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Impacts of visual and cognitive distractions and time pressure on pedestrian crossing behaviour: A simulator study

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ABSTRACT

Distractions have been recognised as one important factor associated with pedestrian injuries, as the increasing use of cell phones and personal devices. However, the situation is less clear regarding the differences in the effects of visual-manual and auditory-cognitive distractions. Here, we investigated distracted pedestrians in a one-lane road with continuous traffic using an immersive CAVE-based simulator. Sixty participants were recruited to complete a crossing task and perform one of two distractions, a visual-manual task and an auditory-cognitive task. Moreover, normal and time pressure crossing conditions were included as a baseline and comparison. For the first time, this study directly compared the impacts of visual-manual, auditory-cognitive distractions, and time pressure on pedestrian crossing behaviour and safety in a controlled environment. The results indicated that although pedestrian safety was compromised under both types of distraction, the effects of the applied distractions were different. When engaged in the visual-manual distraction, participants crossed the road slowly, but there was no significant difference in gap acceptance or initiation time compared to baseline. In contrast, participants walked slowly, crossed earlier, and accepted smaller gaps when performing the auditory-cognitive distraction. This has interesting parallels to existing findings on how these two types of distractions affect driver performance. Moreover, the effects of the visual-manual distraction were found to be dynamic, as these effects were affected by the gap size. Finally, compared to baseline, time pressure resulted in participants accepting smaller time gaps with shorter initiation times and crossing durations, leading to an increase in unsafe decisions and a decrease in near-collisions. These results provide new evidence that two types of distraction and time pressure impair pedestrian safety, but in different ways. Our findings may provide insights for further studies involving pedestrians with different distraction components.

1. Introduction

Pedestrians are generally regarded as the most vulnerable road users due to a lack of protective equipment and a slower pace of movement than other road users. Their safety issues have prompted extensive research and concern from academics and policymakers (El Hamdani et al., 2020). Every year, >300,000 pedestrians are killed worldwide, which accounts for 22 % of all traffic fatalities (World Health Organization, 2018). In particular, pedestrian accidents are common at uncontrolled intersections, as there are no traffic signals to coordinate the behaviour of all road users adequately, and vehicles are not forced to give way to pedestrians at uncontrolled intersections. Hence, crossing at such locations is extremely complex and affected by multiple factors, such as traffic characteristics (Ackermann et al., 2019), road environments (Zhao et al., 2019), and the presence of various distractions (Ropaka et al., 2020). In the context of the increasing use of cell and personal devices, distractions have been recognised as one important contributor to pedestrian injuries (Jiang et al., 2018). Although the number of accidents involving distracted pedestrians is relatively less than those caused by drivers (Campisi et al., 2022), distraction is dangerous because it can significantly compromise pedestrian safety by reducing their looks to the left and right, walking speed, reaction time, and more (O'Dell et al., 2022).

To date, numerous studies (e.g., Jiang et al., 2018; Lin and Huang,

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2017; Neider et al., 2011) have been conducted on distracted pedestrians in road crossing scenarios, whereas there is limited information on the effects of distractions with different components and their safety impacts. Moreover, as personal mobile devices advance in functionality, there is a growing request to reveal the mechanisms of influence of different distraction components to help comprehend various complex forms of distraction (Chen and Pai, 2018b). Specifically, distraction refers to engagement in activities not critical for a safe main task (e.g., road-crossing), such as scanning digital devices, texting, talking on a cell phone, or listening to music (Walker et al., 2012). Distractions are typically categorised into visual, manual, and cognitive based on their components (Engström et al., 2017). The two former distractions involve perceptual or motor processes (e.g., texting messages, web surfing, or gaming). In contrast, cognitive distraction generally refers to the nonvisual and nonmanual tasks that take attentional resources away from the main task (e.g., pedestrians listen to music using a headset, where their vision and movement are not impeded) (Chen and Pai, 2018a; Engström et al., 2017; Walker et al., 2012). Existing studies indicated that the cognitive processes of visual and manual distractions affect pedestrians' ability to allocate attentional resources to road situations (Haga and Matsuyama, 2018). For instance, a field test by Jiang et al. (2018) compared the effects of texting, cell phone conversation, and music listening distractions on pedestrian crossing behaviour and found that texting on a cell phone had the greatest impact because it occupied the most visual attention of pedestrians. Another study from Chen and Pai 2018b indicated that pedestrians playing cell phone games had more unsafe crossing behaviours, such as fewer head-turning frequencies or not looking at traffic before crossing. From a general perspective, such pattern changes caused by distractions are referred to as inattentional blindness, where a human fails to notice an unexpected object while engaged in another task or object (Hyman et al., 2009; Hyman et al., 2014). Current research results share a general consensus that visual and manual distractions impair most aspects of road crossings. However, existing studies offer different opinions in the case of distraction tasks that require pure listening. Some studies indicated that these tasks could slow down pedestrian crossing initiation time (Jiang et al., 2018; Liu et al., 2021), making pedestrians more likely to be hit (Schwebel et al., 2012). On the other hand, evidence from several studies indicated that a listening distraction task did not significantly affect pedestrian crossing behaviour (Neider et al., 2011; Simmons et al., 2020) and sometimes even made them more cautious (Nasar et al., 2008; Walker et al., 2012). Therefore, from the above discussion, there is currently little understanding of the difference between auditory-cognitive distractions (from here on, we will refer to such distractions, including listening to music, as an auditory-cognitive distractions (Siegmann et al., 2017) and other types of distractions, such as those involving visual and manual resources, on pedestrian crossing behaviour and safety.

In addition to the differences between distractions, recent studies have explored the potential pedestrian crossing performance metrics or characteristics associated with distractions, such as walking speed, crossing initiation time, age, gender, and more. Specifically, it has been shown that pedestrians who use a cell phone while crossing the road have a reduced walking speed (Campisi et al., 2022). Although gender may not affect the likelihood of being distracted, males are more likely to be involved in high distraction levels (Larue and Watling, 2022). In addition, age is also a significant factor affecting distraction behaviour, as teenagers are more likely to play with their cell phones while walking (Gitelman et al., 2019; Larue and Watling, 2022). Apart from the factors mentioned above, existing distraction studies rarely shed light on some critical performance metrics related to pedestrian crossing safety (e.g., crossing gap acceptance, time to arrival (TTA) and post encroachment time (PET)). As pedestrians make crossing decisions by judging the gaps between two consecutive vehicles, gap acceptance is a critical performance metric for identifying and quantifying pedestrian crossing behaviour (Oxley et al., 2005; Petzoldt, 2014). Without studying gap acceptance and how distraction affects it, it is hard to clearly understand how pedestrians weigh their safety and efficiency and whether they adopt certain decision strategies to deal with distractions. Moreover, to the best of our knowledge, no studies have explored the relationship between distractions and TTA. Therefore, less is known about how pedestrians adjust their crossing behaviour in different TTA conditions while distracted by secondary tasks. Furthermore, the PET has been applied as a strong indicator of pedestrian crossing safety (Avinash et al., 2019; Hong et al., 2022). However, few studies have investigated how distractions affect pedestrian PET.

