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Display of required crossing speed improves pedestrian judgment of crossing possibility at clearance phase

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A R T I C L E I N F O

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A B S T R A C T

At crosswalks with countdown timers, pedestrians arriving at the clearance phase tend to start crossing when the remaining time is too short. It is unclear whether this phenomenon is due to errors in judging the possibility to finish crossing before signal lights turning red. This study evaluated and compared pedestrians' accuracy in judgment of crossing possibility based on two cues: the amount of remaining time, and the minimum required speed to finish crossing within clearance phase (*road width / remaining time*). The results showed that pedestrians overestimated crossing possibility when they made judgments based on remaining time, especially when the road was narrow. By contrast, the display of required speed resulted in higher overall accuracy and lower false alarm rate, due to higher sensitivity to different crossing possibilities and more conservative set of response criterion. This advantage is consistent across different road widths. These findings suggest that pedestrians' risky decisions based on the countdown timers are partly induced by overestimation of crossing possibilities. The advantages of required-speed display over traditional countdown timers indicate a strong possibility to improve pedestrian judgments by information design.

1. Introduction

1.1. Pedestrian choices at various remaining times

Pedestrian lights usually operate in the sequence of green phase, clearance phase, and red phase. During the clearance phase, a green man or "Don't Walk" message flashes, and a countdown timer displays the remaining time before the red-light onset. In clearance phase, pedestrians that are already on the crosswalk need to hurry up, and those haven't started should not enter the crosswalk. However, pedestrians who arrived in the clearance phase have been observed to make cross-or-wait decisions based on the remaining time, rather than wait at the roadside as required. Lee and Lam (2008) found that most pedestrians would cross the street immediately if they arrived within the first seven seconds of the flashing green phase. If pedestrians arrived within the final six seconds of the flashing green phase, less than 50% made the decision to cross (Lee and Lam, 2008). Similarly, in an observation in Singapore, Koh et al. (2014) found that if the remaining time before the red phase was longer than five seconds, all of the road users (pedestrians and cyclists) crossed. Within the last five seconds of the flashing green phase, 66% of them still chose to cross. More direct evidence shows that when the road width is constant, pedestrians are less likely to cross at shorter remaining time (Zhuang et al., 2018).

Crossing based on remaining time is relatively safe so long as pedestrians can finish crossing within the remaining duration. However, researchers have found that pedestrians tended to cross when the remaining time was too short, indicated by incomplete crossings after the clearance phase ended. Koh et al., (2014) found that all of the road users (including pedestrians and cyclists) failed to finish crossing before red-light onset if they began crossing in the last five seconds of flashing green phase. Even if they started crossing earlier at flashing green phase, 45% of them had incomplete crossings. Since pedestrians have lower speeds than cyclists, in a recent observation of pedestrians who started crossing on flashing green phase, the percentage of incomplete crossings increased to 79% (Zhuang et al., 2018). As a result, although more than half of the pedestrians ran to cross at the clearance phase, they still crossed 41% of the road width during red phase. A direct consequence of crossing the road during red phase is higher probability to encounter intersecting vehicles, thus increases risks to both pedestrians and drivers.

Why do pedestrians decide to cross when the remaining time is too short? While explaining the increased number of "late starters" after installation of countdown timers, Paschalidis et al. (2016) proposed a possible reason: countdown timers led to pedestrians' overestimation of

