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Cross or wait? Pedestrian decision making during clearance phase at signalized intersections

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ABSTRACT

Pedestrians arriving at clearance phase (Flashing *Don't Walk*) face different levels of risk depending on behavioral choice afterwards. However, few studies have focused on the choices pedestrians make *during* this phase. This field study analyzed pedestrian choices after arrival, evaluated safety of the choices, and built a model to identify the predictors of pedestrian choices. It was found that pedestrians arriving during clearance phase made dynamic decisions based on the changing contexts. Specifically, the majority made the decision to "cross" as opposed to "wait" (85.2% vs. 14.8% respectively), although only the latter choice is legal. Seventy-nine percent of the pedestrians did not finish crossing the intersection before the traffic light turned red, and they walked 41% of the road width during a red light. For those waited, roughly half of them waited until green or crossed at an intersecting crosswalk, while others finally started on red light. Nevertheless, the waited pedestrians still faced lower risk than those crossed prematurely in terms of running behaviors, and conflicts with vehicles. Pedestrians are more likely to cross immediately after arrival when they are younger, are not engaged in secondary tasks, arrived at a position farther from approaching vehicles at the near side of the road, or arrived at a time when there are more pedestrians crossing the road. Although fewer pedestrians choose to cross when the required speed is higher (due to a wider road or less remaining time), the required speed they choose to cross at is far higher than their actual speed. These findings are essential for realistic pedestrian simulations and targeted safety countermeasures. They also imply the need for changes to certain traffic regulations and signal design to facilitate safe decision making at clearance phase.

1. Introduction

Pedestrian green light is usually followed by a *clearance phase*, occurring before the light ultimately turns red (see Fig. 1). This phase was implemented to help pedestrians who are already in crosswalks to finish crossing before onset of a red light (Wanty and Wilkie, 2010). The message displayed during clearance phase differs from country to country; it may be signaled by flashing Don't Walk (e.g. USA), flashing Red Man (e.g. Australia, New Zealand) or flashing Green Man (e.g. Japan, China), and is sometimes coupled with countdown timers displaying the remaining time before the light turns red. Although the regulations for clearance phase vary slightly across countries (e.g. USA, Canada, Singapore), a general rule is that pedestrians already in crosswalk at the onset of the clearance phase can continue crossing, but new arrivers cannot enter the crosswalk. The question is, pedestrian even start crossing when they face a red light (e.g. King et al., 2009; Rosenbloom, 2009), will they wait at the flashing green light? If they do wait, will they wait until green light or wait until there is a large gap in traffic that would allow them to cross? What factors will influence their decision? How does their choice affect their safety? This study seeks to answer these questions.

1.1. Pedestrian choices at clearance phase

Pedestrians arriving at clearance phase theoretically can start crossing at either flashing green phase, red phase or green phase (see Fig. 1). Although only the last choice is legal, pedestrians are often reported weighing other crossing choices. While building a pedestrian simulation model, Lee and Lam (2008) recorded that over 50% of the pedestrians they studied arriving during the last six seconds of the flashing green light made the choice to wait, but the majority of pedestrians crossed the road immediately if they arrived at the first seven

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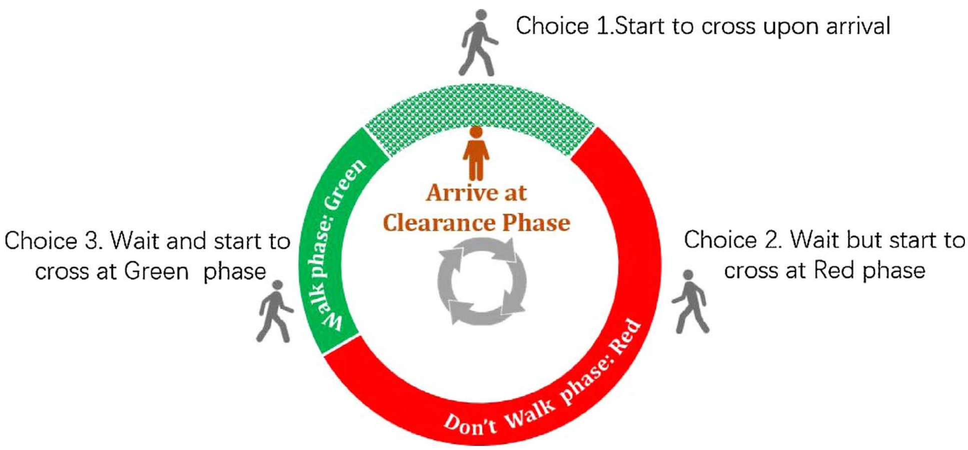

Fig. 1. Cycle of pedestrian signal lights in China and pedestrians' choices after arrival at clearance phase.

seconds of flashing green phase (with total clearance time being 13 s). Similarly, Koh et al. (2014) observed pedestrians and cyclists arriving during flashing green phase in Singapore, and found 34% would wait if they arrived within the last five seconds of the flashing green phase, otherwise, 100% of them chose to cross immediately. In an study in Shanghai, China, Ma et al. (2015) found that 12.4% of the pedestrians older than 50 entered the crosswalk at the flashing green phase. For pedestrians who were younger than 50, the percentage is as high as 92.7%.

Studies on other topics have also reported indirect evidence of pedestrians tending to cross at the flashing green phase. An early study on pedestrian delay found that pedestrian reduced their delay by 22%, mostly through crossing at the flashing green phase. Similar observations came from studies evaluating safety of countdown timers, where researchers typically reported percentage of pedestrians distributed over different signal phases as safety indicators.[1] For instance, Wanty and Wilkie (2010) found 23% of *all* the pedestrians entered the crosswalk at the flashing Don't Walk phase. Similarly, Kim et al. (2013) observed 19% of the pedestrians started crossing at the flashing walking person signal in Korea, and Xiong et al. (2015) reported a higher percentage (25.7%) in China. Besides these findings for adults, an observation of children in Shandong, China found that 6.9% crossed during clearance phase (Fu and Zou, 2016). These studies did not report the arrival time of the pedestrians, but it is likely that these pedestrians arrived during the clearance phase, as pedestrians who arrived earlier would have crossed immediately at green phase.