It is important to note that the observation approaches may also affect the results of distraction studies. A case in point, as mentioned in above section, is that naturalistic observations generally indicated that pedestrians distracted by personal music devices could initiate crossing later and look less at traffic than non-distracted pedestrians (Liu et al., 2021; Pešić et al., 2016; Thompson et al., 2013), resulting in unsafe crossing behaviour. However, several controlled field and simulated tests showed that the use of personal music devices might not have a significant influence on pedestrian crossing behaviour (Neider et al., 2010; Walker et al., 2012). Although naturalistic observations typically reflect the real behaviour of pedestrians, the lack of effective control of variables can make it difficult to draw precise conclusions (e.g., pedestrians selecting music in the device includes visual-manual distractive components, and in a naturalistic setting, it may be difficult to separate such distractions from purely auditory-cognitive music distractions). Accordingly, recent studies have focused on formulating hypotheses about distracted behaviour that occurs in the real world and experimentally testing these ideas in more controlled environments. Simulated experiments are one of the most applied approaches, although it has several possible limitations that need to be further improved. First, some studies applied semi-immersive simulated environments to evaluate pedestrian crossing behaviour, such as screens with fixed visual angles and walking on a treadmill (Lin and Huang, 2017; Neider et al., 2011). Those overly abstract simulated environments may not be able to reproduce the pedestrian crossing behaviour in real traffic. In addition, the head-mounted display (HMD) can obstruct the pedestrians' view making it difficult to interact with real distracting tasks (e.g., using a cell phone). Researchers attempted to add virtual distractions in the simulated environment to solve this problem (Schneider et al., 2019; Sobhani and Farooq, 2018). However, given the essential differences between virtual and real distraction tasks, such manipulations may introduce new and unknown variables to the experiment.

Finally, similar to distractions, time pressure has been regarded as one of the important factors associated with road-crossing safety, which can reduce the quality of decisions (Cœugnet et al., 2019) and increase the propensity to take risks (Madan et al., 2015). It has also been shown that participants with time pressures have high crossing speeds (Kalantarov et al., 2018). The literature, therefore, suggests that in the context of street crossing under time pressure, participants usually prioritise walking progress over safety, which leads to more dangerous behaviour (Cœugnet et al., 2019). Moreover, there exists a mixed situation with pedestrians distracted by their mobile phones or under time pressure to reach their destinations in the real traffic. Concerning the safety impacts of the time pressure mentioned above, it is interesting to know how its effects on pedestrians differ from distractions. A controlled study that includes both factors is needed. However, this kind of research has not been previously done.

In light of the above discussion, the research aims of this study were therefore identified as follows:(i) Investigating the difference between visual-manual and auditory-cognitive distractions in a highly immersive and controlled simulated environment. (ii) Comparing the effects of time pressure and distractions on pedestrian crossing behaviour. (iii) Appling detailed metrics to evaluate the impacts of these secondary tasks on pedestrian crossing behaviour and safety.

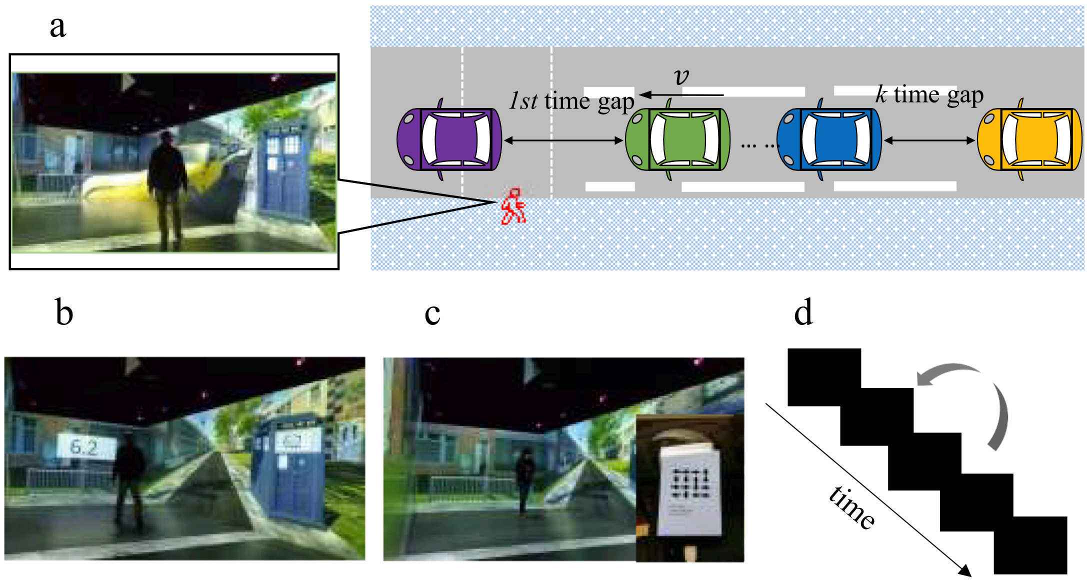

Fig. 1. Experimental scenario and apparatus. (a) Road crossing scenario in the CAVE-based pedestrian simulator. A police box to the right of pedestrians was included in the simulated environment to ensure that the road would not be visible from the participant's starting position. (b) Timer task. (c) Arrows task. (d) *N*-back task.

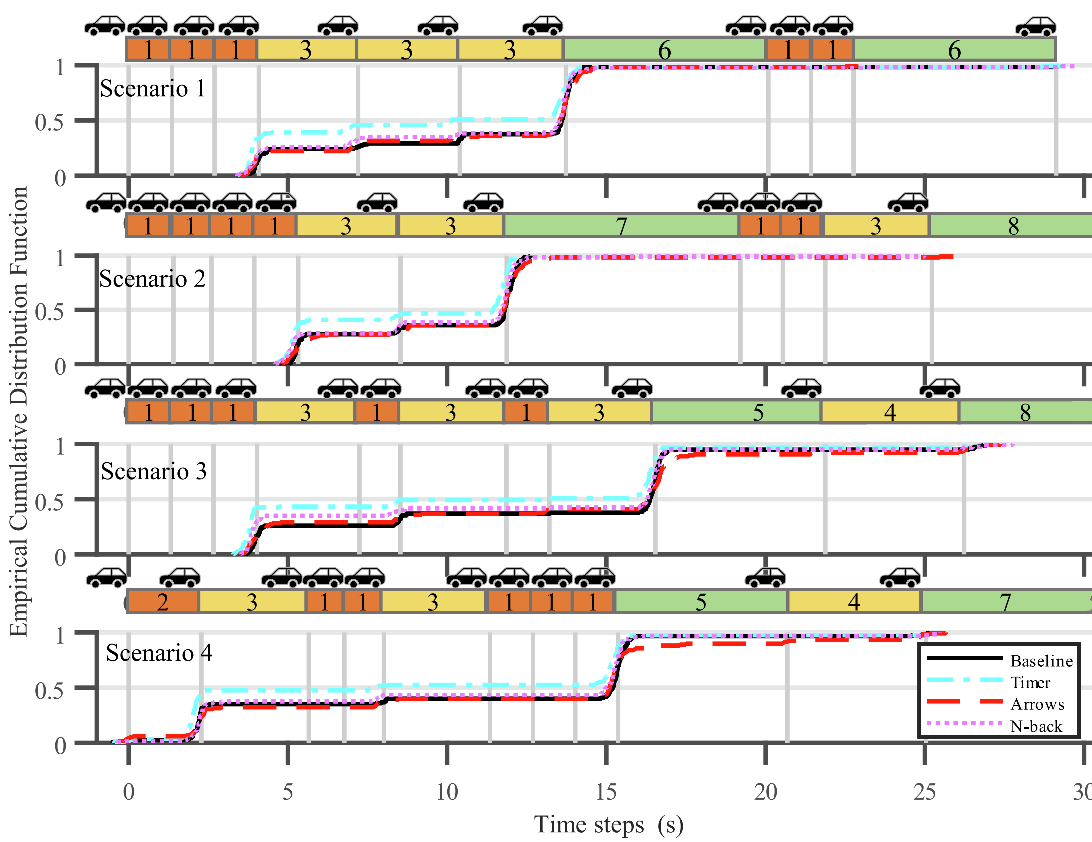

Fig. 2. Empirical cumulative distribution functions of participants' crossings with different secondary tasks in four traffic scenarios. The several boxes above the curve plot denote the time gap sequence for the corresponding traffic scenario. The numbers in the boxes refer to the gap size in seconds. The vertical grey lines indicate the times when the rear end of a vehicle passed the participant's position.

