Accident Analysis and Prevention 65 (2014) 72–84

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Arrival-time judgments on multiple-lane streets: The failure to ignore irrelevant traffic☆

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ARTICLE INFO

Article history:
Received 27 June 2013
Received in revised form 2 October 2013
Accepted 23 December 2013

Keywords:
Intersection-crossing
Time-to-arrival
Multiple gaps
Perceptual averaging

ABSTRACT

How do road users decide whether or not they have enough time to cross a multiple-lane street with multiple approaching vehicles? Temporal judgments have been investigated for single cars approaching an intersection; however, close to nothing is known about how street crossing decisions are being made when several vehicles are simultaneously approaching in two adjacent lanes. This task is relatively common in urban environments. We report two simulator experiments in which drivers had to judge whether it would be safe to initiate street crossing in such cases. Matching traffic gaps (i.e., the temporal separation between two consecutive vehicles) were presented either with cars approaching on a single lane or with cars approaching on two adjacent lanes, either from the same side (Experiment 1) or from the opposite sides (Experiment 2). The stimuli were designed such that only the shortest gap was decision-relevant. The results showed that when the two gaps were in sight simultaneously (Experiment 1), street-crossing decisions were also influenced by the decision-irrelevant longer gap. Observers were more willing to cross the street when they had access to information about the irrelevant gap. However, when the two gaps could not be seen simultaneously but only sequentially (Experiment 2), only the shorter and relevant gap influenced the street-crossing decisions. The results are discussed within the framework of perceptual averaging processes, and practical implications for road safety are presented.

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1. Introduction

In France, a total number of 40,357 accidents occurred at intersections in the years 2010 and 2011 (ONISR, 2011, 2012). Most of these accidents occurred in city surroundings, where the velocity is highly limited, so that only a minor part (approximately 2.2%), led to one or more fatalities. However, these losses at intersections represent an important part of the road causalities, approximately 12% of the death toll. Independently of the responsibilities of the different road users (pedestrians, drivers and cyclists) involved and the multiple and cumulative causes of the accidents, it appears likely that at least one of the actors may have misjudged the time-to-arrival (TA, that is the time remaining before the approaching car reaches the intended crossing path) of the other approaching vehicle. Indeed, before crossing a road or an intersection, road users need to consider the traffic situation and decide whether or not they have enough time to safely complete their crossing maneuver. In such a task, the temporal size of the available gap (i.e., the temporal separation between two consecutive vehicles) has to be anticipated, which requires an accurate estimation of the TA. In this respect, a gap is crossable if its corresponding TA is greater than the crossing time needed by the observer, plus a safety margin. The temporal window available for the observer may or may not be sufficient to accomplish the street crossing maneuver.

Within the last years, it has been proposed that interceptive or avoidance actions, like street crossing actions are, are controlled based on optical expansion cues such as tau [$\tau(\theta)$, the instantaneous visual angle subtended by the object divided by the instantaneous rate of expansion, Lee, 1976] on other tau-like variables (Bootsma and Oudejans, 1993), or simpler optical parameters, such as the bearing angle of the approaching car (the angle subtended by the current position of the car and the direction of the subjects' motion; e.g., Chardenon et al., 2005; Bastin et al., 2006). In addition, previous research suggests that several factors influence street-crossing decisions in pedestrian or driver situations, or more generally the capacity to detect and avoid a collision with an approaching object, mainly the observer's age (e.g., Oxley et al., 2005; Yan et al., 2007; Lobjois and Cavallo, 2009), the approaching vehicle's speed

☆ Part of Experiment 1 has been presented at the Skills conference, 15–16 December 2011, Montpellier, France, under the form of a poster.

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http://dx.doi.org/10.1016/j.aap.2013.12.013

or distance (Cavallo and Laurent, 1988; Alexander et al., 2002; te Velde et al., 2005; Lobjois and Cavallo, 2007), and the relative size of the object (the size-arrival effect, DeLucia and Warren, 1994).

However, little attention has been paid to the situation where several objects have to be avoided in the same time, for example in a street crossing situation when multiple lanes have to be crossed (see e.g., Grechkin et al., 2013). One can conceive of this situation as the task to concurrently judge a number of moving gaps. In the case of two cars approaching in two adjacent lanes, the gaps are defined as the temporal intervals between each car and its respective intersection point with the observers' path (note that this is not equal to the temporal separation between the two cars). This situation is more complex than the typical temporal-range estimation scenarios. We provide what to our knowledge is the first temporal-range estimation data for this rather common situation. City centers abound with streets in which road users may have to cross multiple lanes, and hence are put in a position to deal with more than one gap at the time. It cannot be assumed that the reasonably good performance in the face of one gap necessarily generalizes to situations where several gaps need to be judged simultaneously. The TA perception in multiple-lane streets and the crossing decision based upon it may significantly differ from those obtained in a one-lane street.

Evidence suggesting that such a difference is to be expected in multiple-gap scenarios comes from previous laboratory-based experiments based on the simpler case of multiple concurrent TA estimations of moving objects. They showed that relative and absolute TA judgments were affected by the number of objects that had to be considered (set size). Relative TA judgments assess which of several objects will arrive first, whereas absolute TA judgments assess the exact time at which a given object is taken to arrive. Relative TA judgments were affected by set-size, with a decrease in accuracy as set-size increased (DeLucia and Novak, 1997). Moreover, dual absolute TA estimations have been shown to interfere with one another in an asymmetric fashion (Baurès et al., 2010, 2011), which indicates a perceptual bottleneck at the visual level. When comparing the TA estimates with a one-object condition in which the moving object had the same motion parameters (velocity and TA), the results showed that for two simultaneously moving objects, the TA estimates for the first-arriving object did not differ from the estimates in the one-object situation. However, participants significantly overestimated the TA of the later-arriving object, relative to the one-object condition. The human visual system thus appears to be unable to accurately process two TAs at the same time.

When confronted with multiple gaps, the visual system might resort to perceptual averaging, or statistical summary representations (Albrecht and Scholl, 2010). It has been shown that when observers are confronted with a set of objects, the visual system represents the overall statistical properties of the set rather than individual properties (Ariely, 2001). Based on this hypothesis, when being confronted with multiple gaps, observers might perceive the mean value of the gaps rather than the individual value of each gap, and behave according to this mean value.

To determine if observers' ability to estimate several TAs is indeed distorted in such a manner, we carried out two street-crossing experiments in which observers had to pass through a single gap or through two simultaneous gaps (dual-gap condition). For the sake of simplicity, we illustrate this scenario by taking the situation where the gap is already opened and the critical decision is to judge whether or not the street can be safely crossed before the oncoming traffic reaches the observer. Three potential outcomes can be predicted.

1) *Ideal observer*: For an ideal observer, the decision to cross the street should depend only on the shortest TA, and be independent of the longer ones. If the shortest TA is shorter than the crossing time, then the gap(s) should be refused as unsafe for crossing. If the shortest TA is longer than the crossing time, then the gap should be accepted. Hence, if observers are able to make independent and precise TA estimations for all approaching vehicles, so that they can positively identify the vehicle with the shortest TA, then the number of approaching cars should be irrelevant, and street-crossing decisions should depend only on the value of the shortest TA. Accordingly, for a given shortest gap value, street-crossing decisions should not differ between the single-gap and the dual-gap conditions. The perceptual bottleneck highlighted by Baurès et al. (2010, 2011) predicts this outcome. Note however that as the crossing time may be significantly different when crossing the first lane only vs. the whole intersection (lanes 1 and 2), then the shortest gap value may afford the observer to cross the street if placed in the first lane but not if placed in the farther second lane.
2) *Increased safety margin*: If the two TA estimations are not independent but interfere with each other, then the irrelevant gap may emphasize the perceived danger and decrease the probability that the observers decide to cross the street in the dual-gap condition compared to the single-gap condition. One possibility to explain such a pattern of results would be that the interference between the two TA estimations causes the shortest TA to be underestimated. This would lead observers to think they have less time to cross the street than is actually available, and based on this wrong perception, to refuse the gaps. Alternatively, TA estimations could be less precise in the dual-gap condition, preventing the observers to identify which object has the shortest TA, and therefore inducing the use of a safety strategy that votes for not crossing the street.
3) *Averaging*: Finally, the interference in the TA estimations might increase the probability that the observers decide to cross the street in the dual-gap condition compared to the single-gap condition. Indeed, within the framework of the perceptual averaging hypothesis, the presence of a second gap would lead the observer to base her decision on a mean TA of the two individual TAs. The obvious consequence of such an averaging process leads the shortest TA to be overestimated, and the largest to be underestimated. That is, observers may think they have more time to cross the street than is actually available, and based on this (mis)perception, decide more readily to accept the gaps.