Despite the high percentage of pedestrians starting to cross immediately at the clearance phase, some pedestrians choose to wait. Will the waited pedestrians uniformly wait until green light? A possible answer is "No" based on two indirect evidences. One is that in a model built by Schmitz (2011), arrival at a flashing Don't Walk signal is a predictor of violation, with "enter on red" being one type of the violation. Therefore, it is possible that pedestrians arriving at the clearance phase may wait but finally start to cross at red phase. The other indirect evidence is that pedestrians arriving during red phase are more likely to cross against red light if the waiting time is longer (Brosseau et al., 2013; Gårder, 1989; Houten et al., 2007; Yang et al., 2006). Compared with pedestrians arriving at red phase who typically wait part of a full red phase, pedestrians arriving at clearance phase need to wait a much longer duration, which equals the remaining time in clearance phase plus a full red phase (see Fig. 1). This, again, suggest that the pedestrians originally choosing to wait may end up starting crossing during red phase. In addition to entering crosswalk at red phase, pedestrian may have other choices after they initially decided to wait. To fully understand the dynamic decision-making process in clearance phase, both decisions made upon arrival and afterwards should be tracked.

1.2. Risks for different choices after arrival

The choice to cross immediately upon arrival is risky unless pedestrians can finish crossing before the traffic lights turns red. However, as observed by Koh et al. (2014), 45% of the observed pedestrians and cyclists began crossing at flashing green phase couldn't finish crossing timely. More seriously, for those who began to cross during the last five seconds of the flashing green phase, none finished before red-light onset. In other studies, pedestrians were also observed being trapped in the crosswalk after the clearance phase. Huang and Zegeer (2000) found that 10.5% of *all* pedestrians remaining in the roadway at the end of pedestrian phase. Wanty and Wilkie (2010) found a higher rate of 17%. A similar percent (14%) is observed for child pedestrians in Shandong, China (Fu and Zou, 2016). We can only infer that these late finishers may include pedestrians arriving at clearance phase, as these studies did not provide data as to the arrival time of these pedestrians.

For pedestrians choosing to wait, they are expected to be safer as they cross the street; otherwise the need to comply with crosswalk regulations would be questioned. However, the safety associated with waiting may be compromised by illegal choices made afterwards. In fact, if pedestrians who initially wait at the crosswalk end up crossing at red light, they faced a risk 8 times as high as that of legal crossings (King et al., 2009). Given this statistic, it is uncertain whether the risk for pedestrians who wait but cross illegally is still lower than those crossed upon arrival. To justify the need to wait, the risk levels associated with different choices should be evaluated.

1.3. Predictors of pedestrian decision making at clearance phase

Once the risk levels of different choices were evaluated, specific predictors of risky choice should be identified to avoid unsafe decisions. Pedestrians' decision may be influenced by personal characteristics and contextual factors after arrival. Although no attempt has been made to identify the predictors of pedestrians' decision making at the clearance phase, studies on other violation behaviors have offered some clues on potential factors.

1.3.1. Pedestrian characteristics

Pedestrian characteristics include demographical and behavioral aspects of pedestrians. Previous studies have generally found more males crossing on red than females (Lipovac et al., 2013; Rosenbloom, 2009, 2011; Tom and Granie, 2011), and males usually wait less time before crossing (Hamed, 2001). Besides gender, young pedestrians were also found to be riskier (Rosenbloom, 2009), while old pedestrians

[1] In evaluating the safety of countdown timers, researchers would compare safety indicators with and without countdown timers. The data referred were only observations for sites with countdown timers, because the signal lights in this study all have countdown timers, a module prevalent in Chinese cities.

usually have higher compliance rate (Cook and Koorey, 2013). In Hao et al.'s (2008) model, pedestrians younger than 30 were more likely to cross on red than their older counterparts. At the clearance phase, Ma et al. (2015) found much higher percentage of pedestrians under 50 than those over 50 years old that crossed at clearance phase (92.7% vs. 12.4%). The behavioral difference between the two age groups may reflect a continuous trend, but it requires further confirmation with a more detailed description of pedestrian age groups.

Although secondary tasks such as using cellphone during crossing were associated with careless crossing behaviors (Neider et al., 2010; Pešić et al., 2016), Hao et al.'s (2008) model identified pedestrians without secondary tasks (e.g. luggage, children) as more likely to be compliers at red light. The seemingly contradictory findings made it unclear how pedestrians arrived at the clearance phase were influenced by secondary tasks/distractors.

1.3.2. Contextual factors

Contextual factors refer to the state of environment and behaviors of other pedestrians after pedestrians' arrival at crosswalks. As stated in Section 1.1, time of arrival and remaining time were found to influence pedestrians' choices (Lee and Lam, 2008; Koh et al., 2014). Koh et al. (2014) observed that the number of crossing events increased with *proportion of time left* (calculated by remaining time/maximum time left to red light). As longer remaining flashing green time usually means longer waiting time before the green light, it is unclear whether the effect of proportion of time left implies the level of difficulty to cross before a red light (i.e. required speed), and/or the effect of the length of expected waiting time. Therefore, we will consider the two factors simultaneously.

Behaviors of other pedestrians also influence compliance to red light. Pedestrians are more likely to cross on red light when there are fewer pedestrians waiting at the crosswalk (Rosenbloom, 2009). Similarly, pedestrians reported an increased likelihood to violate when others were crossing the road (Yang et al., 2006; Zhou et al., 2009). Faria et al. (2010) further found that when a pedestrian nearby had started to cross, a pedestrian was 1.5–2.5 times more likely to cross. Given these evidences, it is likely that pedestrian crossing decisions are influenced by the pedestrians waiting or crossing at the crosswalk during clearance phase.

1.4. Stimulus for research

The studies reviewed above show that pedestrians arriving at clearance phase make choices on whether to cross, rather than obey the law uniformly. The phenomenon put pedestrians under risk, as pedestrians starting to cross immediately may finish crossing on red phase, and the pedestrians initially choosing to wait may end up starting on red phase. However, these possibilities were gleaned or inferred from studies focusing on diverse topics, such as the evaluation of countdown timers (Huang and Zegeer, 2000; Kim et al., 2013; Wanty and Wilkie, 2010; Xiong et al., 2015), pedestrian delay (Virkler, 1998), and pedestrians' overall violations including entering or exiting the crosswalk on a red light (Huang and Zegeer, 2000; Schmitz, 2011). In most studies, pedestrian behaviors at the clearance phase were mixed with those arriving during other phases or other types of road users. Few studies have completed an isolated analysis of pedestrians' choices at clearance phase, as well as the consequence and predictors of those choices. Therefore, this study conducted a field observation specially on the pedestrians who arrived at clearance phase.