2. Methodology

2.1. Experiment

Using a CAVE-based pedestrian simulator, an experiment was designed to investigate pedestrian road crossings with and without secondary tasks. The simulator did not have the field of view or movement limitations of past controlled studies and allowed pedestrians to interact directly with a real handheld device. Three secondary tasks, namely, a time pressure task, a visual-manual task, an auditory-cognitive task, and a baseline task, were applied to compare the effects between the different distractions and the effects between them and time pressure in this study. A range of pedestrian crossing performance metrics were investigated, including time gap, gap acceptance, initiation time, walking speed, and PET. The experiment was approved by the University of Leeds ethics committee (reference number: LTTRAN-117).

Experimental design. Three secondary tasks, i.e., time pressure, visual-manual, and auditory-cognitive tasks, were named as Timer, Arrows, and *N*-back. In the Timer task, the participants were informed: "*During these scenarios, please cross the road as quickly as possible, but maintain a safe behaviour and do not run…*". To produce a time pressure effect, two timers were shown prominently on the VR screen to inform participants of the time already spent. Participants could thus adjust their behaviour based on informed timing information (Fig. 1b). The Arrows task has been commonly used as a visual-manual secondary task in driving studies (Engström et al., 2005; Jamson and Merat, 2005), and was adapted here to the pedestrian context. As shown in Fig. 1c, a 4 × 4 grid of arrows was shown on the cell phone screen, and participants were required to find and select the single upward pointing arrow, as quickly as possible, by pressing on the screen, while also maintaining a safe crossing behaviour. Each response prompted a new 4 × 4 grid of arrows. To motivate participants to focus on the task, the phone vibrated after 4 s if they did not respond to the task, and a new set of arrows was displayed. The Arrows task started at the beginning of the trial and ended when participants returned to the starting point. The third task was the auditory version of the *N*-back task, used in multiple research areas to test working memory capacity (Mehler et al., 2011) (Fig. 1d). Specifically, an audio headset worn by participants played a series of numbers, and participants were required to say the number played just before the most recently played number. The *N*-back task started at the beginning of the trial and ended when participants returned to the starting point. Finally, a baseline condition with just the road crossing task, without any of the secondary tasks, was also included.

Regarding the design of the traffic environment, the simulated road and pavement widths were 3.5 m and 1.85 m. Four traffic flow scenarios with different time gap sequences were implemented (Fig. 2), providing various opportunities for participants to cross. For example, in the first scenario, the time gap order was: 1, 1, 1, 3, 3, 3, 6, 1, 1, 6 s. According to our design, most participants would reject the first three one-second gaps. Then, some of them accepted one of the following three three-second gaps. Finally, all reminding participants crossed the road during the six-second gap. Thus, the one-second and two-second time gaps between vehicles were considered dangerous crossing opportunities, that few pedestrians would accept. For the three-second and four-second gaps, decisions were expected to differ significantly between participants, due to their heterogeneity (e.g., age and gender). The time gaps longer than four seconds were included as safe gaps, where most participants would be expected to cross. Therefore, we expected pedestrians to accept different time gaps in terms of their preferences and observed pedestrian crossing performance as a function of time gap size. Moreover, different traffic flow scenarios could avoid the influence of learning effects, as pedestrians had to continually adjust their crossing decisions in terms of traffic. In addition, the use of traffic flow made the crossing task more realistic and immersive. In each scenario, the traffic flow consisted of a range of compact, midsize, van and SUV types of vehicles, ranging in width from 1.67 m to 1.86 m, all driven at 48.3 km/h (30 mph), for an average traffic volume of 22 vehicles per minute. The time duration of the scenarios was between 43 and 62 s.

Procedure. Four tasks (i.e., the Timer, Arrows, *N*-back, and baseline) made up the four experimental blocks separately. Before each block, there was an approximate five-minute practice session to familiarise participants with the task. To counterbalance the order of experimental blocks, participants were spread as evenly as possible across all twenty-four possible orderings of the four experimental blocks. Each participant was randomly confronted with one of the twenty-four possible orderings. For each block, four traffic scenarios were presented in random order and repeated twice so that $4 \times 4 \times 2 = 32$ trials of data were collected for each participant, resulting in a total of $32 \times 60 = 1920$ trials. The whole experiment for each participant took approximately 60 min.

At the beginning of each trial, participants stood on the pavement and behind a police box, positioned there to occlude the participants' view of the road before the start of each trial (Fig. 1b). Once participants felt prepared to start a new trial, they stepped up to the kerb, and (unbeknownst to them) this body movement triggered the start of the traffic scenario. From this position, participants could see the traffic as they stood at the edge of the pavement and prepared to cross the road. One trial was completed after walking to the other side of the road and back to the starting point. In the Arrows and *N*-back blocks, the participants were required to start the secondary task before stepping out from behind the police box in the experiment, to ensure they crossed the road while engaging in distracting behaviour.

Apparatus. As shown in Fig. 1, a single-lane road scenario with vehicles approaching from the right, was generated in a highly immersive CAVE-based pedestrian simulator with 9 × 4 m walking space. Eight 4 K projectors behind glass panels were used to project the scene at 120 Hz. The simulated environment was controlled by eight computers and ten cameras, which tracked the head position through tracking glasses on the participant's head and corrected the projected image to the participant's perspective. The Unity3D platform was used to establish the virtual environment and control the simulation loop. Internal code automatically recorded the positions and velocities of vehicles and participants at 120 Hz (Sadraei et al., 2020).

Participants. Sixty participants, 30 males and 30 females aged 18–68 (M = 37.67, S.D. = 12.72) were recruited via the University of Leeds Driving Simulator recruitment pool. They all declared that they did not have serious mobility problems or medical conditions such as epilepsy. Also, we required them to have either normal or corrected-to-normal vision to make sure they could accurately perceive the traffic scenario. Before participation, each participant provided written informed consent to take part in the study. After the study, £10 was paid to them as compensation for their time.

2.2. Data reduction

Dependent variables. Four dependent variables were defined as pedestrian crossing behaviour indicators: crossing gap acceptance, crossing initiation time, crossing duration, and PET:

(i) Participants' gap acceptance data have a binary structure, representing whether participants crossed the street or not in each time gap in the sequence of vehicles.

(ii) Crossing initiation time refers to the period between when the rear end of the previous vehicle passed the participant's position and when the participant began crossing the road. To calculate the initiation time, the crossing onset time point is defined as the time when the participant walked across the edge of the pavement and stepped into the traffic lane. The detailed criteria include (a) the longitudinal position of the participant should exceed the edge of the pavement; (b) change in longitudinal position in one 120 Hz simulation time step should be bigger than 0.003 m; (c) one second after the first two conditions are met, the participant must have walked one meter from the edge of the pavement. Note that small negative crossing initiation times are possible, if the participants entered the road slightly before the nearest vehicle had completely passed them.

(iii) Crossing duration represents the time between when the participants started crossing and when they arrived at the opposite pavement.

(iv) PET was applied as the safety performance indicator, representing the time difference between the accepted time gap (i.e., remaining time gap at time of crossing initiation) and crossing duration. It has been widely applied to quantitatively describe the risks of pedestrian crossing decisions (Avinash et al., 2019; Lobjois and Cavallo,

Table 1
Results of the Likelihood ratio test for the proposed GLMMs.