Note that compared to the situation with only a single approaching vehicle, the two first cases (1 and 2) would not affect the observer's safety when a second approaching vehicle is added. The third alternative (3), however, implies an increase of hazardous behavior, and may be an important risk factor when crossing a multiple-lane street.

To decide between the three potential outcomes, we carried out two gap-acceptance experiments in which participants faced one (single-gap condition) or two (dual-gap condition) cars that were approaching in adjacent lanes. In the dual-gap condition, the cars were either approaching from the same direction toward the observer (Experiment 1), or from the opposite directions (Experiment 2). At different TAs, the car(s) disappeared from view, and participants were asked to judge whether or not they would have had enough time to safely drive their car through the intersection.

2. Experiment 1

2.1. Materials and methods

2.1.1. Subjects

Fourteen observers (5 women, 9 men, age 31.64 years ± 5.56 (mean ± SD), min. age 25, max. age 43) participated voluntarily after giving informed consent. All participants had normal or

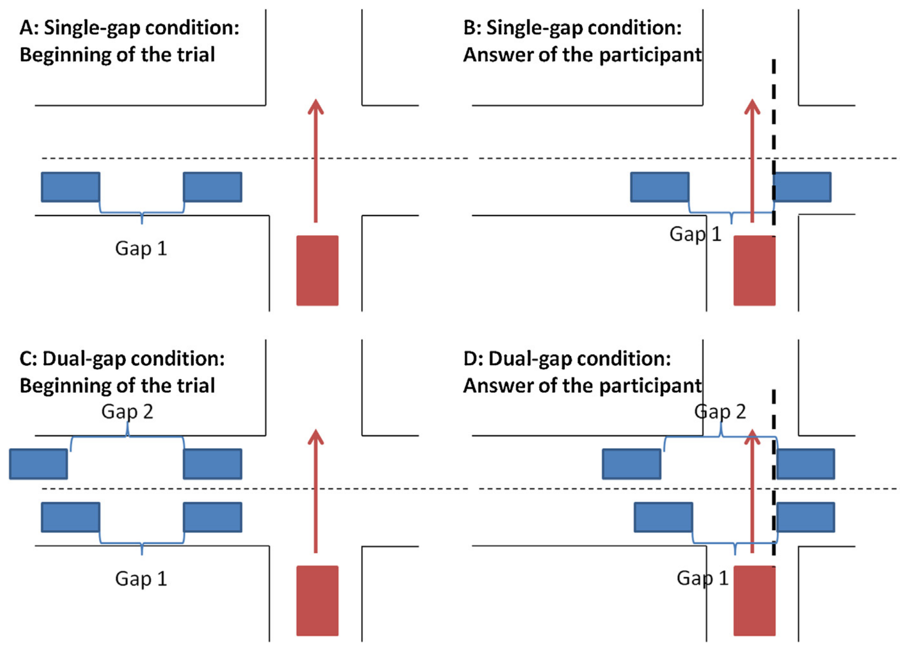

Fig. 1. Schematic representation of the task, from a bird's eye point of view for Experiment 1. Blue rectangles represent the approaching cars, and red rectangles the position of the observer. The red arrows represent the desired movement of the observer to cross the street, and the dashed black line indicates the moment of the disappearance of the vehicles from the screen, when the rear of the opening-gap vehicle reached the dashed line. Panels A and B illustrate the single-gap condition at the beginning of the trial (Panel A), or at the instant when the cars disappeared from the screen and the observers had to give their answer (Panel B). C and D panels represent the same moments in time in the dual-gap condition. For the purpose of illustration, the motorcycle is not displayed on the graph, and the gap 1 is here longer than the gap 2, but note that it was the case in 50% of the trials only. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

corrected-to-normal vision, were healthy and without any known oculomotor abnormalities. Participants were naïve with respect to the purpose of the experiment. All the participants held their driving license for more than 2 years, drove a car on a daily basis, for a declared total of minimum 50 km each week.

2.1.2. Apparatus and experimental procedure

The study was conducted using a high-fidelity, real-time driving simulator. Participants were seated in an instrumented car (Peugeot 308) providing information about gear, acceleration, braking and steering angle that was used to assess the apparent motion of the car through the virtual environment. The car was positioned in the middle of five 1.80 m × 2.50 m (length × height) screens forming an incomplete octagon. Five projection design F22 SX video projectors were used to back-project the virtual environment onto the screens, at a spatial resolution of 1400 × 1050 pixels, and a frame rate of 60 Hz. The device also included a 3D sound-rendition system. The visual scene was generated using an in-house software library developed at Ifsttar, and consisted of two perpendicular roads crossing in front of the driver, who was waiting at a stop sign. The road to be crossed was composed of two adjacent lanes, each having a width of 3 m. In the remaining of this article, this scene will be called the intersection.

In an initial training condition, participants drove the car through the intersection while no car was approaching. Twenty trials were repeated to ensure the participants established an accurate representation of the intersection's width (2 lanes of 3 m width each), the car dynamics, and the consequent crossing time.

Then, in a first condition, from the left side of the road, one group of vehicles (single-gap condition) approached toward the intersection (Fig. 1, Panels A and B). The group of vehicles consisted in an alignment of a motorcycle, a first car (gap-opening vehicle), and a second car (gap-closing vehicle). The group of vehicles was moving at a constant velocity of 30 km/h or 60 km/h. The motorcycle was always placed at the beginning of the trial such as to reach the intersection after 0.5 s of movement. Its role was to ensure to the observers a sufficient viewing time of the approaching gap, but with such a short TA that it prevented in all cases the participant from crossing the street before the relevant gap opened. The first car was placed to reach the intersection after 3 s of movement, and the second car (the gap-closing vehicle) was placed at specific TAs from the first car (the gap opening vehicle). In this single-gap condition, the temporal value of the gap could be 2, 3.5, 5, 6.5 and 8 s, leading to a spatial gap ranging from 16.67 to 66.67 m for the lower velocity and 33.34 to 133.36 m for the higher velocity. In addition, the group of vehicles could be moving in the first or second lane. In a given trial, it resulted that the participants had a constant viewing time before the gap began of 3 s, during which all the vehicles were visible for the participants. At the end of this viewing time, at the time the gap opened, all vehicles disappeared from the screen, with a last visible position for the gap closing vehicle placed at the defined TA. Ten repetitions were made for each single combination, leading participants to perform 200 trials (2 lanes × 2 velocities × 5 temporal gap values × 10 repetitions) randomly presented in this single-gap condition. Participants' instructions were to indicate whether or not they would cross the street through the gap. They should only do so if they felt they could achieve this maneuver as safely as in their normal life. To do so, participants had to press a keyboard key to indicate their decision as fast as possible after the cars' disappearance (A key to accept the gap, P key to refuse the gap, on a French azerty keyboard placed on the participants' knees). No feedback was given to the participants at any time. After the answer, the next trial began after a random pause between 1.5 and 3 s. The choice to record participants' decisions rather than asking them to really drive the car through the intersection was taken for two reasons. Firstly, our focus was on the decision to initiate street-crossing when facing multiple-gaps. In this respect, maintaining the cars present in the display and requiring participants to drive the car through the intersection would have allowed them to vary the initiation time and/or the car's velocity. Doing so, the influence of the number of gaps

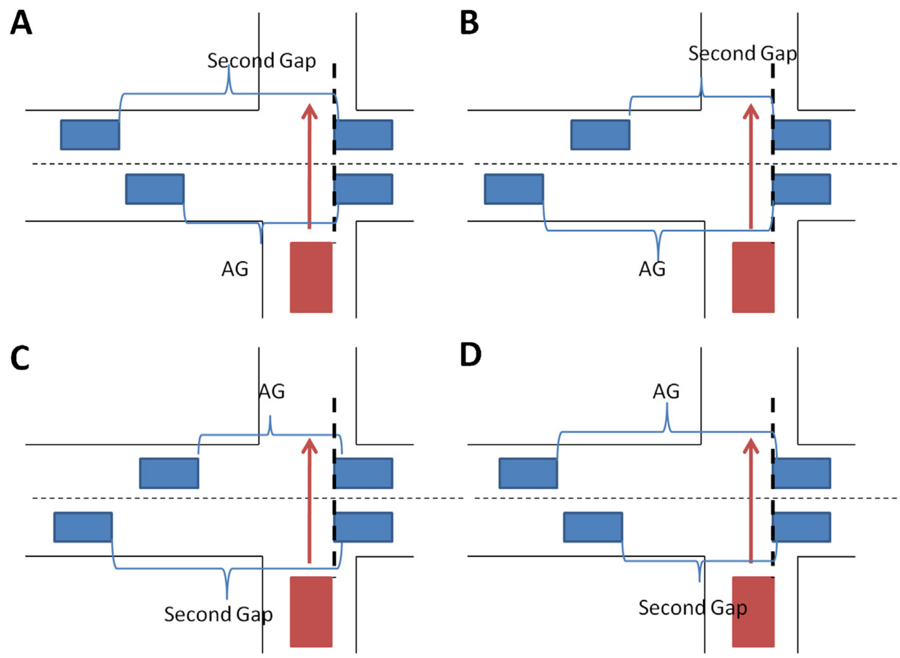

Fig. 2. Potential outcomes of the dual-gap condition for Experiment 1. Panels A and B illustrate the cases where the reference gap is placed in the first lane, and is either shorter (in time) than the second gap (Panel A) or longer (in time) than the second gap (Panel B). Panels C and D represent the cases where the reference gap is placed in the second lane, and is either shorter (in time) than the second gap (Panel C) or longer (in time) than the second gap (Panel D). Both gaps were moving at a velocity of 30 or 60 km/h, independently of the velocity of the other gap.

on the street-crossing decision might have been camouflaged by the participants' control of the action. Secondly, it appeared during the training phase that most of the participants soon suffered from simulator sickness when the observer's car was moving. For this reason, and as participants performed more than 500 trials in the main conditions, we chose to limit the task to the decision phase, rather than covering the complete street-crossing task.