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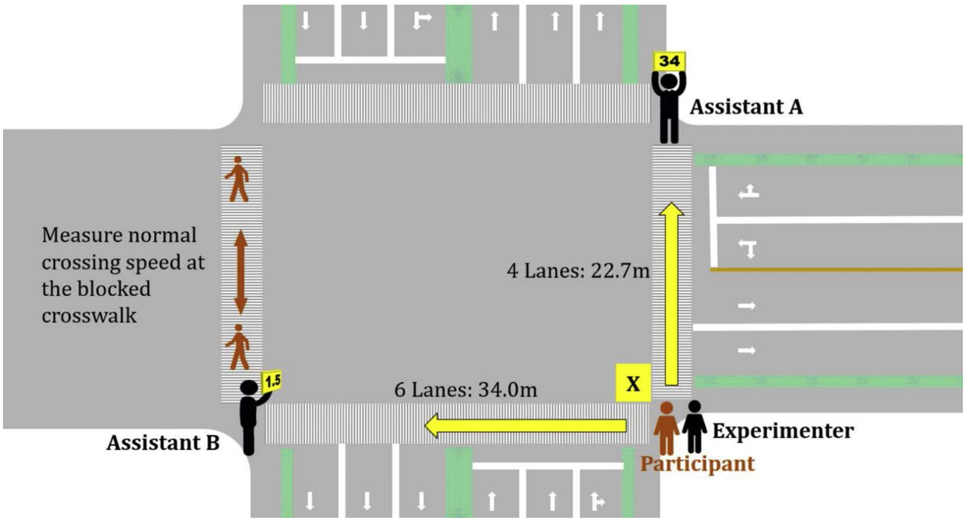

Fig. 1. Illustration of the intersection and experimental setting.

their ability to cross the road in time. That is, the remaining time may lead pedestrians to overestimate the crossing possibility. Yet, this assumption was not, and has not been tested. Thus, one aim of the study is to evaluate the pedestrians' accuracy in judging crossing possibility.

1.2. Information processing in judging crossing possibility

When pedestrians judge crossing possibility based on remaining time, they need to estimate their crossing time and compare it with the remaining time. However, estimating crossing time is itself a challenging task. In an interview (Wanty and Wilkie, 2010), pedestrian verbally reported the time needed to cross an intersection diagonally, and 80% of them underestimated the required time, despite having just crossed the intersection before the interviews were conducted. In another approach, pedestrians estimated crossing time by mentally simulating the process of crossing a road. While researchers reported inconsistent findings on how the accuracy changed with pedestrian age and mobility, they all reported inaccurate (mostly underestimate) estimations in some groups (Dommes et al., 2013; Holland and Hill, 2010; Naveteur et al., 2013; Zivotofsky et al., 2012, Zito et al., 2015). Theoretically, pedestrians can also calculate crossing time from the road width and their own speed. Yet, estimation of road width is not necessarily accurate (Gilinsky, 1951), and calculation is also not a strength of human beings. Therefore, the difficulty in estimating crossing time seem to forecast inaccurate judgments of crossing possibility.

Is it possible to judge crossing possibility without the estimation of crossing time? Yes, if we do not rely on the remaining time to make judgments. Basically, the remaining time is a cue of crossing difficulty indicating how hard it is to cross the street at the moment. Crossing difficulty can be framed as remaining time, or the required speed to cross (Road width/ remaining time). Although the two cues represent the same level of crossing difficulty, the mental processes in judging crossing possibility is different. For example, judgments based on required speed only require a simple comparison between the required speed and their own crossing speed. It relieves pedestrians from estimating crossing time, which may involve error-prone processes like estimating road width and calculating crossing time. Therefore, we expect the "required speed" to be more effective in assisting pedestrian judgment of crossing possibility than remaining time regardless of road widths. As "required speed" is a less intuitive and familiar concept than remaining time, its performance was tested in this study.

1.3. Objectives and hypotheses

The final goal of the study is to explain pedestrians' risky decision-making at the clearance phase and improve pedestrian judgment with intelligent signal design. In addition to the evaluation of pedestrians' accuracy in judging crossing possibility under traditional "remaining time" cue, it also proposed and tested the "required speed" as an alternative cue of crossing difficulty.

The hypotheses for this study were as follows: (1). Pedestrians overestimate crossing possibility when making judgements based on remaining time. (2). The "required speed" leads to more accurate judgments of crossing possibility than "remaining time". (3). The advantage of "required speed" over "remaining time" is independent of road widths.