More specifically, we observed and compared pedestrian choices in detail, analyzed their safety related behaviors afterwards, and built a logistic regression model to identify how pedestrian and contextual factors could predict pedestrians' choices. The findings have deepened our understanding of pedestrian decision making at the clearance phase, and the factors identified may stimulate system design solutions to increase pedestrian safety.

2. Methods

2.1. Site selection

Four sites were selected after screening of local streets via Tencent Street View map and field observations. The final sites have the following features:

- Countdown timers in clearance phase are working properly
- Have more than six lanes: represent a complex traffic condition
- Road markings are in good condition, and have no parked cars: easy for coding
- No police are directing traffics
- Have a good field of view and shelter to hide cameras

Roadway and traffic characteristics of the four sites are displayed in Table 1. Pedestrian flow and vehicle flow respectively refers to the number of pedestrians and vehicles that used the observed crosswalk in one hour, counted at non-rush periods .

Table 1
Traffic characteristics of the four selected sites.

Site	Lanes	Phases(seconds)			Flow(hourly)	
		Clearance	Green	Red	Pedestrian	Vehicle
Datun Rd. (West) + Lincui East Rd.	8	20	12	82	239	2078
Kehui East Rd. (East) + Lincui Rd.	10	20	35	91	78	1403
Beitucheng West Rd. (East) + Changping Rd.	10	20	35	122	672	1740
Beichen West Rd. (North) + National Stadium Rd.	10	25	20	121	267	3711

2.2. Observation

Cameras were used to record the natural scenes at the four sites. At each site, the camera was hid at a shelter near the crosswalk to avoid disturbance. Fig. 2 is an example of the video snapshots. Videos were captured during non-rush hours on sunny workdays. The video lasts 1170 min. After the observation, distances between road markings (e.g. lane markings) were measured for further coding and calculation of distance related variables .

2.3. Coding

Each pedestrian arriving during the clearance phase was coded, unless they were totally blocked from view by vehicles or other pedestrians. Final variables were either coded directly from the video or calculated from initial data on pedestrian, vehicle, and signal states. For example, pedestrian's waiting time was calculated by subtracting the time of starting to cross with the time of arrival. The final variables fall into three categories: Pedestrian characteristics, Contextual state at arrival, and Crossing behaviors (see Table 2). Pedestrian characteristics include the basic demographic and behavioral feature of pedestrians; contextual state at arrival refer to the state of signal lights, vehicles, and other pedestrians when pedestrians arrived; Crossing behaviors refer to pedestrian behaviors or behavioral consequence related to crossing Fig. 3.

3. Results

The coding procedure ended up with 486 pedestrians arriving at flashing green phase. This section describes the basic sample features

Fig. 2. Example of the video snapshots.

Table 2
Variables coded and their definitions.

Category	Variables	Definition and calculation
Pedestrian characteristics	Choices	Whether pedestrians start crossing immediately; Cross: 1; Wait:0
	Gender	Male:1; Female:0
	Age	Age group estimated based on appearance, clothes and gait. It has 12 levels range from 15 to 75 with 5 years as an interval;
	Position	Whether pedestrians are near or far from the waiting vehicles at the near side in intersecting direction (see Fig. 3). Near vehicles: 1; Far from vehicles:0
	Distracted	Whether pedestrian is distracted by a secondary task after arrival (eating, using phones, have kids, luggage etc.) Yes:1, No:0
Contextual state at arrival	RequiredSpd	The minimum speed required for pedestrians to finish crossing within clearance phase = Road width/Remaining time
	ExpectedWait	Expected waiting time = Onset of green light – Time of arrival
	NumPedWait	Number of other pedestrians waiting when the pedestrian arrived
	NumPedCross	Number of pedestrians crossing the road when the pedestrian arrived
	CrossPedLeft	The maximum distance left for the crossing pedestrians when the observed pedestrian arrived. = Distance left/Road width
Crossing behaviors	Run	Whether pedestrian run during crossing; Yes:1; No:0
	Speed	Pedestrian speed in crossing = Crossing distance/Crossing time
	WaitTime	Wait time = Time start to cross – Time of arrival
	DistanceLeft	Distance left when the clearance ended = Distance/Road width
	RedTime	How long the pedestrian stayed on the roadway while the signal is red
	Conflict	The number of times when either the pedestrian or vehicles changed speed in interaction (including turning and straight through vehicles)

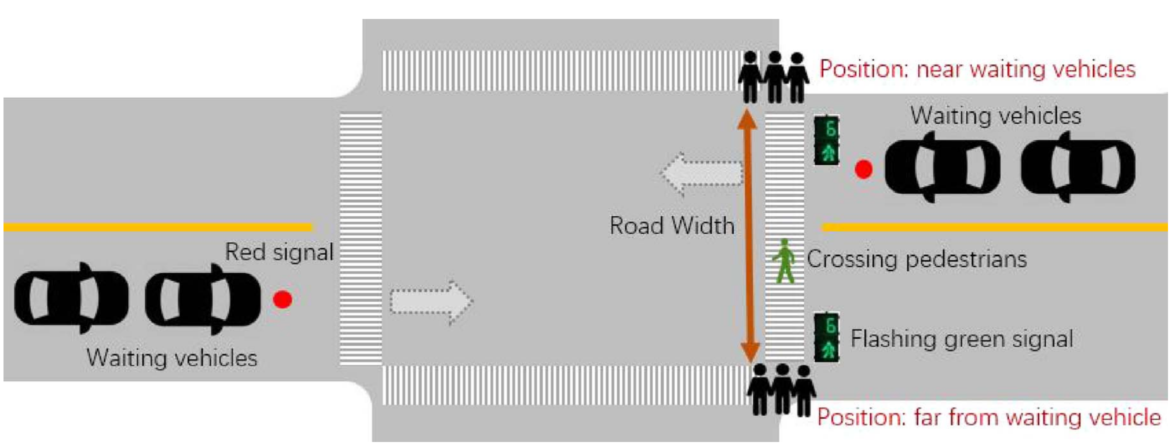

Fig. 3. Pedestrian positions relative to vehicle at the near side of the road. The position is coded to represent different level of risk from waiting vehicles that will start after the clearance phase.

and pedestrian choices, followed by a comparison of behaviors and risks of two crossing choices. Finally, a binary logistic regression model was built to identify predictors of pedestrian decision making.