Model	df	AIC	LL	LRStat	p	Null hypothesis
Basic model	9	2247	−1114	–	–	Rejected
Refined model	10	2241	−1110	7.38	0.01	

2007). In addition, three performance levels were identified to categorise crossing decisions in terms of the PET: 'near-collision' when the PET was<0; 'unsafe' decisions when the PET was between 0 and 1.5 s; 'safe' decisions when the PET was bigger than 1.5 s (Lobjois and Cavallo, 2007). The term, 'near-collision', represents that the accepted time gap is not enough for pedestrians to arrive at the opposite pavement, suggesting a potential collision risk. While the 'unsafe' indicates that the time margin for pedestrian crossings is too small to allow any hesitation.

Independent variables. In this study, several factors in the traffic flow that may influence pedestrian crossing decisions were considered and directly controlled and extracted by researchers, including time gap size, secondary tasks, and traffic flow characteristics:

(i) Time gap size (numerical variable): This is the temporal distance between two consecutive vehicles. As shown in Fig. 2, a variety of time gaps ranging from 1 s to 8 s were used in this study.

(ii) Secondary tasks (categorical variable). Categorical variables were used to represent these tasks (i.e., Timer, Arrows, *N*-back, and normal crossing), and the normal crossing task was set as the baseline.

(iii) Traffic flow characteristics (categorical variables). As pedestrian decisions were made in the context of continuous traffic, the effects of traffic flow should be decoupled to avoid misinterpreting it as the effects of secondary tasks. Prior studies have shown that pedestrian crossing decisions can be affected by traffic flow (waiting time is the frequently used traffic flow related factor), suggesting that pedestrians tend to accept smaller gaps and exposure to more risk as waiting time increases (Tiwari et al., 2007; Zhao et al., 2019). However, Lobjois et al. (2013) have demonstrated that pedestrians who miss a crossing opportunity do not take more risks and accept a shorter gap at the next opportunity. The flow of vehicles might help pedestrians compare gaps between each two consecutive vehicles and better attune their crossing decisions. Moreover, waiting time itself does not directly depict traffic flow characteristics, such as the time gap size and traffic flow density. Therefore, according to Lobjois et al. (2013) and our empirical observation (Fig. 2), we made the following assumptions for crossing decisions in the traffic flow: (i) Pedestrians are unwilling to accept the current gap equal to or smaller than the maximum gap they previously rejected, represented by T_{pre}. For example, if pedestrians reject a three-second gap, they would be more likely to reject the same or a smaller one upstream of traffic. (ii) If pedestrians find the next gap is bigger than the current gap, they prefer to wait for the next gap rather than accept the current one, represented by T_{follow}.

2.3. Statistical analysis

For the analysis of the repeatedly measured data from subjects, population-averaged (PA) regression models violate the independence assumption (Hu et al., 1998). Therefore, mixed-effects regression models (ME), also called hierarchical models, allowing heterogeneity of individuals or groups to be retained, were applied here.

Eq. (1) shows a generalised linear mixed effects model (GLMM) for predicting the effects of independent variables on a binary response (i.e. crossing gap acceptance) (Gelman and Hill, 2006).

$$
\begin{aligned}
&logit\{\Pr(y_{i[j]} = \text{accept})\} = \beta_0 + \beta_1 x_{1,i} + \beta_2 x_{2,i} + \beta_3 x_{3,i} + u_{1,i[j]} z_i + u_{0,i[j]},\ \text{for} i = 1, \cdots, n, \\
&u_{1,[j]} = a_1 + b_1 u_{i[j]} + \tau_{1,j},\ \text{for} j = 1, \cdots, J, \\
&u_{0,[j]} = a_2 + \tau_{2,j}, \text{for} j = 1, \cdots, J,
\end{aligned} \tag{1}
$$

where $\Pr(y_{i[j]} = \text{accept})$ represents the probability that the jth participant's gap acceptance. $x_{1,i}$, $x_{2,i}$ and $x_{3,i}$ are independent variables (e.g., time gap, secondary task and traffic flow characteristics) of the ith trial, and their corresponding coefficients are β_1, β_2 and β_0. These coefficients are known as fixed effects and do not vary across participants. z_i is the independent variables for random effects (i.e., time gap), and $u_{1,i[j]}$ and $u_{0,i[j]}$ are coefficients with random effects of ith trial data, belonging to the jth participant. Each participant's $u_{1,[j]}$ and $u_{0,[j]}$ are assumed to be independently normally distributed with error terms $\tau_{1,j}$ and $\tau_{2,j}$. In other words, the coefficients with fixed effects are modelled based on the average population and do not vary across pedestrians. By contrast, the random coefficients are modelled using the subject-specific data to retain unobserved heterogeneity between participants.

For the non-binary, numerical dependent variables (i.e., crossing initiation time, crossing duration, and PET), a linear mixed effects model (LMM) was applied to estimate the effects of independent variables on a continuous response. The model is given by:

$$
y_{i[j]} = \beta_0 + \beta_1 x_{1,i} + \beta_2 x_{2,i} + \beta_3 x_{3,i} + u_{1,i[j]} z_i + u_{0,i[j]} \tag{2}
$$

Similar to the GLMM model, the LMMs in the study also considered the fixed effects and participants' random effects on the time gap and intercept. The MATLAB function 'fitglme' was used to estimate coefficients of all ME models through the maximum pseudo-likelihood method (MATLAB, 2021).

As described in Section 2.2, this study proposes two novel traffic flow characteristics (i.e., T_{pre} and T_{follow}) to analyse pedestrian crossing behaviour in traffic. To validate if these factors significantly improve the model, the refined models (Eq. (1) and Eq. (2)) are compared to the basic models (similar to Eq. (1) and Eq. (2), but without traffic flow characteristics) through a likelihood ratio (LR) test. In brief, the equation of the LR test can be defined as:

$$
LR = -2(LL^R - LL^U) \tag{3}
$$

where LL^R denotes the log-likelihood of the constrained model (basic model), and LL^U refers to log-likelihood of the unconstrained model (refined model). If the test rejects the null hypothesis (i.e., the performance of the two models is equal), then the refined model performs better than the basic model at a selected significance level. Therefore, the refined model will be applied. Otherwise, if both models have the same performance, the basic model will be performed to analyse the data.

3. Results

In Section 3.1, we first present the results of the GLMM on pedestrian gap acceptance data. In Section 3.2, the impacts of secondary tasks on crossing initiation time are analysed using LMM. Finally, the impact of each task on crossing duration and PET is presented in Sections 3.3 and 3.4.

3.1. Crossing gap acceptance

The cumulative distributions of participants' crossings are shown in Fig. 2. For detailed gap acceptances and rejections for each secondary task and traffic scenario, please see Table A1. Since the four-second gap always occurred after a larger five-second time gap in the experiment (Fig. 2), almost no participants accepted the four-second time gap (Table A1). We thus omitted the four-second time gap from all analyses of results.

First, the results of the likelihood ratio (LR) test on refined and basic GLMMs are presented in Table 1. The null hypothesis is rejected at a 0.01 significance level, indicating that the refined model's performance was significantly better than the basic model. Therefore, the GLMM with traffic flow characteristics was applied to the gap acceptance data.