2. Methods

2.1. Experimental design

The independent variables are cue of crossing difficulty (*remaining time vs. required speed*) and road width (*4 lanes vs. 6 lanes*). The combination of them produces four experimental conditions: display remaining time or required speed at a road that has four or six lanes. Each participant made equal number of judgements in the four conditions. The dependent variable is pedestrian judgement of crossing possibility measured by subjective rating.

2.2. Participants

A total of 44 pedestrians (18 male, 26 female) participated in the experiment. All participants received compensation. They were enrolled in colleges near the experimental site, and had an average age of 23.6 (3.2).

2.3. Experimental setting

The experiment was conducted in the field to simulate true-to-life road-crossing experiences. The site located at an intersection between Kehui South Rd. and Tianchen West Rd. in Beijing, China (see Fig. 1 for a graphic representation). It possessed several characteristics ideal for the experiment, including:

- The countdown timers installed on the pedestrian lights is not working. Therefore, we can present the remaining time or required speed to participants without conflicting with the numbers

Table 1
Required speed and remaining time used in the experiment.

Crossing difficulty	Low			Medium			High		
Cues (Two types)	Required speed (m/s)	Remaining time(s)		Required speed (m/s)	Remaining time(s)		Required speed (m/s)	Remaining time(s)	
Road Width (Lanes)		four	six		four	six		four	six
Display	*0.4*	57	85	*1.1*	21	31	*1.9*	12	18
	0.5	45	68	*1.2*	19	28	*2.1*	11	16
	0.6	38	57	*1.3*	17	26	*2.3*	10	15
	0.7	32	49	*1.4*	16	24	*2.5*	9	14
	0.8	28	43	*1.5*	15	23	*2.7*	8	13
	0.9	25	38	*1.6*	14	21	*2.9*	8	12
	1.0	23	34	*1.7*	13	20	*3.1*	7	11
				1.8	13	19	*3.3*	7	10
							3.5	6	10
							3.7	6	9
							3.9	6	9

Note: Remaining time was rounded to the nearest integer. As a result, some of the required speeds mapped to the same remaining time. However, the approximation did not affect the validity of the conclusions, as the actual required speed was calculated from the displayed remaining time for data analysis.

displayed on the countdown timers.

- The intersecting roads have different widths (four lanes *vs*. six lanes). Pedestrians can judge crossing possibility of two different widths alternately, avoiding perceptual adaptation to the same crossing distance.
- One branch of the intersection is closed, making it safe and efficient to test pedestrian crossing speeds at the crosswalk.

2.4. Materials

Each level of crossing difficulty includes one pair of cues: required speed and remaining time. The two cues in each pair were respectively printed on two sides of a card (A4 art coated paper), with Arial Black 480 font to ensure clear reading six lanes away. The specific values of the 26 pairs of cues are shown in Table 1.

We expect that it is easy to judge crossing probability for both extremely low and extremely high required speeds. By contrast, the judgement will be much harder in the middle range of required speeds when it is closer to pedestrian speed. To avoid extensive experiments on easy-to-judge speed range, we set the range of required speed and number of trials with three criteria. First, the range of crossing difficulty were chosen according to pedestrians' normal crossing speeds. Based on an observational study in Beijing (Wu et al., 2004), pedestrian crossing speed ranged from 0.4 m/s to 4 m/s, with the 15th and 85th percentile being 1.1 m/s and 1.8 m/s, respectively. Therefore, crossing difficulty in this study was categorized into three groups: Low difficulty (0.4–1.0 m/s), medium difficulty (1.1 m/s–1.8 m/s), and high difficulty (1.9 m/s–4 m/s). Second, given the broad range of the required speed in the high difficulty group (2.1 m/s), the speed values were chosen every 0.2 m/s, instead of 0.1 m/s as in other groups. Third, the difficulty levels in the medium difficulty were tested twice, while difficulty levels in other groups were tested once.