At the end of this first condition, we determined for each participant and in each combination of lane and velocity (2 lanes × 2 velocities) the individual temporal gaps for which the participant decided to cross the street in half of the trials (we call this accepted gap or AG). Each participant thus had after this first condition four AG values. The AG was computed by fitting a cumulative normal function using the pmf.m routine developed in the p-signifit toolbox.

Then, in a second and final condition, from the left side of the road, two pairs of vehicles (dual-gap condition) approached the intersection in the two adjacent lanes (Fig. 1, panels C and D). Most of the parameters were kept constant compared to the first condition: presence of a motorcycle to prevent early crossing decision, velocity of the approaching cars (30 km/h or 60 km/h, independently one of the other), and presentation time before all the vehicles disappeared (3 s). The first cars of each group were placed to reach the intersection at the same time, implying that the two gaps opened in synchrony. One of the pairs was considered as defining the reference gap, and the second group as forming the second gap. The reference gap could be moving either in the first or second lane (while the second gap was moving in the other lane). For each participant, the temporal value of the reference gap was set to the AG of one of the four individual values computed from the single-gap condition, depending on the lane and velocity factors. For example, if the reference gap was moving in the second lane at a velocity of 30 km/h, then its value was the AG computed from the trials moving in the second lane at a velocity of 30 km/h during the single-gap condition. The temporal value of the second gap was a modification of the AG value determined in the single-gap condition for the same lane and velocity. For example, if the second gap was moving in the first lane at a velocity of 60 km/h, then its value was a modification of the AG value computed from the trials moving in the first lane at a velocity of 60 km/h during the single-gap condition. This modification, termed ΔGap, could be −50%, −25%, +25%, or +50%. Hence, in case of negative ΔGap, the second gap was shorter than the reference gap, while in case of positive ΔGap, the second gap was longer than the reference gap (see Fig. 2 for a representation of the different outcomes, and Table 1 for the mean reference gap and second gap values for each lane, velocity and ΔGap conditions). Ten repetitions were made for each single combination of lane position, AG velocity, second gap velocity and ΔGap, leading participants to perform 320 trials (2 lanes × 2 AG velocities × 2 second gap velocities × 4 ΔGap × 10 repetitions) randomly presented in this dual-gap condition.

In order to ensure that the gaps used in the dual-gap condition presented the same crossing possibility for all the participants, we decided to use the AG design rather than presenting fixed gaps for all participants in the dual-gap condition. Indeed, such a design would have led the gap temporal value to interfere with the street crossing decision, and may have masked the influence of the number of gaps. For example, a minimal gap of 5 s may have been considered as large enough for some participants to cross the street, but not for more conservative participants, and therefore the influence of the number of gaps would have been camouflaged by the gap values itself. Ensuring that all participants were presented with gaps that afforded comparable street-crossing actions, allowed us to avoid this confound. However, this design is not consequence-free, as it required all participants to perform the single-gap condition before the dual-gap condition, and therefore participants' performance in the single-gap condition may have influenced the performance in the dual-gap condition. To limit learning form this order, we decided to give no feedback in the two conditions. From our point of view, the advantages of using the AG design (individual gaps representing the same crossing possibility for all participants) far outweighed the disadvantages (single-gap conditions presented before the dual-gap condition).

Table 1
Experiment 1. Mean AG and second gap values used in the dual-gap condition as a function of the lane, velocity and ΔGap conditions.

MAG			Second gap			
Lane	Velocity (km/h)	Value (s)	Lane	Velocity (km/h)	ΔGap (%)	Value (s)
1	30	6.02 (±1.38)	2	30	−50	2.96 (±0.59)
					−25	4.44 (±0.88)
					25	7.40 (±1.47)
					50	8.88 (±1.77)
				60	−50	2.44 (±0.51)
					−25	3.66 (±0.77)
					25	6.10 (±1.28)
					50	7.32 (±1.53)
	60	4.81 (±0.94)		30	−50	2.96 (±0.59)
					−25	4.44 (±0.88)
					25	7.40 (±1.47)
					50	8.88 (±1.77)
				60	−50	2.44 (±0.51)
					−25	3.66 (±0.77)
					25	6.10 (±1.28)
					50	7.32 (±1.53)
2	30	5.92 (±1.18)	1	30	−50	3.01 (±0.69)
					−25	4.51 (±1.04)
					25	7.52 (±1.73)
					50	9.03 (±2.08)
				60	−50	2.41 (±0.47)
					−25	3.61 (±0.70)
					25	6.01 (±1.17)
					50	7.22 (±1.41)
	60	4.88 (±1.02)		30	−50	3.01 (±0.69)
					−25	4.51 (±1.04)
					25	7.52 (±1.73)
					50	9.03 (±2.08)
				60	−50	2.41 (±0.47)
					−25	3.61 (±0.70)
					25	6.01 (±1.17)
					50	7.22 (±1.41)

2.1.3. Data analysis

One of the most important questions addressed in our study was: Does the presence of cars in two lanes systematically influence the decision whether or not to cross the road, compared to a situation with cars in one lane only? More specifically, imagine the situation with only one car approaching the crossroad and a gap duration where the participant is indifferent whether or not to cross the street, that is, $p_{cross} = .5$. Now, if an additional car is presented in the other lane with a longer gap duration (objectively irrelevant for the decision), will this second car nevertheless influence the proportion of trials in which the participant decides to cross the road, or will the subjects only base their decision on the value of the shorter gap (gap_{min}), which would be the optimal strategy?

To analyze the effect of the second car on p_{cross}, it is necessary to select an analysis procedure capable of handling binary data, and of taking into account the within-subjects (repeated-measures) design of our experiment. A well-established and powerful data analysis approach for such a situation are Generalized Linear Mixed Models (GLMM, cf. McCullagh and Nelder, 1989). These models follow the same rationale as the general linear model for continuous, normally distributed response measures (e.g., ANOVA), but use a logit link function to account for the binary nature of the responses (i.e., “cross” or “no cross”).

Due to the repeated-measures structure of the data, a subject-specific random-effects model approach was used (Hu et al., 1998; Liang and Zeger, 1993; Pendergast et al., 1996). Subject-specific models assume regression parameters (e.g., intercept and slope) to vary from subject to subject. Random-effects models belong to the class of subject-specific models and model the correlation structure by treating the subjects as a random sample from a population of all such subjects. This model can be used to estimate the population parameters describing the relation between (a) the duration of the task-relevant shorter gap (gap_{min}) and the probability of deciding to cross the street (p_{cross}), (b) the effect of number of cars on this probability, and (c) the interaction between the two predictors. Details concerning the data analysis are provided in Appendix A. Parameter estimates, standard errors, and tests of significance are displayed in Table 2.

A similar analysis was conducted to determine if the difference between the two gaps (ΔGap) influences the crossing decision. Only the data from the dual-gap condition entered this analysis. For each participant, the differences between the longer and the shorter gap were classified into three bins (three percentile groups; short, medium and large), and analyzed with the same type of GLMM as above. In the model, p_{cross} was assumed to depend on the shorter gap (gap_{min}) presented on a given trial, and on the

Table 2
Experiment 1. Population parameter estimates, standard errors and Wald p-values for the GLMM analysis of the effect of gap_{min} and number of cars on p_{cross}. *Note*: DF: degrees of freedom computed according to the Kenward and Roger (1997) procedure. The β parameters refer to Eq. (1) in Appendix A.