3.1. Sample characteristics and pedestrian choices

Pedestrian choices were categorized into two types: Cross and Wait. "Cross" means pedestrians start to cross the road at the clearance phase, while "Wait" means that pedestrians wait to cross at other phases or change direction to cross at other crosswalks. Pedestrian characteristics and the contextual state at their arrival in both groups were shown in Table 3, Fig. 4.

Overall, 85.2% of the sample chose to start crossing during the flashing green phase, with only 14.8% waited. Fig. 4 is a more detailed description of the pedestrian choices, inclusive of six types based on pedestrian start-end time. Among the 85.2% pedestrians that did not wait, 79% did not finish crossing before the onset of red lights. In fact, only 6.2% could make it. Although 15% people waited, more than half of them (7.8%) started crossing at red light.

Some pedestrian characteristics are related to choices. Younger ($\chi^2(1) = 19.0$, $p < 0.001$) or undistracted pedestrians ($\chi^2(1) = 29.1$, $p < 0.001$) tended to violate crosswalk regulation more. Similarly, if vehicles were waiting at the other side of the intersection in the near side of the road, pedestrians were more likely to cross than if the vehicles were waiting near them ($\chi^2(1) = 8.9$, $p < 0.01$). *T*-test also show that pedestrians tended to cross at the clearance phase if the required speed was lower (t (75.5) = 5.22, $p < 0.001$), or there were more pedestrians crossing the road (t (484) = 4.8, $p < 0.001$); or the crossing pedestrians were farther from destinations (t (484) = 4.5, $p < 0.001$).

3.2. Risks for different choices at clearance phase

As shown in Table 4, pedestrians who crossed at the flashing green phase started crossing immediately after their arrival, with an average waiting time of 0.2 s. They saved 85.2 s compared with those waited. However, the efficiency is accompanied by risks.

They were more likely to run across the road (52.9% vs. 11.9%, $\chi^2(1) = 34.9$, $p < 0.001$), which could also be seen from the speed difference (1.8 m/s vs. 1.2 m/s, t (136.6) = 13.3). Although the two types spent similar amount of time on the roadway during red light (t (71.3) = −1.2, $p = 0.244$), pedestrians crossing immediately had more interactions with vehicles (t (125.4) = 5.4, $p < 0.001$). Moreover, for the 384 pedestrians starting at flashing green phase but couldn't finish crossing before the light turned red, the distance left to cover at red light onset constituted 41% of the road width, meaning that nearly half of pedestrians' total crossing distance occurred during the red phase. Fig. 5 is an intuitive display of their positions at the end of the clearance phase.

Table 3
Pedestrians information sorted based on choices.

		Cross		Wait	
Pedestrian characteristics	**Levels**	**Cases**	**%**	**Cases**	**%**
Gender	Male	221	86	35	14
	Female	193	84	37	16
Age [a] ***	Teenager (≤20)	15	100	0	0
	Young (20, 30]	190	88	25	12
	Middle age (30,55]	187	85	32	15
	Senior (> 55)	22	59	15	41
Position**	Far from vehicles	211	90	23	10
	Near vehicles	203	81	49	19
Distracted***	Yes	105	72	41	28
	No	309	91	31	9
Contextual state at arrival		**Mean**	**Std.Dev**	**Mean**	**Std.Dev**
RequiredSpd***(m/s)		4.4	5.48	12.5	12.93
ExpectedWait (seconds)		117.7	19.63	116.1	17.87
NumPedWait		0.1	0.39	0.2	0.52
NumPedCross***		4.3	2.96	2.5	2.65
CrossPedLeft***		0.6	0.30	0.4	0.33

Note: [a]Age has 12 levels with 5 years as the interval. It was organized into four groups here to simplify the descriptive results, while at the same time considering the sample size in each group.
*** p < 0.001, ** p < 0.01, * p < 0.05. Categorical variables were tested with χ^2 test; Age was tested with Fisher Exact test, while all other variables, independent sample *t*-test.

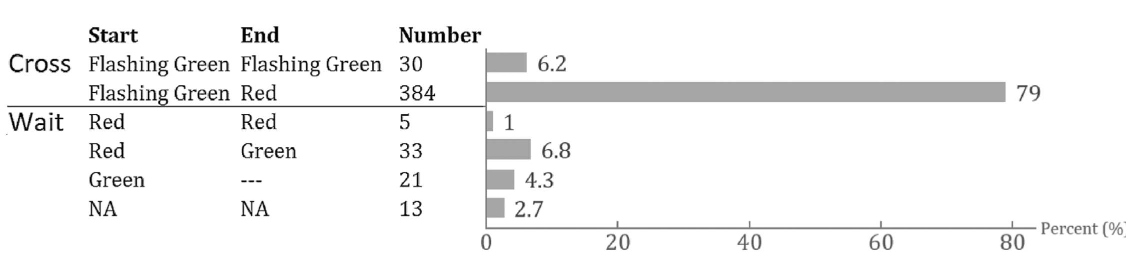

Fig. 4. Distribution of pedestrian choices based on start-end time. Pedestrian started at Green light were not observed for their ending time. "NA" means that pedestrians did not cross at the observed crosswalk; instead, they turned to cross at an intersecting crosswalk. This usually happens when they want to cross diagonally.

Table 4
Behavioral consequences of pedestrian choices.

	Cross		Wait	
	Mean	*Std.Dev*	Mean	*Std.Dev*
WaitTime (s) ***	0.2	0.8	85.4	46.3
Speed (m/s) ***	1.8	0.6	1.2	0.3
RedTime (s)	9.1	10.4	11.1	11.9
Conflict***	0.9	1.2	0.3	0.9
Run	52.9%		11.9%	
DistanceLeft	0.4	0.3		

Note: *** p < 0.001, ** p < 0.01, * p < 0.05.