2.5. Procedure

As shown in Fig. 1, the experimenter and the participants stood at one corner of the intersection (position X), while two assistants stood beside the crosswalk light located at the end of the two crosswalks. Assistant A displayed the set of cards corresponding to the four-lane road, while assistant B displayed cards for the six-lane road.

Each participant finished two blocks of tasks. In block A, the assistants showed the set of cards that displayed remaining time. For example, a card displaying "34" meant that there were 34 s left before red-light onset. In block B, the assistants showed the set of cards that displayed required speed to cross successfully. For example, a card displaying "1.5" meant that the minimum walking speed required to finish crossing before red-light onset was 1.5 m/s. The order of the two blocks alternated among all participants.

Each block includes 34 random trials. A trial began with participants facing one of the assistant as instructed by the experimenter. Then, the participant would look at the crosswalk, read the card displayed by the assistant, make a judgement, and quickly tick the crossing possibility on a six-point Likert scale (1–6 denoting *very improbable, improbable, somewhat improbable, somewhat probable, probable, very probable,* respectively). Afterward, the participant turned 90° to face the other assistant, initiating another trial at a different road width. Finally, pedestrians' crossing speeds were measured twice with a stopwatch at the blocked crosswalk.

3. Results

3.1. General trend in pedestrian judgment of crossing possibility

For a specific pedestrian, the difference between required speed and pedestrian speed determines the actual crossing possibility. Its relationship with pedestrian judgment of crossing possibility was plotted in Fig. 2.

Pedestrians' confidence in judgment increased with the gap between required speed and pedestrian speed (absolute value). At both ends of the speed difference, pedestrians become very certain about whether they can cross the road. The trend confirmed our assumption in choosing the required-speed range for experiment, and validated the choice of the range of required speed (see Section 2.4).

Pedestrians' judgement of crossing possibility in both cues decreases with the speed difference, which is reasonable because the actual crossing difficulty has decreased. Despite the similarity, the leaf-shaped polygon formed by all data points indicates differences in judgments based on the two cues. Judgments that made based on required speed is lower and more sensitive to changes in speed difference than that made based on remaining time. For example, when the remaining time was displayed, pedestrians thought they could cross until the difference was larger than 1m/s. By contrast, when required speed was displayed, pedestrians reversed their judgments immediately when the speed difference passed zero. In addition, when crossing difficulty was displayed in required speed, the judgment at different road widths nearly overlapped; Whereas judgment of crossing possibility is higher in the four-lane road than the six-lane road when the crossing difficulty is displayed as remaining time.

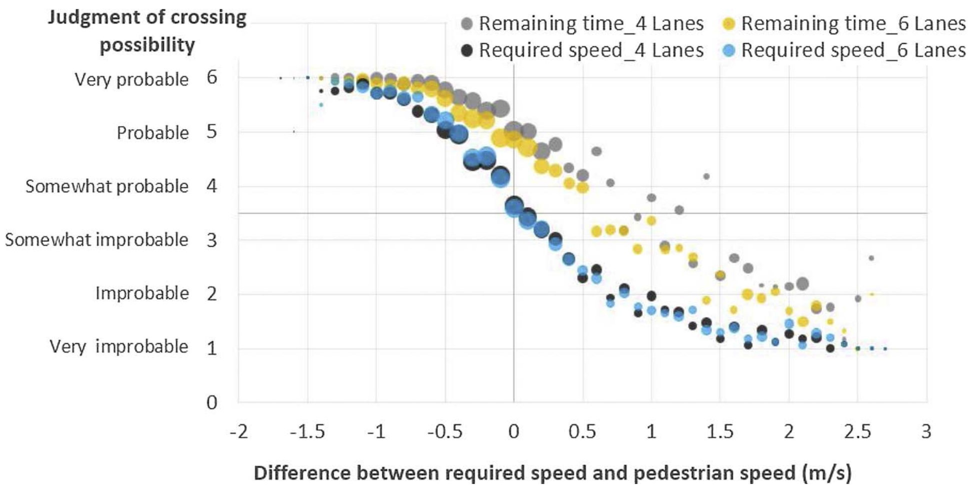

Fig. 2. Relationship between pedestrians' average judgement of crossing possibility and the difference between required speed and actual speed (rounded to one decimal place). The area of the bubble denotes the number of pedestrian judgments averaged for a certain level of speed difference.