Effect	Estimate	Standard error	DF	t value	p
Intercept	−9.8641	0.6730	246	−14.66	<.0001
Car number	1.4844	0.3916	246	3.79	.0002
Gap_{min}	1.7059	0.1595	86.09	10.69	<.0001
Car number × Gap_{min}	−0.1032	0.1220	34.79	−0.85	.4032

Table 3
Experiment 1. Population parameter estimates, standard errors and Wald *p*-values for the GLMM analysis of the effect of gap_{min} and ΔGap on p_{cross}. *Note*: As explained in the text, ΔGap was binned for the analysis, and was therefore entered as a dummy coded predictor.

Effect	Estimate	Standard error	DF	*t* value	*p*
Intercept	−6.6658	0.3343	320	−19.94	<.0001
Gap_{min}	1.5316	0.1367	25.82	11.21	<.0001
Short gap_{diff}	−4.3514	0.5825	158.4	−7.47	<.0001
Medium gap_{diff}	0.1073	0.4066	181	0.26	.7922
Large gap_{diff}	0	–	–	–	–
Gap_{min} × short gap_{diff}	0.6537	0.1309	65.76	5.00	<.0001
Gap_{min} × medium gap_{diff}	−0.06667	0.09950	67.01	−0.67	.5051
Gap_{min} × large gap_{diff}	0	–	–	–	–

(binned) difference between the two gaps (ΔGap; with the levels short, medium or large). Parameters estimates, standard errors, and tests of significance are provided in Table 3.

Finally, the individual mean crossing time (CT) was computed for each participant on the basis of their last 10 trials of the training phase. The CT was defined as the time needed by the participant to drive the car from its initial position through the two lanes. Based on this value, in the single-gap condition, gaps were defined as safe if 1.5 times greater than the time the participant would need to cross the street (Schwebel et al., 2009). For the dual-gap condition, a trial was classified as safe only if the two gaps were greater than 1.5 times the individual crossing times for their respective lane. This takes into account the TA estimation and crossing time variability, and the safety margin as the difference between the safe gap threshold and the CT.

2.2. Results

2.2.1. Influence of the second gap

As expected, the GLMM showed that the relevant gap_{min} significantly affected the probability that participants accepted to cross the street, $F(1, 86.09) = 114.37$, $p < .001$, with a higher probability of a accepting the gap as a function of the increase in gap_{min} size (see Fig. 3). The number of gaps also significantly influenced the crossing decision, $F(1, 246) = 14.37$, $p < .001$. As shown in Fig. 3, participants were more often willing to cross the street (for a given gap_{min}) in the dual-gap condition compared to the single-gap condition, which is incompatible with the strict use of a safety margin. For example, for $gap_{min} = 5$ s, participants crossed the street in 40% of the trials in the single-gap condition, but in 65% of the trials in the dual-gap condition. For binary outcomes, the odds ratio (OR) can be used as a measure of effect size. For our case, the OR is the odds of deciding to cross the street, $p_{cross}/(1 - p_{cross})$, when there are two gaps, divided by the odds of crossing the street when there is only one gap. At the mean value of gap_{min}, the OR was 2.77 (95%-CI [1.035, 7.393]), that is, the odds of crossing were 2.77 times higher with two gaps compared to one gap, which represents a rather strong effect.

Finally, gap_{min} and number of cars did not interact, $F(1, 34.79) = 0.72$, $p = .403$. Thus, the slope of the psychometric function relating gap_{min} and p_{cross} did not differ between the single-gap and the dual-gap condition.

2.2.2. Influence of the lane

Did it matter which lane contained the shorter moving gap_{min}? No, it did not influence the street-crossing probability. A GLMM analysis including only the trials from the dual-gap condition, and with the independent variables gap_{min} and lane(gap_{min}), showed no significant effect of lane(gap_{min}) on p_{cross}, $F(1, 154.3) = 2.41$,

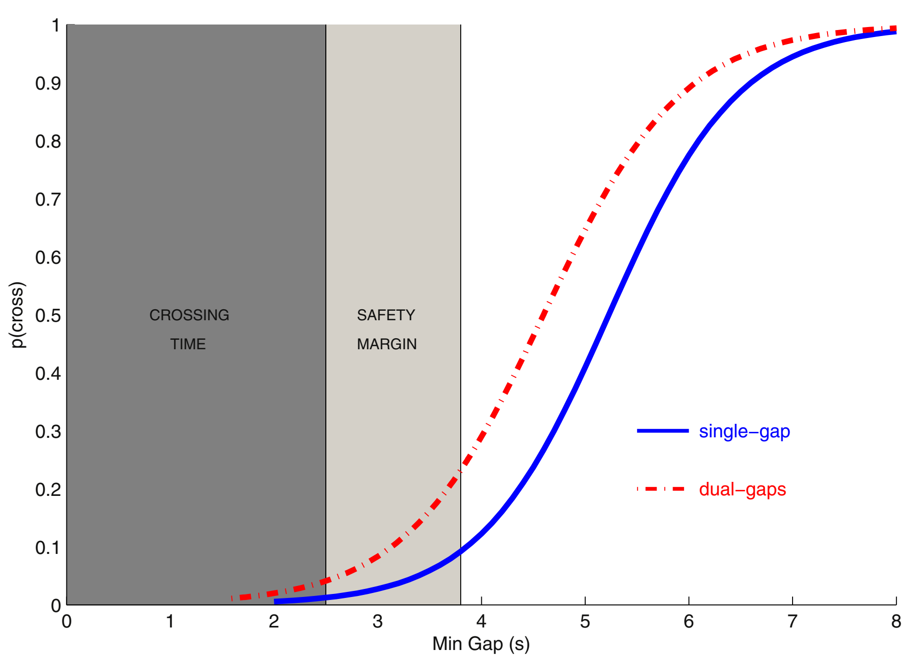

Fig. 3. Observers' probability to cross the street as a function of the minimal gap and number of cars (single-gap condition in blue, and dual-gap condition in red) in Experiment 1. The lines represent the mean crossing probability (aggregated across the different participants) estimated with the GLMM. Dark gray area represents the mean crossing time of the participants, during which a positive street crossing decision would lead to a collision with the oncoming car, and light gray area represents the safety margin of the participants, during which a positive street crossing decision would lead to an incomplete safety margin. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

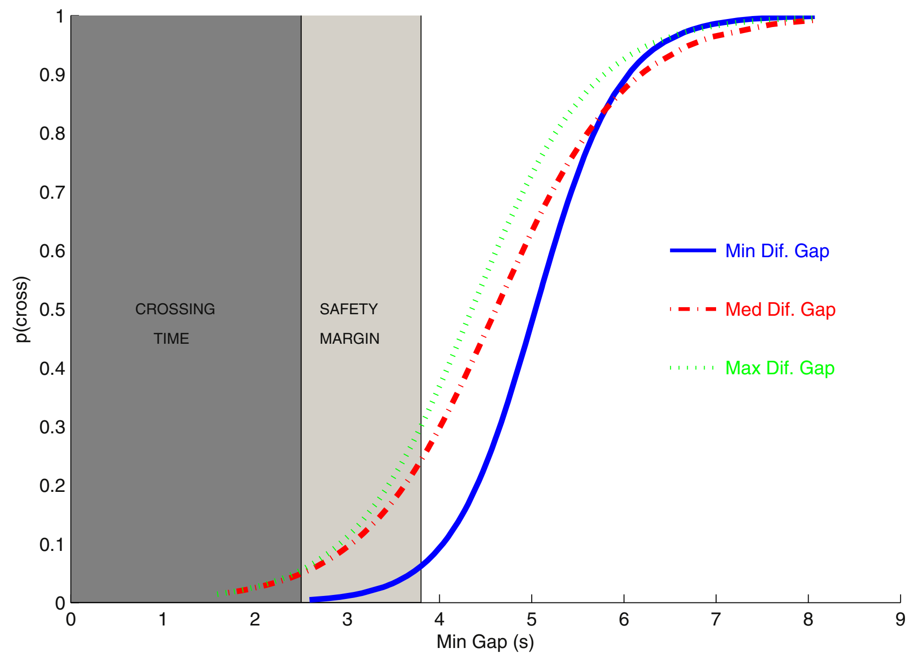

Fig. 4. Dual-gap condition. Observers' probability to cross the street as a function of the minimal gap and tertiles (i.e., 3-quantiles) of the difference between the longer and the shorter gap presented on a given trial (minimal difference in blue, medium difference in red, and maximal difference in green) in Experiment 1. The lines represent the mean crossing probability (aggregated across the different participants) estimated with the GLMM. The dark gray area represents the mean crossing time of the participants, during which a positive street crossing decision would lead to a collision with the oncoming car, and light gray area represents the safety margin of the participants, during which a positive street crossing decision would lead to an incomplete safety margin. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

$p = 0.12$. The $gap_{min} \times lane(gap_{min})$ interaction was not significant, either, $F(1, 26.04) = 0.01$, $p = 0.93$. To examine this lack of $lane(gap_{min})$ effect further, the AG obtained in the single-gap condition was analyzed by a 2×2 (lane × velocity) repeated-measures ANOVA using a univariate approach, which confirmed the absence of lane effect on the AG value. The results showed no influence of the lane, $F(1, 13) = .011$, $p = .919$, but the velocity did influence the AG, $F(1, 13) = 35.68$, $p < .001$, $\eta^2 = .73$, showing a higher AG (5.97 ± 1.26 vs. 4.84 ± 0.96) when the velocity was 30 km/h as compared to 60 km/h. These two factors did not interact, $F(1, 13) = 1.25$, $p = .284$.