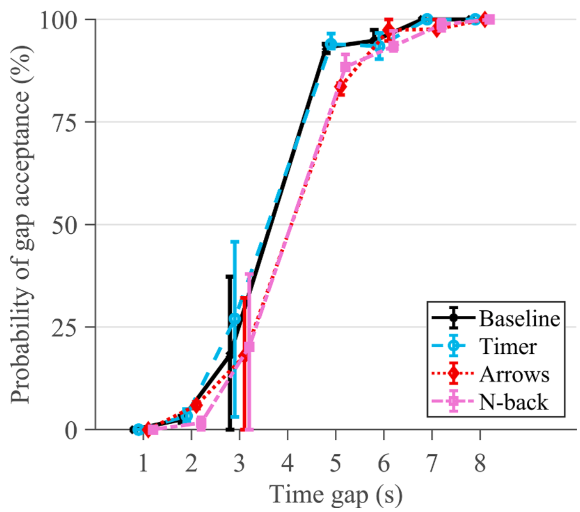

Fig. 3. Means and 95 percentiles (error bars) of crossing gap acceptance for each time gap and secondary task.

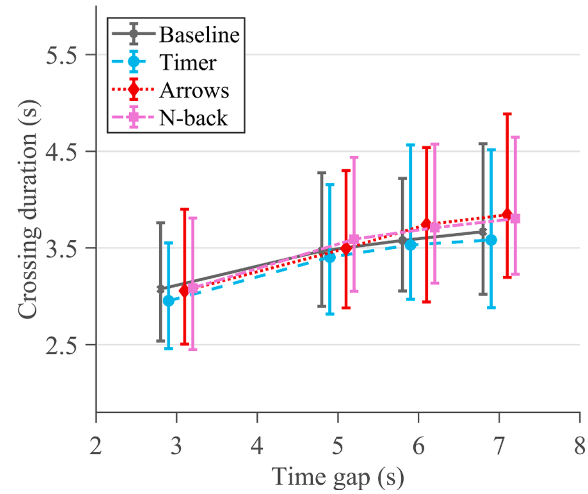

Fig. 5. Means and 95 percentiles (error bars) of crossing duration for each task and time gap.

Table 2
Crossing gap acceptance for T_{pre} and time gaps. The term ' Yes ' indicates that participant has previously rejected a bigger or equal gap in the same scenario; otherwise, it is indicated by ' No'.

T_{pre}	Probability of gap acceptance (%) for time gaps (s)	
	3	6
Yes	9.27	33.33
No	32.03	96.82

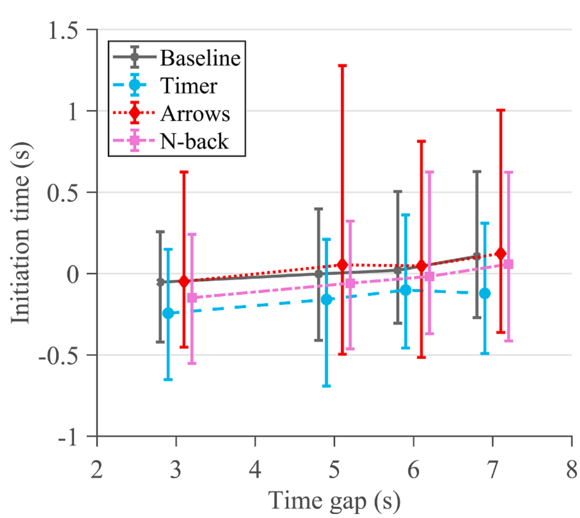

Fig. 4. Means and 95 percentiles (error bars) of initiation time for each task and time gap.

The probability of gap acceptance is plotted as a function of the time gap and secondary task in Fig. 3. Specifically, the GLMM indicated that the gap acceptance increased with the time gap (Coef. $= 5.01$, z $=$ 16.53, $p < 0.001$). A significant main effect of the Timer task was found, whereby participants accepted smaller gaps under time pressure (Coef. $= 1.51$, z $= 8.70$, $p < 0.001$). The *N*-back task also significantly affected participants, who chose smaller traffic gaps (Coef. $= 0.41$, z $=$ 2.55, $p < 0.05$). No significant main effect of the Arrows task was found. The pairwise comparison showed that the participants' gap acceptance behaviour was significantly different in Arrows task than in the *N*-back task (Contrast $= -0.55$, $p < 0.01$). Moreover, there was a significant interaction between the time gap and Arrows (Coef. $=$ -1.07, z $= -4.59$, $p < 0.001$). In other words, the effect of time gap on gap acceptance was different between Arrows and baseline. Interestingly, only participants in the Arrows task accepted the four-second gap (Table A1). As shown in Fig. 2, the four-second gap always occurred after a larger five-second time gap. The phenomenon, therefore, showed that some participants under the visual-manual distraction rejected a bigger gap, but accepted a smaller gap upstream in the traffic flow. Finally, a significant main effect of T_{pre} was found (Coef. $= -0.32$, $p < 0.05$). As shown in Table 2, participants had a reduced tendency to accept 3 s and 6 s time gaps if they had previously rejected an equal or larger gap. However, T_{follow} did not have a significant influence.

3.2. Crossing initiation time

Fig. 4 shows the mean and 95 percentiles of initiation time for each secondary task and time gap. For detailed descriptive statistics of initiation time, please refer to Table A2. The LR test was applied to the LMM, indicating that the two models performed equally. Thus, the basic LMM model was used for the initiation time data. The effects of time gap, Timer, and *N*-back tasks were significant. In particular, initiation time increased with time gap (Coef. $= 0.04$, z $= 6.26$, $p < 0.001$) for all tasks. Compared to the baseline, participants started crossing quicker in the Timer (Coef. $= -0.18$, z $= -12.38$, $p < 0.001$) and *N*-back tasks (Coef. $= -0.07$, z $= -4.79$, $p < 0.001$). However, the Arrows task did not significantly affect participant initiation time (Coef. $= 0.02$, z $=$ 1.69, $p = 0.09$). The pairwise comparison indicated that the influence of the Arrows on initiation time was significantly different from the *N*-back (Contrast $= 0.08$, $p < 0.001$).

3.3. Crossing duration

Since the effects of traffic flow characteristics on crossing duration were not significant, a basic LMM was applied, which revealed signifi-

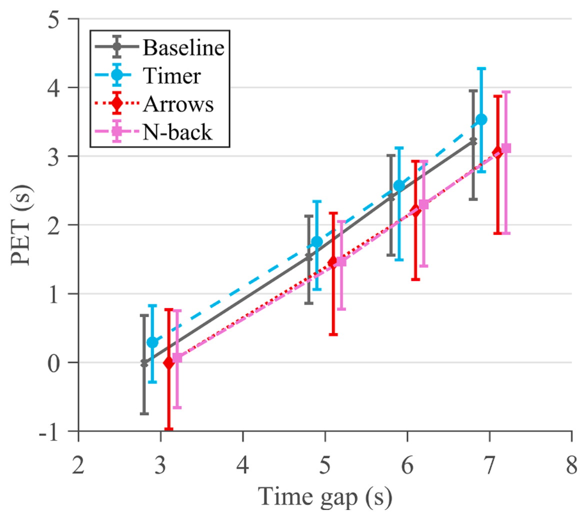

Fig. 6. Means and 95 percentiles (error bars) of PET for each task and time gap.