3.2. Evaluation of pedestrian judgment

Pedestrian responses were coded into four categories following the framework of signal detection. When required speed is smaller than or equal to the actual speed, the response is a *hit* (judged crossing possibility ≥ 4) or a *miss* (judged crossing possibility ≤ 3). When required speed is larger than actual speed, pedestrian response is a *false alarm* (judged crossing possibility ≥ 4) or a *correct rejection* (judged crossing possibility ≤ 3). Fig. 3 shows the percentage of the four responses in each condition.

The four responses were also calculated for each pedestrian to perform statistical tests. For the overall accuracy, repeated measure analysis of variance showed that the main effect of the cue of crossing difficulty was significant with medium effect size, F (1, 43) = 9.16, $p = 0.004$, $\eta^2 = 0.075$. That is, pedestrians judged crossing possibility more accurately when the cue of crossing difficulty was presented as required speed than when it was presented as remaining time. Due to the small effect size in the effect of road width, F (1, 43) = 3.46, $p = 0.07$, $\eta^2 = 0.005$, and its interaction with the cue of crossing difficulty, F (1, 43) = 1.95, $p = 0.17$, $\eta^2 = 0.003$, pedestrians' overall accuracy did not differ significantly across two road widths.

Since false alarm indicates risky crossing, we also conducted a similar analysis with false alarm rate as the dependent variable. The cue of crossing difficulty was significant with large effect size, F (1, 43) = 43.92, $p < 0.001$, $\eta^2 = 0.209$. The effect of road width and its interaction with the cue of crossing difficulty were both significant with small effect size, F (1, 43) = 9.37, $p = 0.004$, $\eta^2 = 0.008$; F (1, 43) = 8.23, $p = 0.006$, $\eta^2 = 0.007$. Further analysis showed that pedestrians had lower false alarm rate when crossing difficulty was displayed as required speed than when it was displayed as remaining time, regardless of the road width ($ps < 0.001$). In addition, pedestrians had similar false alarm rate at different road widths when crossing difficulty was displayed as required speed ($p = 0.653$), but they had higher false alarm rate at narrower road when crossing difficulty was displayed as remaining time ($p = 0.004$).

3.3. Judgment ability and response bias

Combining the results for overall accuracy and false alarm rate, we can conclude that pedestrians tend to overestimate the crossing possibility. Based on signal detection theory (Macmillan and Creelman, 2004), the overestimation may be caused by low sensitivity in discriminating among different crossing possibilities and/or a low criterion in cutting different crossing possibilities into binary judgments (Can cross *vs*. Can't cross). To determine whether and to what extent these factors are at play, pedestrians' sensitivity (d') and response bias (β) were calculated for different conditions (see Fig. 4).

Repeated measure analysis of variance was conducted with crossing difficulty and road width as independent variables. When sensitivity d' was considered as the dependent variable, the main effect of the cue of crossing difficulty was significant, F (1, 43) = 12.83, $p = 0.001$, $\eta^2 = 0.110$. Effect of road width was not significant, F (1, 43) = 1.17, $p = 0.286$, $\eta^2 = 0.002$, neither was its interaction with the cue of crossing difficulty, F (1, 43) = 0.42, $p = 0.522$, $\eta^2 = 0.001$. Therefore, pedestrians were better at judging crossing possibility based on required speed than on remaining time, regardless of the road width (see d' in Fig. 4).