This lack of an effect of which lane contained the shorter gap might be related to the large difference between the AG and the second gap, compared to the small difference in crossing time to drive the car through the first lane (CTL1) vs. through the whole intersection (CTL2) in the training phase. Indeed, on the one hand, average CTL1 was of 2.01 s, and average CTL2 of 2.55 s (defining a safety margin of 3.83 s according to Schwebel et al.'s (2009) definition), the mean difference between CTL1 and CTL2 being of 0.54 ± 0.08 s. On the other hand, the mean difference between the AG and the second gap was of 2.03 ± 1.09 s. Hence, the small amount of time required to cross the second lane, the observer's car having already reached a sizable velocity at of the point where the first lane had been crossed, is likely to explain the lack of an effect: because the difference in the crossing times of lane 1 and lane 2 is much smaller than the difference between the gaps, drivers may not have taken the lane factor into account. The case should be different for pedestrians carrying out the same task. Their slower crossing speed is likely to make the lane factor relevant for their street-crossing decision.

In sum, the presence of a second approaching vehicle influences street-crossing decisions. This happens although the objectively available time to cross the street remains exactly the same. Thus, the data are in agreement with the third of our initial hypotheses (averaging). The presence of the second-arriving vehicle, which would be discarded by an ideal observer, interferes with TA estimation. The longer and irrelevant TA is in some sense averaged in with the relevant shorter TA. This averaging produces a systematic and potentially unsafe tendency toward crossing the street when in fact one should step on the brakes.

2.2.3. How the second gap influences the decision

Does the mere presence of a second gap lead to such an increase in the rate of street-crossing decisions, or do specific features of the longer gap modulate the effect? For example, the TA estimation of the shortest gap may be biased by a constant offset due to the mere presence of the second gap, or alternatively the bias in the TA estimation may be a function of specific characteristics of the longest gap. To answer this question, we conducted a third GLMM analysis, again including only the trials from the dual-gap condition, to assess the influence of the time difference between the longer and the shorter gap, termed ΔGap. As Fig. 4 shows, gap_{min} again significantly influenced the probability that participants decided to cross the street, $F(1, 19.55) = 181.96$, $p < .001$, with the probability of crossing increasing as a function of the size of gap_{min}. In addition, the analysis also showed that ΔGap had a significant effect on the street-crossing probability, $F(2, 148.1) = 35.32$, $p < .001$. As visible in Fig. 4, for a given value of the shorter gap, participants decided to cross the street more often for *longer* TAs of the second-arriving car. For example, for $gap_{min} = 5$ s, participants crossed the street on 50% of the trials when the TA of the second-arriving car was only slightly higher than gap_{min} (small ΔGap), but in 63% of the trials when ΔGap was medium, and finally in 75% of the trials when ΔGap was large. This is a substantial interference of the irrelevant information. Again, the main influence of the larger gap seems to be upon the number of unsafe decisions (when gap_{min} is shorter than CT + safety margin) rather than on the truly hazardous decisions (when gap_{min} is shorter than CT, causing the participant to be hit by a car). Moreover, gap_{min} and ΔGap interacted, $F(2, 64.53) = 19.29$, $p < .001$, showing a higher slope for small values of ΔGap than for the medium and large values of ΔGap.

The above analyses showed an increase in the probability of decisions to cross the street in the dual-gap compared to the single-gap condition.

2.2.4. Consequences of the second gap on the number of unsafe decisions

Did the presence of the second car result in a higher proportion of unsafe decisions? To answer this question, based on the individual crossing times for lane 1 and lane 2, we classified each trial as safe or unsafe.

We compared the proportions of unsafe decisions (i.e., number of positive decisions to cross on unsafe trials divided by the number of these trials) between the single-gap and the dual-gap conditions by means of a Wilcoxon test for paired samples. The proportion of unsafe decisions was significantly higher in the dual-gap (M = .082, SD = 0.081) than in the single-gap condition (M = .025, SD = 0.033), z = 2.62, p = .009. Participants seem to encroach upon the safety margin in the dual-gap situation, therefore increasing the risk of collision.

2.3. Discussion of Experiment 1

Taken together, these results indicate that participants are generally more willing to cross the street in the dual-gap condition compared to the single-gap condition. Superficially, this finding seems to be in agreement with previous findings showing that drivers accept riskier gaps when under greater cognitive demands (Horswill and McKenna, 1999; Cooper and Zheng, 2002), if judging multiple gaps can be taken to increase cognitive demand. However, we suggest that our results cannot be interpreted along these lines because the value of the longer gap also plays a role in the decision. The hypothesis of greater cognitive demand and processing bottlenecks leading to riskier gap acceptances does not predict such an effect. In this case, the street crossing decisions based upon the shortest TA should be independent of the value of the longest TA, as traditionally shown in dual-task literature (see e.g. Pashler, 1994; Lien et al., 2006). Our results show this is not the case, with an influence in the crossing decisions due to the value of the longest TA.

This indicates that the two TA estimations are not merely competing about processing resources. Instead, they are dependent upon one another, observers seem to base their decision to cross the street on some type of a weighted average between the two TAs (Rushton and Wann, 1999; Oberfeld and Hecht, 2008). As evidenced, street-crossing decisions, which for an ideal observer should be based only on the TA estimate for the shorter gap, are modulated by the size of the longer gap. Specifically, the influence of the second-arriving car increases as a function of the difference between the two gaps. Hence, for a given value of the decision-relevant shorter gap, the decision-irrelevant longer gap will increase the probability that the participant decides to cross the street, and this effect is stronger if the second-arriving car will arrive late.

3. Experiment 2: approaching gaps from opposite directions

As evidenced in Experiment 1, having two gaps within the visual field affects the perception of the relevant time-to-arrival (TA) as basis for the crossing decision. Would this effect also hold if the two gaps would approach the observer from opposite directions, so that the observer could only see one at a time? In other words, does the influence of the longer TA upon the perception of the shorter one reflect a limitation of basic visual processing to acquire two independent TA estimates at the same time, or is the averaging process made at a later stage when the gaps are not visible anymore? This would represent a limitation in storing and combining two independent TA estimates. To answer this question, we carried out a second gap-acceptance experiment in which participants faced one (single-gap condition) or two (dual-gap condition) cars that were approaching in adjacent lanes but from opposite directions toward the observer. At different TAs, the car(s) disappeared from view, and participants were asked to judge whether or not they would have had enough time to safely drive their car through the intersection.

3.1. Materials and methods

3.1.1. Subjects

Twelve observers (4 women, 8 men, age 28.92 years ± 3.82 (mean ± SD), min. age 23, max. age 34) who were not involved in Experiment 1 participated voluntarily after giving informed consent. All participants had normal or corrected-to-normal vision, were healthy and without any known oculomotor abnormalities. Participants were naïve with respect to the purpose of the experiment. All the participants held their driving license for more than 2 years, drove a car on a daily basis, for a declared total of minimum 50 km each week.

3.1.2. Apparatus and experimental procedure

This second experiment used the same apparatus as Experiment 1, and the same virtual environment.

In an initial training condition, participants drove the car through the intersection while no car was approaching. Twenty trials were repeated to ensure the participants established an accurate representation of the intersection's width (2 lanes of 3 m width each), the car dynamics, and the consequent crossing time.

Then, in the main condition, one pair of vehicles (single-gap condition) or two pairs of vehicles (dual-gap condition) approached toward the intersection. The single-gap condition was strictly identical to the one used in the Experiment 1, except for the number of trial repetitions. Eight trials were presented for each combination of the independent variables (2 lanes × 2 velocities × 5 temporal gap values), corresponding to a total of 160 trials.