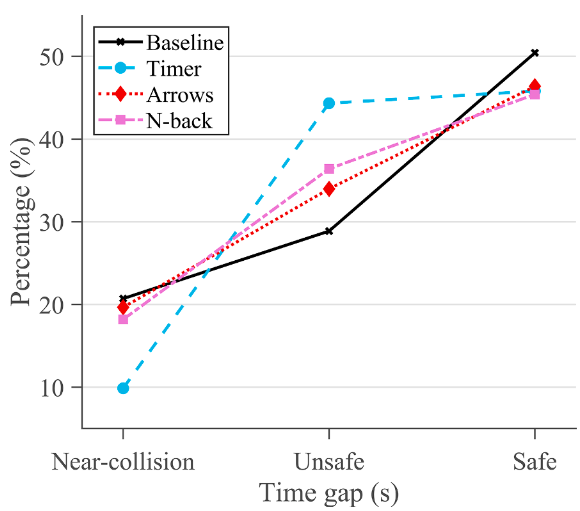

Fig. 7. Percentages of decision categories for each task.

cant main effects of the time gap, Arrows, *N*-back and Timer, as shown in Fig. 5. In particular, crossing duration under all tasks increased with time gap (Coef. = 0.14, z = 17.24, $p < 0.001$), showing a tendency for participants to cross more slowly as traffic gaps increased. In the Timer task, participants had a smaller crossing duration than in the baseline (Coef. = −0.10, z = −6.82, $p < 0.001$). A main effect of the Arrows task indicated that participants under the visual-manual distraction had a longer crossing duration than in the baselines (Coef. = 0.06, z = 4.06, $p < 0.001$). A similar main effect (Coef. = 0.07, z = 4.93, $p < 0.001$) was found in the *N*-back task. The interaction between the Arrows task and time gap showed that the bigger the time gap, the more the crossing duration increased compared to baseline (Coef. = 0.03, z = 3.23 $p < 0.001$). The pairwise comparison revealed no significant difference between the *N*-back and Arrows task. For detailed descriptive statistics of crossing duration, please refer to Table A2.

3.4. Post encroachment time

A basic LMM was applied on PETs, as shown in Fig. 6. Participants' PETs significantly increased with time gap (Coef. = 0.82, z = 81.56, $p < 0.001$). In the Timer task, participants had bigger PETs than in the baseline (Coef. = 0.28, z = 14.78, $p < 0.001$). The Arrows task had significantly negative effects on pedestrians' safety (Coef. = -0.09, z = −4.51, $p < 0.001$). By contrast, no significant effect of the *N*-back task was found. Further, there was an interaction indicating that the PETs of the participants in the Arrows (Coef. = −0.04, z = −3.45, p =0.001) and *N*-back (Coef. = −0.04, z = −2.92, $p = 0.003$) tasks did not increase as strongly with increasing time gaps as in the baseline. For detailed descriptive statistics of PETs, please refer Table A2.

The above PET analysis shows the average level of safety of participants at each time gap. However, since the secondary tasks also affected participant gap acceptance, the PET analysis alone does not fully describe the safety implications. Accordingly, a decision category analysis was conducted based on participant crossing decisions and PETs. First, each participant's crossing decision was grouped into three levels (i.e., near-collision, unsafe, and safe) in terms of the definition in Section 2.2. To determine the proportion of each decision category, the frequency of the decision category was divided by the number of trials with each secondary task. In other words, this analysis treats each full trial in the experiment as one measurement, where the obtained data point is the safety of the crossing that the participant eventually made in that trial, which thus depends both on which gap the participant chooses to cross in, as well as their crossing performance in that gap. The detailed results are summarised in Table A3.

A multinomial logit regression was applied to these crossing outcome data, with secondary tasks as independent variables. As the results show in Fig. 7, whereas fewer participants made 'near-collision' crossing decisions (i.e., 9.9 % < 20.7 %) under time pressure (Coef. = −0.71, z = −3.43, $p < 0.001$), their 'unsafe' crossings were significantly increased (i.e., 44.3 % > 28.9; Coef. = 5.19, z = 3.58, $p < 0.001$). Since most participants under time pressure accepted the three-second gap, rather

Table 3
Summary of influences of secondary tasks on participants, compared to the baseline. When an interaction with time gaps is mentioned, the stated interaction effect is for increasing time gaps.

Performance metric	Effect of the secondary task, and interactions with the time gap		
	Time pressure	Visual-manual distraction	Auditory-cognitive distraction
Gap acceptance	Smaller; No significant interaction	No significant main effects; Decrease with time gaps	Smaller; No significant interaction
Initiation time	Earlier; No significant interaction	No significant main effects; No significant interaction	Earlier; No significant interaction
Crossing duration	Shorter; No significant interaction	Longer; Increase with time gaps	Longer; No significant interaction
PET	Larger; No significant interaction	Smaller; Decrease with time gaps	No significant main effects; Decrease with time gaps
Proportion of decision category	Fewer 'near-collision' decisions	No significant main effects	No significant main effects
	More 'unsafe' decisions	More 'unsafe' decisions	More 'unsafe' decisions
	Fewer 'safe' decisions	Fewer 'safe' decisions	Fewer 'safe' decisions

than waiting for larger gaps, it led some participants to miss out on safer opportunities (e.g., five-second gap) (Table A3). There was no significant difference in 'near-collision' decisions between the Arrows and baseline. However, the percentages of 'unsafe' decisions were bigger than the baseline (i.e., 34.0 % > 28.9 %), with a corresponding reduction in safe crossings (Coef. = −0.53, z = −2.19, $p < 0.05$). Regarding the *N*-back task, the performance of the participants was very similar to the Arrows task in that they had bigger percentages of 'unsafe' decisions (i.e., 36.4 % > 28.9 %) and smaller percentages of 'safe' decisions(i.e., 45.4 % < 50.4 %) than in the baseline (Coef. = −0.46, z = −1.94, $p < 0.05$). Finally, according to the pairwise comparison, there were no differences between the Arrows and *N*-back tasks for all decision categories.

4. Discussion

In this section, a detailed discussion of the research results is presented. Table 3 summarises all the effects of secondary tasks on participants.

4.1. Time pressure

Our results demonstrated that participants tended to accept smaller time gaps in the Timer task than in the baseline, suggesting that time pressure makes them pursue riskier crossing opportunities, which is consistent with previous research that time pressure increases pedestrians' propensity to accept small gaps (Lobjois and Cavallo, 2007; Morrongiello et al., 2015). At the same time, participants started earlier and walked faster under time pressure than when they crossed the road normally, which could be seen as a form of compensation for their acceptance of smaller gaps, to nevertheless achieve successful crossings (Kalantarov et al., 2018). Although a similar previous study (Kalantarov et al., 2018) found that time pressure did not increase 'near-collision' decisions, we further indicated that such 'compensatory' behaviour appeared to effectively cover some of the reduction in safety, whereby their PETs were bigger than in baseline across all time gaps, leading to a reduction in the proportion of 'near-collision' decisions. However, the increased PET for each time gap does not mean that their performance during time pressure was safer than that in the baseline. As noted in Section 3.4, time pressure increased the amount of 'unsafe' decisions and decreased the number of 'safe' decisions. Similar results were also reported by Kalantarov et al., 2018 and Lobjois and Cavallo, 2007. The possible explanation for this is that time pressure causes pedestrians to accept small gaps and finalise decisions quickly, thus losing opportunities to choose big gaps upstream of the traffic flow. As a result, time pressure leads some participants who could have crossed the road at a safe gap to choose a smaller gap, thus compromising their safety.

Therefore, although the 'compensatory' strategy might mitigate seriously dangerous situations (e.g., the 'near-collision' decision), it is not sufficient to cover all reductions in safety. Time pressure can still impair participant safety in three ways: (i) by limiting the pedestrians' options (i.e., they focus on the current choice at the expense of subsequent choices), (ii) by reducing the time for judgment and reflection, and (iii) by increasing the propensity to take risky decisions (Cœugnet et al., 2019). Finally, beyond the current knowledge of time pressure, our results firstly found that, unlike distractions (further discussed in Section 4.2), the impacts of time pressure did not interact with the traffic gap size. This could be taken to suggest that time pressure does not affect participants' perception of the traffic environment as such, but rather their actions in response to what they perceived.