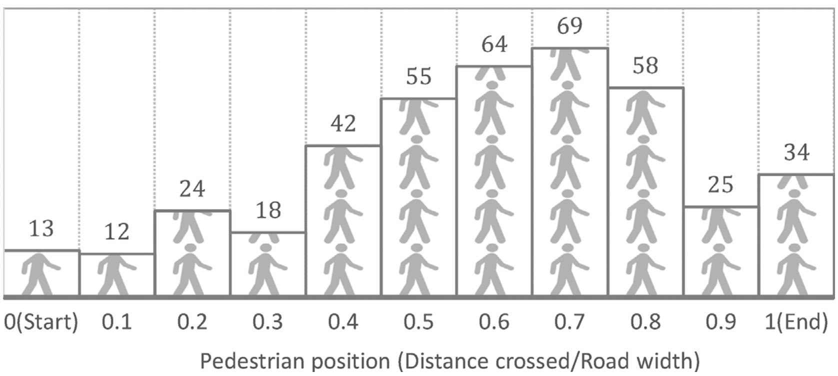

Fig. 5. Pedestrian position at the end of clearance phase. The figure can be viewed as a crosswalk, where 0 means start,1 means end of the crosswalk. Each pedestrian in the figure represents 15 pedestrians.

Table 5
Predictors of pedestrian choice estimated by binary logistic model.

Predictors	Estimate	Std.Error	*p*	Odds ratio
Gender				
Male vs. Female	0.28	0.32	.374	1.33
Age***	-0.27	0.06	.000	0.77
Position**				
Near vehicles vs. Far from vehicles	-0.99	0.33	.003	0.37
Distracted***				
Distracted vs. Undistracted	-1.58	0.32	.000	0.21
RequiredSpd***	-0.12	0.02	.000	0.89
ExpectedWait	0.01	0.01	.466	1.01
NumPedWait	-0.07	0.34	.832	0.93
NumPedCross*	0.17	0.08	.029	1.18
CrossPedLeft	1.12	0.60	.059	3.05
Constant	3.11	1.10	.004	22.45

Note: Significant difference between cross and wait: *** p<.001, ** p<.01, * p<.05

3.3. Behavioral and context predictors of pedestrian choices

As stated in 3.1, pedestrian choices were related to pedestrian and contextual characteristics. Given that complex correlations may exist among these characteristics, can they predict pedestrian choices while controlling for other variables?

Table 5 is the modeling results of binary logistic regression, where “1” means pedestrian choose to cross at flashing green light, and “0” refers to wait. The model has a good fit for the observed data when evaluated with Hosmer and Lemeshow test ($\chi^2(8) = 6.7$, $p = 0.57$). Overall, it can predict 90.3% of pedestrians’ choices.[2]

Table 5 indicates that pedestrians are more likely to cross the road when they are younger, have no distractors (luggage, kids, talking), arrive at a position farther from vehicles at the near side of the road, arrive at a time when the speed required to cross the road is lower (longer time left before red light or narrower road), and when there are more pedestrians crossing the road. The distance left for those crossing pedestrians also seemed to influence pedestrian choice (marginally significant, p = 0.059).

Since the odds ratio means the change in probability of crossing resulting from a one-unit increase in the predictor, the last column in Table 5 also shows that pedestrians were 2.7 times more likely to cross if they were farther from vehicles waiting at the near side of the road. Similarly, pedestrians without secondary tasks were 4.9 times more likely to cross than distracted ones. Although pedestrians adjusted their behaviors based on the required speed to cross, they were much more likely to make a “cross” decision (see Figs. 6 and 7). The average speed of pedestrians was only 1.7 m/s, but 78% of the pedestrians chose to

[2] Future studies on pedestrian simulation can apply the model with the significant predictors. In that case, the model is still valid ($\chi^2(8) = 7.8, p = 0.45$), and it can predict 89.5% of all cases. The probability of crossing is: $p(cross) = 1/(1 + e^{-x})$, where $x = -0.26\ Age - Position - 1.53\ Distracted - 0.12\ RequiredSpd + 0.25\ NumPedCross + 4.23$.

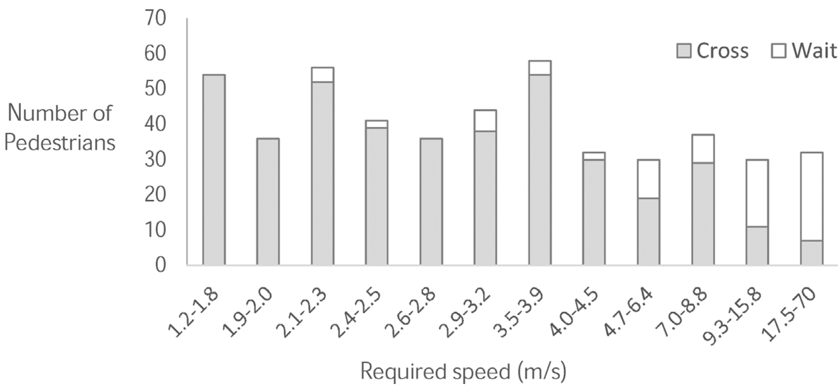

Fig. 6. Pedestrian choices across different ranges of required speed. The range was determined by sample size falling in each range to make sure every group has at least 30 pedestrians.

cross rather than wait when the required speed to cross was 7.0 m/s–8.8 m/s; Even when the required speed was higher than 9.3m/s, nearly 30% of the pedestrians started crossing immediately .

To avoid making conclusions that would be significantly affected by extreme risk takers, pedestrians who crossed when the remaining time was less than five seconds (including 5 s) were excluded for further analysis, resulting in 352 pedestrians. Fig. 7 shows the required speed at which pedestrians choose to cross and their actual crossing speed.

The points above the reference line represents pedestrians who crossed when the required speed was higher than their actual speed. These pedestrians accounted for 90.3% of the 352 pedestrians plotted in Fig. 7. Given that pedestrian risk at the second half of the last lane is low, the required speed is also lowered by removing one half of the lane width from the total distance to cross. Yet, the adjusted required speed is still higher than pedestrian actual speed in 90.1% of the cases.