The dual-gap condition replicated strictly the dual-gap condition of the Experiment 1, with the exception of two features: the direction of movement and the TA. Firstly, the two pairs of gap were now approaching from opposite directions: left to right for the cars placed in the first lane, and right to left for the cars placed in the second lane, conforming to the driving code in France (Fig. 5). Secondly for the TA, one of the pairs was considered as defining the shorter gap, and the second group as forming the longer gap. For each participant, the temporal value of the shorter gap could be 2, 3.5, 5, 6.5 and 8 s. The temporal value of the longer gap was a modification of the value of the shorter gap, called ΔGap, which could be +0, 1, 2, and 3 s (note that if ΔGap = +0 s then the two gaps had the same temporal value). Four trials were presented for each combination of the independent variables (2 lanes × 2 shorter gap velocities × 2 longer gap velocities × 5 gap value × 4 ΔGap), resulting in a total of 640 trials in this dual-gap condition.

Trials from the single-gap and dual-gap conditions were randomly interleaved and presented in random order in a single session, for a total number of 800 trials performed for each participant. We chose to modify the experimental design used in Experiment 1 to reduce its complexity. To avoid the concern of fixed-gap values (see Experiment 1, Section 2.1) we carefully examined the gap values used in Experiment 1 to define the values of the gaps in Experiment 2. First of all, it appeared that in the dual-gap condition of Experiment 1, 96% of the trials had a shorter gap included in a range of 2–8 s. Moreover, the 95% confidence intervals (depending on lane and velocity conditions) for the AGs used in Experiment 1 were all included between 4.3 and 6.8 s. We therefore decided to use a 2–8 s range to define our gap values in the Experiment 2, as it appeared to be large enough to contain the

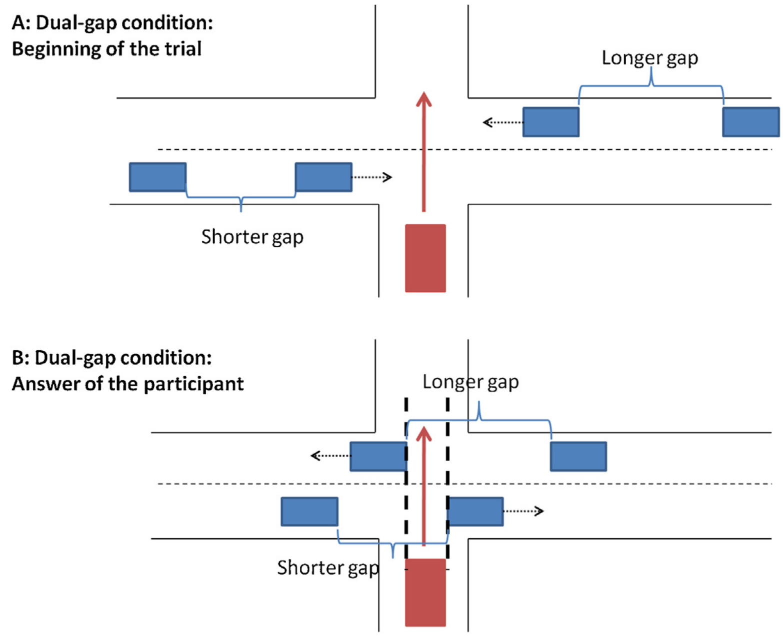

Fig. 5. Schematic representation of the task, from a bird's eye point of view for Experiment 2. Blue rectangles represent the approaching cars, and red rectangles the position of the observer. The red arrows represent the desired movement of the observer to cross the street, and the dashed black line indicates the moment of the disappearance of the vehicles from the screen, when the rear of the opening-gap vehicle reached the dashed line. Panels A and B illustrate the dual-gap condition at the beginning of the trial (Panel A), or at the instant when the cars disappeared from the screen and the observers had to give their answer (Panel B). Both gaps were moving at a velocity of 30 or 60 km/h, independently of the velocity of the other gap. For the purpose of illustration, the motorcycle is not displayed on the graph, and the shorter gap is here placed in the first lane, but note that it was the case in 50% of the trials only. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

crucial transition point from which the participants switch from a gap refusal to gap acceptance. In addition, to define the ΔGap values, we looked at the range of gap difference in Experiment 1. It turned out that the 95% confidence interval of gap difference in Experiment 1 was [1.64: 2.42] s, justifying our choice for a ΔGap in the [0: 3] s range. Therefore, the gaps the participants encountered in Experiments 1 and 2 had the exact same velocity and lane parameters and were in the same range of gap value in a large proportion of the trials. The only major – and intended – difference was that in Experiment 1 the vehicles always came from the same side, whereas in Experiment 2 the gaps came from the opposite sides.

Participants' instructions were to indicate whether or not they would cross the street through the gap. They were asked to only do so if they felt they could achieve this maneuver as safely as in their normal life. The participants had to press a keyboard key to indicate their decision as fast as possible after the cars' disappearance. After the answer, the next trial began after a randomly selected pause between 1.5 and 3 s.

3.1.3. Data analysis

The data were analyzed with the same method as in Experiment 1 (see Appendix A), using a Generalized Linear Mixed Model (GLMM) to analyze the effect of $\mathrm{gap_{min}}$ and the number of gaps on p_{cross}. The population parameter estimates are displayed in Table 4.

As in Experiment 1, the individual mean crossing time (CT) and safety margin were computed for all participants on the basis of their last 10 trials of the training phase.

3.2. Results

3.2.1. Influence of the longer gap

As expected, the GLMM showed that $\mathrm{gap_{min}}$ significantly affected the probability that participants accepted to cross the street, with a higher probability of a accepting the gap at larger values of $\mathrm{gap_{min}}$ (Fig. 6). The number of cars had no significant effect on the crossing decision. Thus, the results of Experiment 2 differed from the pattern observed in Experiment 1 where the participants were more often willing to cross the street in the dual-gap condition compared to the single-gap condition.

As in Experiment 1, $\mathrm{gap_{min}}$ and the number of cars did not interact. Thus, the slope of the psychometric function relating $\mathrm{gap_{min}}$ and p_{cross} did not differ between the single-gap condition and the dual-gap condition.

3.2.2. Effect of ΔGap

In a second GLMM analysis conducted on only the trials from the dual-gap condition, we examined the effects of the shorter gap ($\mathrm{gap_{min}}$) and of the time difference between the longer and the shorter gap, ΔGap. The population parameter estimates are displayed in Table 5. The value of the shorter gap ($\mathrm{gap_{min}}$) again significantly influenced the probability that participants decided to cross the street. The difference between the longer and shorter gap, ΔGap, however, had no significant effect on the street-crossing probability (Fig. 7), confirming the difference between the results

Table 4
Experiment 2. Population parameter estimates, standard errors and Wald p-values for the GLMM analysis of the effect of $\mathrm{gap_{min}}$ and number of cars on p_{cross}.

Effect	Estimate	Standard error	DF	t value	p
Intercept (β_0)	−7.3305	0.6996	476	−10.48	<.0001
$\mathrm{Gap_{min}}$ (β_1)	1.6170	0.2146	63.16	7.53	<.0001
Number of cars (β_2)	−0.02996	0.4108	476	−0.07	.9419
Number of cars × $\mathrm{gap_{min}}$ (β_3)	−0.00898	0.1738	29.97	−0.05	.9591

Table 5
Experiment 2. Population parameter estimates, standard errors and Wald *p*-values for the GLMM analysis of the effect of gap_{min} and ΔGap on p_{cross} (dual-gap trials only).

Effect	Estimate	Standard error	DF	*t* value	*p*
Intercept	−7.7350	0.3046	236	−25.39	<.0001
Gap_{min}	1.6351	0.1373	28.46	11.91	<.0001
ΔGap	0.2694	0.1988	114.4	1.36	.1780
$Gap_{min} \times \Delta Gap$	−0.01879	0.1262	20.41	−0.15	.8830