4.2. Distractions

Our results revealed significant impacts of distractions on pedestrian crossing behaviour. Regarding the visual-manual distraction (i.e., Arrows), we showed that its impacts on gap acceptance and crossing duration varied across the time gaps. With the increase in time gap, the tendency to accept gaps did not go up as much as in the baseline condition. A multimodal attention orientation theory (Davis et al., 2019) may provide explanations for this pattern in that participants allocate different proportions of attention on the crossing task and the visual-manual distraction, based on the gap size. Specifically, when the time gap is short, participants need to concentrate on the crossing task and give low priority to their cell phones. In contrast, the amount of attentional resources allocated to distraction tasks increases with a long time gap. Similar to a recent study by Larue and Watling 2022, the effects of distractions are not necessarily a constant. Pedestrians may regulate their level of distraction when they recognise the changes in situations. Moreover, evidence in the case of driving tasks also suggests drivers may be able to compensate for the influences of distractions to some extent by self-regulating their engagement in a secondary task (Davis et al., 2019). Interestingly, only the participants in the Arrows task ever crossed in the four-second time gap. This behaviour would seem unreasonable because participants chose a riskier gap (i.e., four-second) after rejecting a safer gap (i.e., five-second) (Fig. 2, Scenario 3 and 4). The potential mechanism is that the Arrows task involves both visual and manual components, which not only limits the frequency with which individuals scan the environment but also greatly affects their ability to allocate attentional resources for information processing (Jiang et al., 2018; Lin and Huang, 2017). In other words, due to the visual distraction, some participants seem to have missed the opportunity to cross in the five-second gap, thus causing them to cross in the smaller and potentially less safe four-second gap succeeding.

Our study found a quasi-significant effect on participant initiation time, compared to other studies indicating that cell phone use significantly slowed participants' initiation speed (Simmons et al., 2020). A potential reason for this could be that the artificial surrogate task we used (i.e., Arrows) may not be as difficult or as engrossing as real cell phone distraction (e.g., texting or reading) and may not have made participants concentrate as they do in reality. However, this pattern may also be in line with the multimodal attention orientation theory (Davis et al., 2019). The lifelike traffic flow scenario in the study might motivate pedestrians to self-regulate their attentional resources on the secondary task, thereby compensating for some of the effects caused by distraction.

With regards to the auditory-cognitive task (*N*-back), similar to the effect of the visual-manual task, the results indicated that the distraction could lead participants to walk slower than in the baseline condition. However, except that, participants' performances in the *N*-back task were somewhat unexpected. In particular, the auditory-cognitive task not only failed to make participants conservative about their crossings but led them to accept smaller gaps and initiate earlier crossings. There are some possible explanations for these results. First, compared to visual-manual distractions, auditory-cognitive distraction does not require any pedestrian visual resources (Jiang et al., 2018; Pešić et al., 2016), such that basic visual monitoring of the oncoming traffic is left unaffected. Second, the cognitive control hypothesis (Engström et al., 2017), applied to the driving task, may provide some insight into this behaviour pattern. It is argued that cognitive distraction could selectively impair main tasks that rely on cognitive control (e.g., brake response to the brake light of a lead vehicle) but leave well-practised and consistently mapped tasks unaffected, and even affected in the opposite way (e.g., brake response to looming stimulus of a lead vehicle may be enhanced by cognitive load). In the crossing task, pedestrians perceive the looming stimulus of approaching vehicles to make street crossing decisions similar to the braking task (Petzoldt, 2014; Tian et al., 2020). In light of the cognitive control hypothesis, pedestrian performance may not be negatively influenced by auditory-cognitive distraction since road crossing based on a looming stimulus is a well-practised task. (See also the literature on how cognitive load can improve drivers' lane-keeping performance, seemingly due to narrowing of the visual focus, increased arousal, or both) (Engström et al., 2017; Li et al., 2018). Moreover, due to the loss of auditory cues, pedestrians may enhance their visual perception or compensate for their decision-making to achieve a "risk homeostasis" (Walker et al., 2012), leading to more active decision-making behaviour. For instance, evidence from some simulator studies shows that participants accepted small gaps and initiated quickly when they omitted the noise of the vehicle (Soares et al., 2021; 2020). In addition, similar research showed that the pedestrian under auditory-cognitive distractions reacted quicker than the baseline (Siegmann et al., 2017).

Another important finding of the study was that the decision category analysis showed that both Arrows and *N*-back distractions increased participants' 'unsafe' decisions and reduced their 'safe' decisions. However, the reduced safety for Arrows and *N*-back distractions were associated with different road crossing performances. For the visual-manual distraction, greater crossing duration compared to the baseline was the main reason for reducing safety. By contrast, pedestrian safety under the auditory-cognitive distraction was mainly impaired because of the smaller accepted gap and greater crossing duration compared to the baseline. Based on these findings, we show that visual-manual and auditory-cognitive distractions affect pedestrian safety by influencing different crossing performance metrics.

4.3. Traffic flow

Interestingly, a significant effect of the traffic flow characteristics was found, indicating that fewer participants accepted a gap equal to or smaller than the maximum gap they previously rejected. Previous studies suggested that pedestrians tended to accept smaller gaps after missing several opportunities or waiting for a long time, thus negatively impacting their safety (Tiwari et al., 2007; Zhao et al., 2019). Contrarily, new findings from our research provide a different source and explanation of the traffic flow effect on crossing behaviour, indicating that pedestrians do not always become anxious when waiting for crossing opportunities. Instead, they can keep cautious and make rational cross decisions to maximise their safety and efficiency. Similar findings from Lobjois et al. (2013) indicated that pedestrians waiting for an available traffic gap was not accompanied by an increased risk of crossing. After rejecting several gaps, pedestrians could accurately estimate the approach of coming vehicles and think more carefully by comparing the current gap to previously rejected ones, thus avoiding unsafe behaviour.

4.4. Implications

The present results have several important implications in different areas. (1) Our findings have important meanings for understanding the influences of auditory-cognitive distractions and visual-manual distractions. First, the effect of distractions with different components on pedestrian crossing behaviour may not always be similar. Sometimes, they may work in an opposite way. The differences found in this study regarding the initiation and gap acceptance patterns of these two types of distractions have interesting parallels to the existing findings on how these distractions affect driving performance. Second, the effects of distractions may be influenced by the traffic gap size, i.e., pedestrians could actively self-regulate their engagement in the main and secondary tasks depending on their time gap to the approaching vehicle. (2) Our findings provide new evidence that time pressure negatively affects pedestrian crossing safety by limiting pedestrians' choices and increasing their propensity to accept risky crossing opportunities. Unlike effects of distractions, time pressure effects are not affected by the traffic gap size. Moreover, (3) based on these findings, our study may provide insights for researchers to conduct new or in-depth studies on pedestrians engaged in different types of distracting behaviour, for example, investigating the impacts of real-life distraction tasks in a controlled environment. (4) Existing research on traffic flow-related crossing behaviour is limited. Our results provide a novel perspective to understand pedestrian behaviour in complex traffic and can serve to help future research on this topic. In addition, (5) the results may also have significance in pedestrian behaviour modelling. Established safe and naturalistic traffic simulation or pedestrian-vehicle interactive models requires a deep understanding of pedestrian behaviour patterns. Our research results could provide insights into the improvement of crossing decision-making models related to distracted pedestrians and traffic flow.