The mismatch between pedestrians' actual speed and the required speed reflects the potential risk of inaccurate decision making. Correlation analysis shows that although the number of conflicts was not found to increase with required speed ($r = 0.01, p = 0.772$), higher required speed was coupled with longer uncrossed road distances at the end of the clearance phase ($r = 0.59$, $p < 0.001$), as well as longer duration on the road at the red phase ($r = 0.28$, $p < 0.001$). Pedestrians were also more likely to run across the road when the required speed to cross is higher ($r = 0.27$, $p < 0.001$).

4. Discussions

The study found that pedestrians arriving during clearance phase were strongly biased towards "cross" over "wait" decision (85.2% vs. 14.8%). However, only 6.2% successfully traversed crosswalks before red-light onset, while others covered 41% of the crosswalk during red lights. For those who waited to cross, nearly half of them start crossing on red phase, but still faced lower risk as measured by the choice to run and conflicts with vehicles. Binary logistic models identified several predictors of crossing immediately after arrival, including being younger, having no distractors, being farther from waiting vehicles, and arriving at a time when the required speed to cross is lower or there are more pedestrians crossing the road. Our findings were compared with previous related studies, and their implications are discussed in this section.

4.1. *Pedestrians choices at clearance phase: biased, dynamic*

Although it is illegal to start crossing at clearance phase, pedestrians' choices were severely biased towards cross than wait. The percentage of pedestrians who started to cross immediately (85.2%) is lower than the 100% reported by Koh et al. (2014). The difference may be resulted from three differences in contexts and definitions. First, the Road Safety Act in Singapore *advises* people not to start crossing at flashing green light, while Chinese traffic regulations *forbid* pedestrians from entering crosswalk at clearance phase. Second, Koh et al.'s (2014) observation of pedestrians arriving at clearance phase does not include those arriving at last five seconds of arriving, whose rate of crossing is 66%. If this group was included, the percent of pedestrians who started immediately after arrival would have reduced. Third, Koh et al.'s (2014) observation included cyclists, who need less time to finish crossing, thus more of them may choose to cross for a given remaining time. The difference also explains why only 45% of the sample in Koh et al. (2014) could not finish timely, whereas we observed a much higher percentage of 79%.

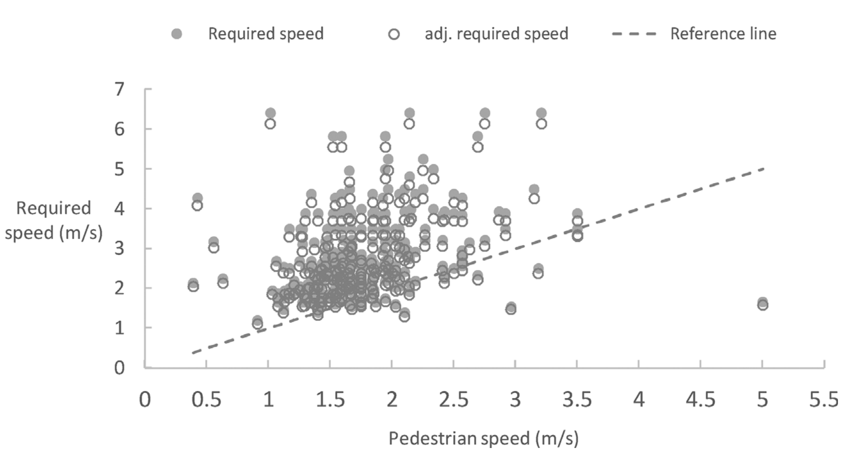

Fig. 7. Pedestrian actual speed and required speed at which they choose to cross. Adjusted required speed reduced the distance to cross by subtracting the half of the last lane on the road (i.e. Road width-0.5*Lane width).

Pedestrians also make dynamic decisions based on the changing context, instead of making a decision and sticking to it. Previous research on pedestrian violation has in general categorized pedestrians as compliers or violators in terms of whether they enter or exit the crosswalk on a red light (Brosseau et al., 2013; Schmitz, 2011). However, exiting on red phase is not a choice, but a consequence of previous choices. Pedestrian does not foresee consequences long after the present. Instead, they observe and make responsive decisions afterwards. For instance, the waited pedestrians may choose to cross on red when it seems safe to cross. The behavior of pedestrians who wanted to cross diagonally is a good manifestation of the dynamic nature in decision making. They planned to cross at the observed crosswalk at first, but stopped later at the flashing green light (perhaps due to the short remaining time). After a short hesitation, they turned direction to cross at the intersecting crosswalk of the intersection, where the signal would soon turn green. The dynamic process in decision making suggests the complexity in realistic simulation of pedestrian behaviors. It also explains why we only divided pedestrian decisions into "cross" and "wait" in the model, instead of including their choices afterwards in a multinomial logistic model, as those choices were not made at the same time.

4.2. Factors related to pedestrian decision making

Similar with previous work on pedestrian violation (Cook and Koorey, 2013; Diaz, 2002; Hao et al., 2008; Ma et al., 2015; Rosenbloom et al., 2004), older pedestrian has lower violation rate. In a survey on crossing against red light, Zhou et al. (2009) found that pedestrian age is negatively related to attitude towards violation, subjective norm, and perceived behavioral control. These traditional constructs in the theory of planned behavior may also explain the age effect in violation at clearance phase. However, since the study is only a natural observation of pedestrian behavior, and the sample size in each group were not controlled, the conclusion on age effect should be made with care.

Although previous work generally associate distractors with risks (Hatfield and Murphy, 2007; Nasar and Troyer, 2013; Neider et al., 2010), distracted pedestrians were found 4.9 times less likely to cross than undistracted ones in this study, similar to the effect observed in crossing against red lights (Hao et al., 2008). The similarity between arriving at flashing green phase and red phase is that they both require pedestrian to wait until a green light. Based on the Attention Gate Model of time estimation, distracted pedestrians will allocate some attention on secondary tasks, thus reduced their attention on timing, resulting in shorter estimation of waiting time (Block and Zakay, 1996). Therefore, distractors may reduce pedestrians' anxiousness during waiting. Moreover, crossing at illegal phase require pedestrians to cross fast and response quickly to potential risks, but having a distractor impaired these abilities. To accommodate for these limitations, pedestrians had to choose a safer but less demanding behavior.