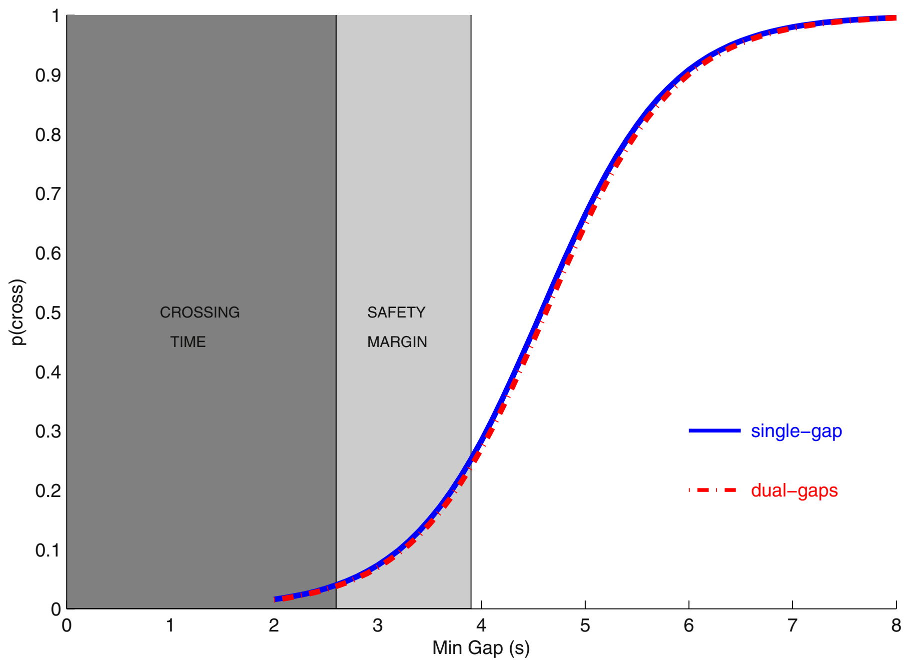

Fig. 6. Observers' probability to cross the street as a function of the minimal gap and number of cars (single-gap condition in blue, and dual-gap condition in red) in Experiment 2. The lines represent the mean crossing probability (aggregated across the different participants) estimated with the GLMM. Dark gray area represents the mean crossing time of the participants, during which a positive street crossing decision would lead to a collision with the oncoming car, and light gray area represents the safety margin of the participants, during which a positive street crossing decision would lead to an incomplete safety margin. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

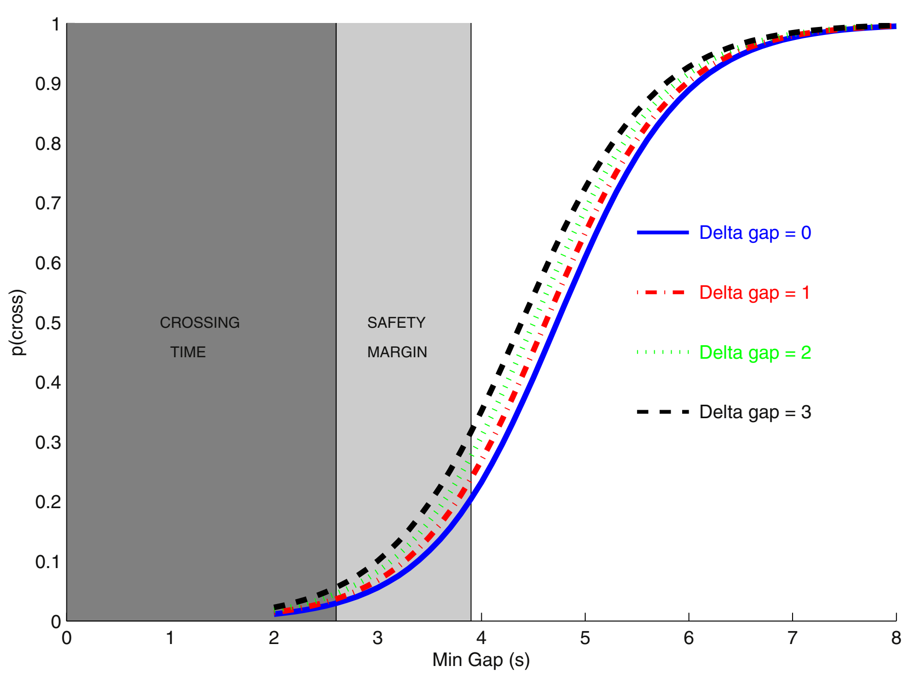

Fig. 7. Dual-gap condition. Observers' probability to cross the street as a function of the delta gap value in Experiment 2. The lines represent the mean crossing probability (aggregated across the different participants) estimated with the GLMM. The dark gray area represents the mean crossing time of the participants, during which a positive street crossing decision would lead to a collision with the oncoming car, and light gray area represents the safety margin of the participants, during which a positive street crossing decision would lead to an incomplete safety margin.

from Experiment 1 and Experiment 2. The $gap_{min} \times \Delta Gap$ interaction was also not significant.

3.3. Discussion of Experiment 2

This second experiment failed to show an influence of a second – and larger – gap on observers' decision to cross or not the street. As in Experiment 1, participants increased their willingness to cross the street as the smaller gap increased, which is of course the expected pattern. However, and in contrast to Experiment 1, no influence was found of the larger gap on this decision. It therefore appears that when the two gaps are not in sight at the same time, no interference occurs between the two TA estimations. The crossing decision is thus made on the basis of the only relevant information, the shortest TA. In this respect, the participants behaved like an ideal observer, as defined earlier: street-crossing decisions depended only on the value of the shortest TA, and accordingly, for a given shortest TA, street-crossing decisions did not differ between the single-gap and the dual-gap conditions.

4. General discussion

The goal of this study was to determine how observers decide when to drive through a single-gap or multiple-gaps to cross a street. The single-gap case is now well studied and well documented, showing that factors like vehicle's time-to arrival (TA), distance and speed, influence the decision. However, to our knowledge no previous study investigated a dual-gap condition where two gaps placed on two adjacent lanes had to be assessed in the street crossing decision. We did so and found an alarming impact of the irrelevant gap on decision making.

From laboratory-based experiments, which showed that multiple TA estimations are severely impaired in comparison to a single TA estimation, we had entertained three potential outcomes. These predicted either (1) no influence of the second TA estimation on the street-crossing decision (ideal observer case), (2) an increase in the safety margin leading to more gap refusal, and finally (3) an averaging process leading the observers to base their answer on the average of the shorter and longer TA. The latter strategy would have potentially dangerous consequences as observers would have less time before the closing of the shorter gap than they think.

The two experiments of the present study showed that the outcome depends on whether the two gaps are simultaneously visible or whether they can be viewed only sequentially. When the two gaps approached from the same direction (Experiment 1), and were therefore visible simultaneously, the presence of a second, longer, and therefore theoretically irrelevant TA had an effect on the street crossing decision. When a second, longer gap was present, participants were more often willing to cross the street, compatible with the idea that observers might base their decision on an average of the two estimated TAs. In contrast, when the two gaps approached from opposite directions (Experiment 2), none of these effects appeared, and participants appeared to behave on the sole basis of the shortest TA, as an ideal observer would do.

Surprisingly, these results are not directly compatible with previous studies, which showed a unilateral influence of the first-arriving object on the TA estimate of the later-arriving object (Baurès et al., 2010, 2011). The straight-forward way to reconcile the difference would suggest that the dissimilarity between the gap crossing task and the direct TA task is decisive, Baurès et al. required participants to perform two absolute TA estimates, that is, to indicate the arrival time of each of the two objects. In this case, it was found that the visual system does not have enough resources to conduct these two estimations in parallel, and consequently the TA estimates of the second-arriving object is overestimated. The current task presented here is more complex. It asked the participants to make a relative estimation, that is to determine which TA is the shortest, then make an absolute estimate of the shortest TA, and finally to put it in relation with their own crossing time. In this case, our results demonstrate that estimating the TA of a second approaching object (presented along with the decision-relevant object) alters the TA perception. Such averaging has already been reported for task-irrelevant distractor objects (Oberfeld and Hecht, 2008; Novak, 1998).

Outside the domain of time-to-contact estimation, our present findings are consistent with other examples of perceptual averaging. When observers are confronted with a set of objects, the visual system rather represents the overall statistical properties of the set rather than individual properties (Ariely, 2001), a phenomenon called statistical summary representations (SSRs). As pointed out by Albrecht and Scholl (2010), such a process has been shown to occur over many different dimensions of visual scenes, including size (e.g., Ariely, 2001), length (e.g., Weiss and Anderson, 1969), inclination (e.g., Miller and Sheldon, 1969), motion direction (e.g., Dakin and Watt, 1997), speed (e.g., Watamaniuk and Duchon, 1992), orientation (e.g., Parkes et al., 2001), spatial position (e.g., Alvarez and Oliva, 2008), and even higher-level information such as emotion or gender (e.g., Haberman and Whitney, 2007, 2009). Similar phenomena have been reported for other sensory modalities (e.g., Oberfeld, 2007). Note, however, that averaging typically improves performance (Ariely, 2001) and can be considered a useful feature of information integration. In the case of our street-crossing paradigm, averaging has an opposite detrimental effect.

In addition, the discrepancy in the outcomes of the Experiment 1 and Experiment 2 informs us about both the visual perception of multiple TAs, and more generally about the properties of the perceptual averaging process. The first implication of our results is that the visual system is limited in its ability to simultaneously pick up two TA estimates from two information sources (i.e., moving objects), or to optimally combine the two TA estimations. However, if the two approaching objects are not in sight simultaneously, and for this reason if the visual processing of the two information sources is not concomitant but rather consecutive, then each TA estimation appears to be accurate and unaffected by the second TA. Thus, these results indicate that the visual perception of one TA interferes with the visual perception of a second TA, while the storage in memory of one TA does not affect the visual perception of a second TA for its part.