When response bias β was considered as the dependent variable, the effect of the cue of crossing difficulty was still significant, F (1, 43) = .15, $p < 0.001$, $\eta^2 = 0.126$. However, different with that of sensitivity, the effect of road width became marginally significant, F (1, 43) = 3.59, $p = .065$, $\eta^2 = 0.002$, and its interaction with the cue of crossing difficulty became significant, F (1, 43) = 4.12, $p = 0.049$, $\eta^2 = 0.002$, although both had a low effect size. Further analysis showed that pedestrians were more likely to think they could cross successfully when judging based on remaining time than on required speed, regardless of road width ($ps < 0.001$). In addition, pedestrians became more conservative as the road width increased when judging based on remaining time ($p = 0.041$). When required speed was displayed, however, their criteria remained stable across two road widths ($p = 0.909$, see β in Fig. 4).

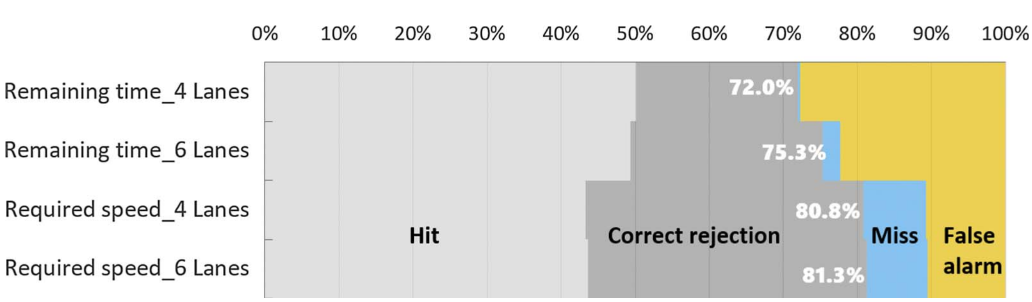

Fig. 3. Percentage of four types of pedestrian judgements. The percentage on the graph is the percentage of correct judgments (i.e. hit plus correct rejection).

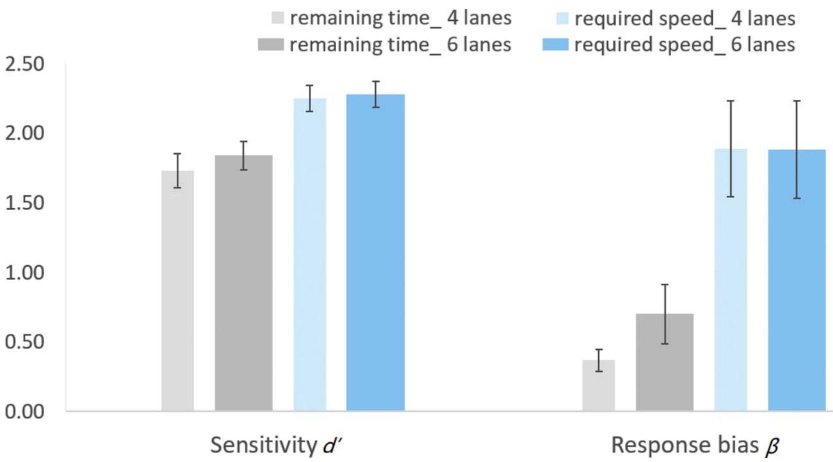

Fig. 4. Sensitivity (d') and response bias (β) in judging crossing possibility.

4. Discussions

The field experiment found that pedestrians' judgments of crossing possibility at crosswalks were susceptible to errors. When crossing difficulty was displayed in remaining time as in a traditional countdown timer, pedestrians overestimated their ability to cross successfully. Compared with remaining time, display of required speed led to higher overall accuracy and lower false alarm rate in pedestrians' judgments. Signal detection analysis further revealed that the improvements were due to higher sensitivity to different crossing possibilities, as well as a more conservative criterion of response, regardless of road width. This section discusses these findings and their implications beyond the context of this experiment.

