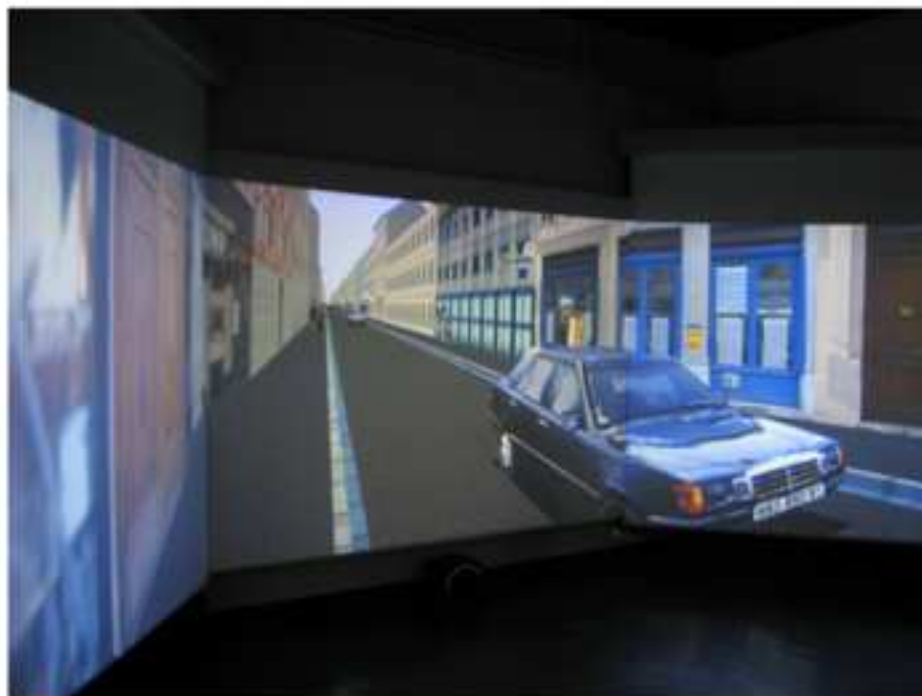


Figure 2

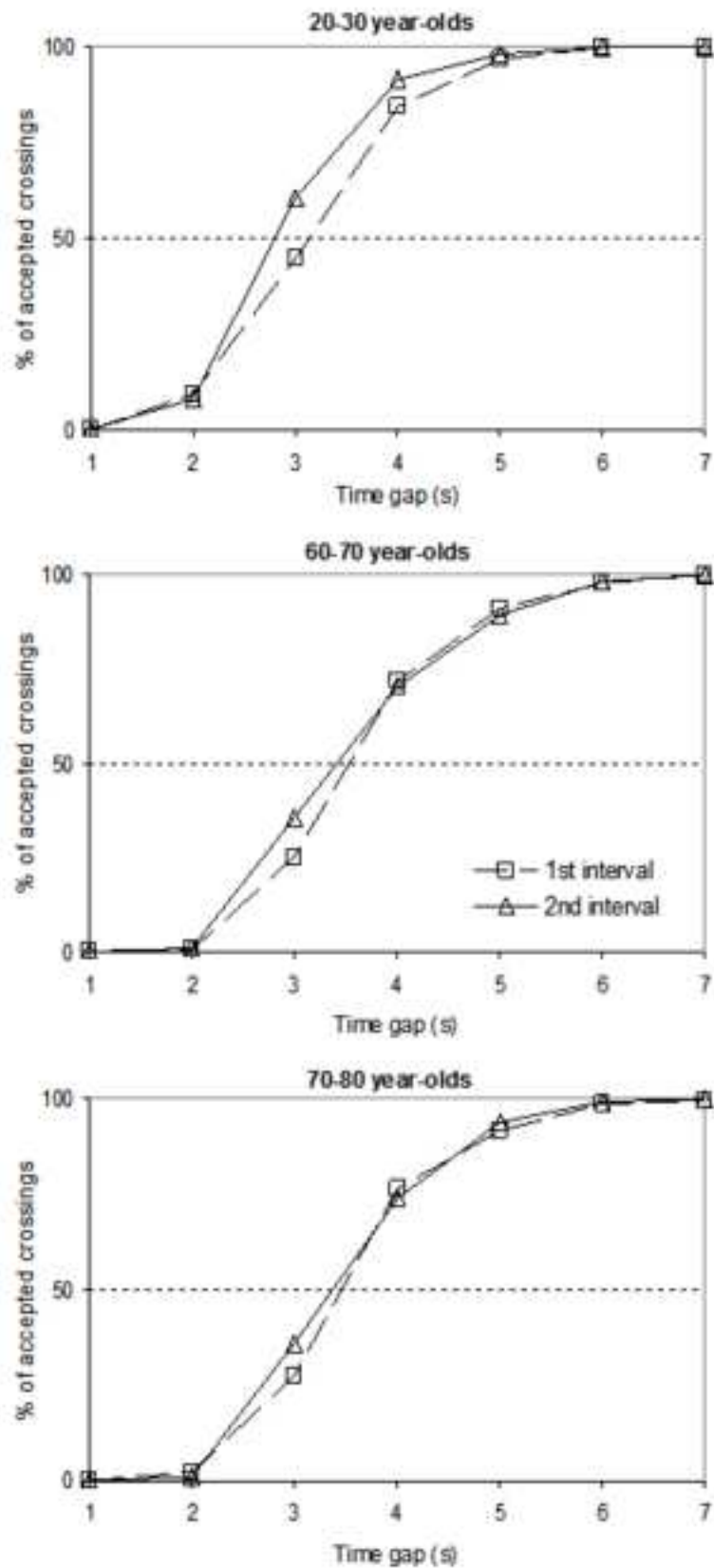


Figure 3