Compared with the factors similar to predictors of other violation behaviors, we have found two factors that are specific to pedestrians' decision making at the clearance phase, but may cause risk to pedestrians. One is the required speed to cross, the other is pedestrian position relative to vehicles.

4.2.1. Required speed to cross

Koh et al. (2014) observed that number of crossing events (*all* arriving pedestrians and cyclists) increased with the proportion of time left to red man onset (remaining time/maximum time left to red light). For pedestrians arriving at the clearance phase, longer remaining time usually means longer expected waiting time (remaining time + red phase), thus it is not clear whether pedestrian made decisions based on remaining time or expected waiting time. In this study, we found insignificant effect of expected waiting time on pedestrian choices, but a related indicator "required speed" proved significant. Therefore, the phenomenon observed by Koh et al. (2014) is due to crossing difficulty indicated by required speed, rather than expected waiting time. "Required speed" is similar to "proportion of time left to red man onset" in that both aim to describe the moment of arrival without considering cycle variations across sites, but "required speed" unified pedestrians' arrival relative to the road width, rather than total pedestrian phase, making it a more specific and intuitive index of crossing difficulty.

Pedestrians are less likely to cross the road when the required speed is higher. Since higher required speed is related to higher levels of risk, pedestrians have adjusted their decisions in the right direction. However, their overall performance showed that the amount of adjustment was not enough, with 79% of the pedestrians crossed when the required speed was higher than actual speed. In fact, pedestrians crossed when the required speed was much higher than their actual crossing speed, even when extremely risky pedestrians were excluded, and the distance to traverse were shortened. While the risky decisions could be resulted from motivational factors like risky attitude, subjective norm etc., errors in information processing cannot be neglected.

A potential error in the decision making of pedestrians at clearance phase is overestimation of their crossing ability. After reviewing studies on evaluation of countdown timers, Paschalidis et al. (2016) indicated the possibility of overestimation of one's ability to cross within the remaining time to explain high number of "late finishers". In an earlier study, Wanty and Wilkie (2010) interviewed 68 pedestrians who had just finished crossing an intersection on how much time they needed to cross that intersection diagonally, and found over 80% of them underestimated the time to cross when compared with the average crossing time (Road width/Average pedestrian speed, which is 1.5 m/s in Netherland). There are also several experimental studies on pedestrian estimation of crossing time (Dommes et al., 2013; Holland and Hill, 2010; Naveteur et al., 2013; Zivotofsky et al., 2012), but all of them used "imaged road crossing" method to get estimated crossing time and their findings were not consistent with each other. Moreover, pedestrians do not necessarily imagine crossing the road to judge crossing time before actually starting to cross at flashing green phase. Therefore, it is possible that pedestrians may not have accurate judgment of their crossing ability, but strong evidences are still needed. This is important, because errors in information processing usually manifest instinctive limitations in all human beings and can be remedied by assistive system design in large scale.

4.2.2. Pedestrian position relative to vehicles at the near side of the road

Pedestrian position relative to vehicles is an index of risk from waiting vehicles that will start at the end of the clearance phase. Pedestrians were more likely to cross when they were farther from waiting vehicles at the near side of the road. Pedestrian may have made the decision based on the current state of the vehicles at the near side of the road. Previous work has observed pedestrian make "cross or wait" decisions based on gap between pedestrians and approaching vehicles (Yannis et al., 2013; Zhuang and Wu, 2013), which is closely related to distance and speed of moving vehicles. However, in the current study, decision based on this criterion is not appropriate, since the vehicles were stationary and wouldn't start until the end of the clearance phase. Given that most pedestrian would have crossed more than half of the road by that time (see Fig. 7 for pedestrian position at the end of clearance phase), only vehicles at the ending half of the road were sources of risks. For pedestrians who were originally near the waiting vehicles, the vehicles at the ending side were at the other side of the intersection. In contrast, for pedestrians who were originally far from vehicles, the vehicles at the ending side will approach from the same side of the intersection, which are close to them and pose higher risk than those approaching from the other side of the intersection.

4.3. Implications and limitations

4.3.1. Implication for targeted countermeasures and further research

The findings have several implications for practice and future research. First, young pedestrians were more likely to cross than older pedestrians, thus safety campaign and further exploration of design solutions should focus on young pedestrians. Second, the studies found pedestrians made different choices after arrival, and some were unexpected (for instance, those turning direction to cross at an intersecting crosswalk). The behavioral patterns, as well as the predictors identified are useful for simulation of real pedestrian behavior. In Lee and Lam (2008), they simply cut pedestrian choice into two types and set the criteria based on remaining time (> 6 s, cross; otherwise wait until green light). The simulation would have been closer to reality if the predictors of pedestrian choice were included. Moreover, the results from the logistic model could be integrated into the decision-making server of cognitive models like Queuing Network-Model Human Processor (Wu et al., 2008), to model pedestrian behaviors in detail. Besides the two points, our findings also recommend potential changes in traffic regulation and traffic signal design for clearance phase.

4.3.2. Rethinking about the clearance phase and signal design

There's a large percent of pedestrians violating the regulation, although instinctive responses will be educating or punishing the violators, the findings in this study lead us to rethink plausibility of the traffic regulation to have a clear cut between "cross" and "wait". First, from the pedestrians' point, it does not make sense the pedestrians arrived just one second before you can cross but you can't, even if there are several seconds left and the vehicles are waiting. Recall that pedestrians are more likely to cross if there are more pedestrians already crossing and the crossing pedestrians haven't gone far from the starting point. The effects may indicate how pedestrians position themselves along the signal cycle: they belong to the former group, not the latter one. Moreover, the duration of clearance phase is set based on the time needed to cross the road by pedestrians that walk slower than 85% of all pedestrians. The criterion is so low that it ensures safety of the slow walkers at the sacrifice of efficiency of quick walkers. If we delay the onset of flashing green, then the efficiency of quick walkers will improve, but more slow walkers will be left on red phase.