One might wonder if this finding is an instance of the more general level of perceptual averaging process described by Ariely (2001). In an usual task, participants are presented a set of *N* objects all at the same time, and then a single object. Participants have to report either if the individual object is or is not a member of the set of objects, or if its size is larger or smaller than the average size of the set. Whereas participants produce very poor results in the first task, indicating that they do not perceive the individual sizes of the objects, they perform much better when having to compare the secondly presented object to the mean size of the set of objects, indicating a pretty good perception of the average set-size. Our results suggest that if the N objects presented in the set had not been presented all in the same time but in a row, then the perceptual averaging process would not have occurred and participants' answer would not strive toward the average set-size. Further experiments are required to confirm this assumption.

Alternately, the visual system may have reached an attentional limit, such that it is not able to ignore irrelevant information that is in plain view, whereas it is able to suppress information that is spatially or temporally removed.

4.1. Implication for road safety when gaps are approaching from the same direction

Our intuitive notion that the visual system should represent the window for safe road crossing is challenged by our results when the two gaps are approaching toward the observer from the same direction. All participants were asked to cross only when they thought this could be done safely. One would expect them to reduce – or at least keep unchanged – their willingness to cross a street when traffic becomes more complex. In complex busy situations the odds are much higher that we overlook something. It turns out, however, that we do just the opposite. When the two gaps were in sight in the same time, observers decided to cross the street more often when two cars were approaching as opposed to just one. Specifically, the simultaneous availability of a longer gap led drivers to accept the shorter gap more often. This appears to be a quite counterintuitive and unsafe behavior. Moreover, the more distant in time from the observer the second-arriving – and thus decision-irrelevant – car is arriving, the more likely will the observer decide to move across the intersection. This could indicate that the relevant TA is overestimated when two cars are approaching the observer due to the SSR process used by the visual system. An overestimation of TA has important practical consequences for road safety, as road users have less time than they think to carry out the crossing action. At the limiting case, such misestimate would cause them to initiate maneuvers at unsafe TAs.

The results could also indicate that we switch into a different mode when encountering a complex situation. After all, the more traffic there is, the more likely it is that we are in for a long wait. So if we want to arrive at our destination, we may willingly accept a higher risk. When crossing a lonely country road, we can afford to let the occasional car pass even if TA is sufficiently large. If, on the other hand, we forego the opportunity to exploit a small but sufficient gap on a busy street, we may have for a long time until the next opportunity arises. Note, however, that it is not easy to explain why such a strategy would occur only when the two gaps are in sight in the same time, and not when the two gaps are coming from different directions.

Although we used a driving simulator setup with rather realistic viewing conditions, it should be noted that the task studied in our experiments differed from real street-crossing actions in a number of respects. While we limited our experiments to the decision phase ("cross" or "no cross"), real street-crossing situations allow the observers to modify the trajectory and kinematics to compensate for potential TA misperception. In other words, the misperception of the approaching TA does not automatically lead to a crash with the car, as the pedestrian or driver may accelerate for example. Second, the gaps in our scene all moved at a constant velocity, and opened simultaneously. This may have made the task easier compared to a real traffic situation where approaching vehicles might accelerate or decelerate. Third, no feedback was given to our participants. Studying the influence of these choices would allow stronger conclusions concerning the applicability of our findings to real street-crossing actions.

In summary, our perceptual ability to estimate several TAs in the context of crossing a multiple-lane street is influenced by the visual availability of the irrelevant (as well as the relevant) gap. When both gaps cannot be seen in the same time, the decision is properly made upon the shortest gap, as one would expect in such a situation. However, if the two gaps are in sight at the same time, then the irrelevant longer gap interferes with the perception of the relevant shorter gap, enhancing the probability for the observer to cross the street while the available time remains constant. Street-crossing decisions appear to be based on a perceptual averaging of the two gaps. As a consequence, driver and pedestrian safety education should point out the hazard of multiple vehicles approaching from the same side. In line with the current development of Intelligent Transport Systems (ITS), our results also argue for the integration of our findings into future collision warning and avoidance systems (e.g., Jurgen, 2007; Mundewadikar et al., 2008). They should be able to detect among several approaching vehicles which has the shortest TA, and if its value affords a safe gap crossing. The capacity of these systems to ignore other irrelevant TAs would make them superior to a human observer provided the relevant TA can be clearly determined. Finally, at the infrastructure management level, road designers may limit the number of lanes with vehicles moving in the same direction to be crossed in the same time. For example, the implementation of traffic islands on multiple-lane streets would promote making two separate TA estimates one after the other, rather than two concurrent ones, and thus allow safer street-crossing decisions.

Acknowledgements

We would like to thank Fabrice Vienne (IFSTTAR-LEPSIS) for his great help with stimulus generation. The work was funded by an IFSTTAR post-doctoral grant to the first author and a grant to the third author (Deutsche Forschungsgemeinschaft Sachbeihilfe HE 2122/6-1: Kontaktzeitschätzung im Kontext). The authors declare that they had no conflicts of interest with respect to their authorship or the publication of this article.

Appendix A.

The effects of the independent variables on the probability to cross the street (p_{cross}) were analyzed with generalized linear mixed models (GLMMs) using a logit link function (McCullagh and Nelder, 1989; Littell et al., 2006). As an example, in the model analyzing the effects of the shorter gap ($\mathrm{gap}_{\min}$) and the number of cars (n_{cars} = 1 or 2) on p_{cross}, the log odds for crossing were assumed to depend on $\mathrm{gap}_{\min}$ and on n_{cars} as

$$\ln\left(\frac{p_{\mathrm{cross}}(i, \mathrm{gap}_{\min}, n_{\mathrm{cars}})}{1-p_{\mathrm{cross}}(i, \mathrm{gap}_{\min}, n_{\mathrm{cars}})}\right) = (\beta_0 + b_{0,i}) + (\beta_1 + b_{1,i}) \cdot \mathrm{gap}_{\min} + (\beta_2 + b_{2,i}) \cdot n_{\mathrm{cars}} + (\beta_3 + b_{3,i}) \cdot \mathrm{gap}_{\min} \cdot n_{\mathrm{cars}} \quad (1)$$

The index i represents the different subjects, $\mathrm{gap}_{\min}$ is the duration of the shorter gap, and n_{cars} is the number of cars (1 or 2). The regression parameters β_0 through β_3 are the population parameters (i.e., fixed effects) for the intercept, the slope of the (logistic) psychometric function relating $\mathrm{gap}_{\min}$ and p_{cross}, the effect of the second car, and the interaction between $\mathrm{gap}_{\min}$ and the number of cars, respectively. Of primary interest for the current analysis are the parameter β_2, which represents a systematic shift in p_{cross} toward higher or lower values induced by the second car, and the interaction (β_3) representing a change in the slope of the psychometric function relating $\mathrm{gap}_{\min}$ and p_{cross} induced by the second car. The parameters $b_{i,0}$ to $b_{i,3}$ represent the inter-individual differences between the regression coefficients. The model assumes that the subjects are randomly sample from the population, and that the parameter values for the subjects follow a multivariate normal distribution. Thus, the $b_{i,j}$ are random effects, with $b_{i,0}$ representing for example the deviation of the intercept for subject i from the population intercept β_0. The $b_{i,j}$ are assumed to be normally distributed with mean 0 and covariance matrix $\boldsymbol{C}$, $b_{i,j} \sim N(0, \boldsymbol{C})$. The model was fitted using SAS 9.2 PROC GLIMMIX (Littell et al., 2006) with a residual (restricted) pseudo-likelihood method (Wolfinger and O'Connell, 1993). The covariance matrix $\boldsymbol{C}$ was assumed to be of type "first-order autoregressive" (AR(1), Wolfinger, 1993). We used this type of covariance matrix because the models did not converge with more complex covariance matrices. For significance tests of the regression parameters and Type-3 tests of the fixed effects, the

Kenward and Roger (1997) method for computing the degrees of freedom was used.

The SAS syntax used for fitting the model specified in Eq. (1) was

```
proc glimmix method=rspl;
      class subject;
      model nCross/N = gapMin numCars gapMin*numCars /dist=binomial
LINK=LOGIT ddfm=KR s;
      random gapMin numCars gapMin*numCars /subject=subject type=ar(1) s;
run;
```

The dependent variable is the number of trials on which a subject decided to cross the street (*nCross*), divided by the number of trials presented in a given condition (*N*).

For the other analyses, the same model structure but different predictor variables were used (e.g., $\text{gap}_{\min}$ and ΔGap). One analysis used a dummy-coded predictor.

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