4.1. Advantages of required speed cue over remaining time cue

Overall, the required-speed cue outperformed remaining time in terms of both overall accuracy and overestimation rate. Given that required speed is an unfamiliar cue and pedestrians were not given chances to evaluate their own normal crossing speed, it would have produced even better judgments if it were used in the same way as the remaining time, which is a prevalent cue displayed on counterdown timers.

One factor underlying the advantage of "required speed" is pedestrians' higher sensitivity to differences among crossing possibilities at various levels of crossing difficulty. Judging crossing possibility based on remaining time may involve estimation of road width, personal speed, and mental calculation of the total time needed to cross. By contrast, the cue of required speed transfers these error-prone tasks from pedestrians to traffic lights with better function allocation. As a result, pedestrian only need to compare one's own speed with the required speed. For pedestrians, the new function allocation has transformed a hard knowledge-based task to a much easier rule-based task (Rasmussen, 1983). When task difficulty decreased, human capability relatively increased. Therefore, the display of "required speed" improved pedestrian ability to discriminate different crossing difficulties.

The other factor related to the advantage of "required speed" over "remaining time" is more conservative criterion in judgments. An explanation for the difference is information framing. Behavioral economics have long recognized that the framing of information influences choices (Tversky and Kahneman, 1981). Although required speed and remaining time refer to the same level of difficulty, they frame information differently. Just as shops offer discounts for limited amounts of time to induce scarcity, the cue of remaining time frames crossing difficulty as "the remaining chance to cross", making pedestrians more sensitive to the cost of losing a chance. By contrast, the cue of required speed guides pedestrians to frame crossing difficulty as the "requirement to cross", thus making pedestrians more conscious of whether they can cross and the consequence of inability to finish timely.

Of note is that when pedestrians judge crossing possibility based on required speed, the width of the road is irrelevant information. Therefore, pedestrians' response criteria were the same at two road widths. However, pedestrians became more conservative when crossing wider roads if the crossing difficulty was displayed in the form of remaining time (despite a small effect size, $\eta^2 = 0.002$), resulting in lower false alarm rate at wider road. Given that wider roads are usually accompanied by higher possibilities of unexpected incidents, the adjustment to a more conservative criterion indicate a lower confidence in judgment. The shift is a strategy to compensate for uncertainties resulting from low level of confidence in judgment.

4.2. Practical implications for safety promotion

The advantages of required speed cue over remaining time cue suggest that pedestrian signal lights can be improved to include "required speed" information to assist pedestrian judgments of crossing possibility. In that case, the signal lights can store the width of the road where it is installed, and report the required speed based on the remaining time. Pedestrians can measure and remember their crossing speeds as a piece of personal data (like height or weight), and make decisions based on that data.

Display of required speed can also facilitate innovations in traffic regulation. In many countries (such as the US, China and Japan), pedestrians are not allowed to enter crosswalks at clearance phase, regardless of the amount of remaining time. The one-size-fit-all regulation ensures safety at the sacrifice of efficiency, because the duration of the clearance phase is set based on a relatively slow pedestrian speed (usually 15 percentiles of pedestrian speed) to avoid incomplete crossings when the clearance phase ends. For quick pedestrians, even if they arrive during the clearance phase, they can still finish crossing before the light becomes red (Zhuang et al., 2018).

In other countries such as Canada, traffic regulation is more flexible by giving pedestrians the chance to judge whether it is possible to cross. Pedestrians are not considered as violators so long as they can finish crossing within the remaining time displayed on countdown timers (Brosseau et al., 2013). The flexible regulation is more pedestrian friendly than indiscriminately forbidding all pedestrians from crossing, on condition that pedestrian can make accurate judgments and ensure their own safety. We expect that the display of required speed will carry these regulation innovations a step forward.