The problem here is that the signal wants to set a unified criterion for pedestrians with different speeds. Yet, a unified regulation is inevitably accompanied by compromise of safety and efficiency. Therefore, rather than setting a one-size-fits-all regulation, it is more plausible to give pedestrian the chance to judge the crossing possibility based on their own speed, and assist them to make accurate judgment. The former change has been seen in some countries. We've mentioned earlier that in Singapore, pedestrians at clearance phase were *advised* not to cross during flashing green phase (Koh et al., 2014). In Canada, if the countdown timer is present, and pedestrian can finish crossing within the remaining time, they are *not* considered as violators (Brosseau et al., 2013). The change of regulation stepped towards a more pedestrian-friendly signal system. Nevertheless, they could go further to help users to make more accurate judgment.

Currently, the only information provided is remaining time before the light turns red. The remaining time is intuitive, but that does not make it the best cue to help pedestrians. From system design approach, the traffic system should not burden the users (here, the pedestrians). However, to judge whether the remaining time is long enough to cross safely, mental processes may include estimation of road width, one's own speed, and complex computation (e.g. road width/speed) that human beings are instinctively not good at. As we observed in this study, display of remaining time resulted in 78% of the pedestrians choose to cross when the required speed is more than 7 m/s. If we directly display such a high required speed (7 m/s), it is very likely that pedestrian would realize their overestimation of crossing ability. Besides, with information like "required speed", pedestrians only need to compare it with their own speed. The task is much easier. Another way to avoid burdening pedestrians is to use color as an additional cue. For example, when the remaining time is too short for most people to cross, use flashing red or red as the final warning of stopping crossing. The following Fig. 8 shows an illustration of the proposed signal design for clearance phase.

In the proposed design, when the required speed is within the 15^{th} and 85^{th} percentile of pedestrian speed, the signal light display assistive information such as required speed. Each pedestrian makes a decision by comparing the feedback and one's own speed. For some quick pedestrians, the comparison leads to a "cross" decision, while for slow pedestrians, the comparison may lead to "wait" decision. At higher required speed, a flashing red light warns all pedestrians from entering crosswalk. Theoretically, the proposed design had higher efficiency without harming safety of slow walkers. Besides, the design extended the range within which quick walkers can cross. That is, fewer pedestrians will be required to wait, and those waited also need to wait shorter time than that in the original design, so the number of pedestrians initially choosing to wait but later starting to cross on red light may also decrease.

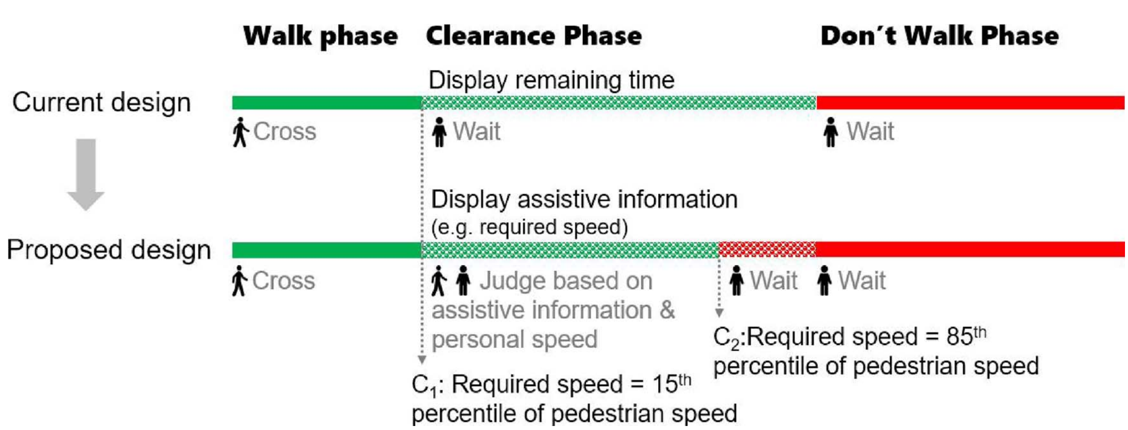

Fig. 8. Information display and ideal pedestrian action in the current and proposed design of signal lights at the clearance phase. C1, C2 are time points stated in the form of required speed, which equals to 15^{th} and 85^{th} percentile of pedestrian speed respectively.

4.3.3. Limitations

The study has several limitations inherited from the method adopted. First, as the first step towards pedestrians' decision making at clearance phase, only observational method was used to collect data. However, decision making, as a mental process, although can be uncovered partly through overt behavior, is different with behavior. Further experiments and surveys are needed to discriminate potential errors in information processing and risk perception, attitude etc., to get a systematic understanding of the mechanisms underlying pedestrian choices at clearance phase. Second, we assumed that pedestrians made crossing decisions after arrival, and use the contextual factors at that moment to predict pedestrian decision. However, it is unknown exactly when pedestrian made the decision to cross or wait. The flashing green light can be seen at a distance. Pedestrians may have made the decision several meters before arrival at the crosswalk. A similar simplification regards the risk from vehicles. Pedestrians may perceive risk from turning vehicles, and may predict vehicle behaviors if they crossed, yet we only included pedestrian position at arrival to represent the risk from vehicles. Further study can start to observe pedestrian behavior at earlier phase or combine survey with observation to determine pedestrian "decision point" and their perception of risk from vehicles at that time. Finally, pedestrians' behavior in this study were observed at sites with more than six lanes at non-peak hours. It is unknown whether pedestrian decision making is influenced by increased number of both vehicles and pedestrians in peak hour. Whether pedestrians will become riskier at narrower roads (two-lane, four-lane etc.) also need to be tested in future works.

5. Conclusions

Pedestrian arriving at clearance phase generally choose to cross instead of waiting, even if the remaining time is short. However, the pedestrians choosing to wait usually can't finish crossing before red-light onset. The waited pedestrians make dynamic decisions based on the context, thus may choose to cross on red light, green light, or temporarily change destinations, but they still face lower risks as measured by running behavior and conflicts with vehicles. Pedestrian are more likely to cross when they are younger, have no secondary tasks, and are farther from stopped vehicles at the near side of the road. Although they do consider the remaining time displayed on countdown timers, it is not the expected waiting time but the required speed to cross before red light that influences the decision to cross or not. The high percentage of violation at clearance phase, even when the probability to finish before red light is rather small, indicates potential errors in estimation of one's own crossing ability.

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