4.3. Theoretical implications for future research

When pedestrian made judgments based on the remaining time, the false alarm rate for four-lane and six-lane roads were 27.7% and 22.3%, respectively. That is, pedestrians overestimated crossing possibility at least once in five judgments. The overestimation can explain why pedestrians entered crosswalks when the remaining time was insufficient (Koh et al., 2014; Lee and Lam, 2008; Zhuang et al., 2018). However, compared with previous findings, the overestimation rate is much lower than percentage of pedestrians who crossed when the remaining time is insufficient (e.g. 79%, Zhuang et al., 2018; More than 45%; Koh et al., 2014). The gap between the overestimation rate and risky crossing decision implies that some pedestrians choose to cross even if they know they cannot finish before red-light onset. Therefore, both overestimation of crossing possibility and risky attitudes play a role in pedestrians' risky decision making at clearance phase. Future studies need to explore how motivational aspects of decision-making determine pedestrians' crossing behaviors at the clearance phase.

The study also demonstrated how a simple change in the presentation of information improved pedestrian judgments. In the field of driving safety, lots of efforts have been made to explore and model how characteristics of information could influence driver performance (e.g. Zhang et al., 2016). By contrast, although pedestrian signal lights have evolved from a simple Green/Red light configuration to an information center inclusive of a flashing green signal, a countdown timer, and even a screen to display safety messages, studies around pedestrians' information processing in relation to these new systems are still missing. Future studies need to explore how information can be designed to assist pedestrian decision making.

4.4. Limitations

The study has several limitations that may influence the extension and application of its findings. First, pedestrians were told to judge crossing possibility based on normal crossing speed. "Normal crossing speed" was also measured when they walked on the crosswalk without running or hurry across the crosswalk for safety purposes. However, pedestrians may adapt their speed to the remaining time in the countdown timer by walking faster or running at shorter remaining time (Paschalidis et al., 2016). Therefore, whether a crossing difficulty belongs to a 'signal' or 'noise' is dependent on the adaptive speed of pedestrians, rather than a binary value determined by normal walking speed. Future work on related topics need to apply fuzzy signal detection theory (Parasuraman et al., 2000) to address the fuzziness of pedestrian speed.

Second, although the experiment was conducted in the field to create a realistic simulation of a crosswalk environment, crossing difficulty was shown on a static display. However, traditional countdown timers are dynamic displays that keep updating decreasing numbers. Since countdown timers and decreasing progress bars are often used to stimulate time pressure (e.g. Maule et al., 2000), and time pressure can change information processing strategies (e.g. Young et al., 2012), we infer that the dynamic display will cause time pressure to pedestrians, and ultimately influence pedestrians' judgment of crossing possibility. To overcome this limitation, we suggest testing pedestrians' judgments with dynamic displays.

Finally, the participants enrolled for this study are college students aged 19 to 33. While the age range covered the main age group of violators at the clearance phase (Zhuang et al., 2018), it is not clear whether our findings apply to other type of pedestrians. Previous studies have found that old pedestrians had lower accuracy in estimating crossing time than young pedestrians (Dommes et al., 2013; Holland and Hill, 2010; Zivotofsky et al., 2012). At best, they can estimate as accurate as young pedestrians (Naveteur et al., 2013; Zito et al., 2015). From these evidences, we can infer that old pedestrians can also benefit from the cue of "required speed", which relieved pedestrians from the error-prone process of time estimation. Another concern is that the participants in this study are educated college students who understand the "required speed" clearly. Other pedestrians, especially kids and illiterate pedestrians, may find it less intuitive than remaining time. Consequently, future application of the findings requires systematic test on all pedestrians involved.

5. Conclusions

With college students as participants, we find that pedestrians tend to overestimate crossing possibility at the clearance phase at crosswalks with countdown timers, but this tendency can be decreased by providing a different cue related to crossing difficulty: required speed. When the required speed to cross safely, rather than remaining time to cross safely, is displayed to pedestrians, their judgments are more consistently accurate. This advantage is due to higher sensitivity and a more conservative response criterion.

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