4.5. Limitations

Several limitations of the present study should also be borne in mind. One limitation is that while the Arrows and *N*-back tasks clearly single out visual-manual and auditory-cognitive aspects of distraction, respectively, this also means that these tasks are different from the real distracting behaviours that pedestrians engage with in real traffic. For this reason, the results cannot be directly generalised to pedestrians in actual traffic. Second, although similarly to many previous studies in simulated environments (Lin and Huang, 2017; Sobhani and Farooq, 2018) our results here were generally consistent with those from naturalistic studies on pedestrian distraction, and although the experimental apparatus we used here was arguably the most immersive used so far in a simulator study on pedestrian distraction (large walkable CAVE environment, handheld physical device), one must still assume that there are differences in behaviour between virtual and naturalistic settings. Moreover, the scope of the study is limited to the studied experimental scenarios. We only considered constant-speed traffic flow, i.e., vehicles do not give way to participants, which is similar to crossing scenarios at unmarked crossroads. However, the crossing behaviour of distracted pedestrians at controlled crossings may be different, which needs to be further studied in the future. Finally, the experiment could be further improved in several ways: (i) In the experiment, participants stood at the curb and started to cross the road instantly after finalising their decision, whereas in real traffic, pedestrians typically have a relevant period of walking while appraising the upcoming crossing location and traffic, and this walking phase may also be affected by distractions. However, this aspect was not addressed in our study. Furthermore, (ii) as we focused on investigating pedestrian crossing behaviour, we did not analyse pedestrian performance on the distraction tasks. However, these results may provide further insight into the impacts of traffic factors on distraction effects. Therefore, it would be valuable to investigate the above-mentioned aspects in the future.

5. Conclusion

This study investigated the effects of distractions and time pressure on pedestrian crossing decisions in a road crossing environment with continuous traffic, using a CAVE-based pedestrian simulator. The research results show that revealing the mechanisms of influence of different distraction components is a pressing issue for pedestrian road behaviour research as it was found that the two applied distractions impaired pedestrian crossing safety in different ways. Compared to the baseline task, the visual-manual distraction led to a longer crossing duration and a reduced tendency to accept a gap as the time gap increased. In comparison, participants under auditory-cognitive distraction tended to accept smaller gaps, had a longer crossing duration, and initiated their crossing earlier than in the baseline. This has interesting parallels to existing findings on how these two types of distractions affect driver performance. Furthermore, in this study, we highlighted the dynamic pattern that the effects of visual-manual distraction on pedestrians changed over the time gap size. This self-regulation pattern of distraction suggests that the distraction effect is not necessarily a binary measure, but will instead change with the traffic environment. This situation-dependency of pedestrian distraction effects warrants considerable further research (Larue and Watling, 2022). Finally, regarding time pressure, it caused participants to accept smaller gaps, initiate earlier, and use shorter crossing duration than in the baseline. Its safety impacts have two sides. On the one hand, participants under time pressure tended to take a risk and accept small gaps, causing them to lose the opportunity to cross in safe gaps. On the other hand, participants seemingly applied a 'compensatory' strategy to cover some of the reduction in safety caused by their risk-taking behaviour, by crossing earlier in the gap and walking faster.

CRediT authorship contribution statement

Kai Tian: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Gustav Markkula:** Conceptualization, Supervision, Writing – review & editing. **Chongfeng Wei:** Supervision, Writing – review & editing. **Ehsan Sadraei:** Data curation, Resources. **Toshiya Hirose:** Conceptualization, Data curation. **Natasha Merat:** Conceptualization, Writing – review & editing. **Richard Romano:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

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Table A1
Gap acceptance for tasks and traffic scenarios.

Task	Scenario	Decision	Position of the gap in traffic flow										
			1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th
Baseline	One	Accept	0	0	0	29	6	10	73	0	0	0	2
		Reject	120	120	120	91	85	75	2	2	2	2	0
	Two	Accept	0	0	0	0	33	10	77	–	–	–	–
		Reject	120	120	120	120	87	77	0	–	–	–	–
	Three	Accept	0	0	0	31	0	13	0	1	68	0	6
		Reject	119	119	119	88	88	75	75	74	6	6	0
	Four	Accept	3	39	0	0	6	0	0	0	68	0	4
		Reject	117	78	78	78	72	72	72	72	4	4	0
Timer	One	Accept	0	0	0	47	8	6	57	0	0	0	2
		Reject	120	120	120	73	65	59	2	2	2	2	0
	Two	Accept	0	0	0	0	49	7	64	–	–	–	–
		Reject	120	120	120	120	71	64	0	–	–	–	–
	Three	Accept	0	0	0	52	0	7	0	2	55	0	4
		Reject	120	120	120	68	68	61	61	59	4	4	0
	Four	Accept	4	53	0	0	6	0	0	0	54	0	3
		Reject	116	63	63	63	57	57	57	57	3	3	0
Arrows	One	Accept	0	0	0	26	11	5	72	0	0	3	–
		Reject	117	117	117	91	80	75	3	3	3	0	–
	Two	Accept	0	0	0	0	32	10	73	0	0	0	2
		Reject		117	117	117	85	75	2	2	2	2	0
	Three	Accept	0	0	0	34	0	9	0	5	58	2	9
		Reject	117	117	117	83	83	74	69	11	9	0	–
	Four	Accept	7	31	0	0	9	0	0	0	59	4	8
		Reject	111	80	80	80	71	71	71	71	12	8	0
N-back	One	Accept	0	0	0	31	11	4	71	0	0	1	2
		Reject	120	120	120	89	78	74	3	3	3	2	0
	Two	Accept	0	0	0	0	34	12	73	0	0	0	1
		Reject	120	120	120	120	86	74	1	1	1	1	0
	Three	Accept	0	0	0	42	0	8	0	1	62	0	7
		Reject	120	120	120	78	78	70	70	69	7	7	0
	Four	Accept	2	43	0	0	7	0	0	0	60	0	4
		Reject	118	75	75	75	68	68	68	68	8	8	4

Table A2
Means and S.D. of the initiation time and PET for tasks and time gaps.

Condition		Time gap (s)						
		2	3	4	5	6	7	8
IT	Baseline	−0.27 (0.22)	−0.05 (0.16)	–	−0.00 (0.20)	0.02 (0.20)	0.11 (0.22)	0.17 (0.26)
	Timer	−0.09 (0.27)	−0.24 (0.19)	–	−0.16 (‘0.23)	−0.10 (0.23)	−0.12 (0.20)	0.01 (0.25)
	Arrows	−0.09 (0.16)	−0.05 (0.26)	−0.02 (0.32)	0.05 (0.44)	0.05 (0.34)	0.12 (0.34)	0.12 (0.40)
	N-back	−0.22 (0.19)	−0.15 (0.19)	–	−0.06 (0.21)	−0.02 (0.25)	0.06 (0.41)	0.32 (0.45)
CD	Baseline	2.58 (0.22)	3.07 (0.30)	–	3.47 (0.34)	3.58 (0.33)	3.67 (0.36)	3.69 (0.26)
	Timer	2.46 (0.11)	2.95 (0.35)	–	3.40 (0.35)	3.53 (0.43)	3.58 (0.42)	3.83 (0.39)
	Arrows	2.48 (0.30)	3.06 (0.33)	3.57 (0.73)	3.49 (0.34)	3.74 (0.42)	3.84 (0.47)	4.25 (0.86)
	N-back	2.45 (0.14)	3.09 (0.34)	–	3.59 (0.35)	3.71 (0.38)	3.80 (0.39)	4.15 (0.48)
PET	Baseline	−0.31 (0.86)	−0.01 (0.33)	–	1.53 (0.33)	2.40 (0.38)	3.22 (0.35)	4.04 (0.24)
	Timer	−0.36 (0.24)	0.29 (0.35)	–	1.76 (0.32)	2.57 (0.40)	3.53 (0.39)	4.14 (0.43)
	Arrows	−0.37 (0.43)	−0.01 (0.41)	0.45 (0.81)	1.45 (0.46)	2.21 (0.46)	3.05 (0.51)	3.60 (0.73)
	N-back	−0.23 (0.24)	0.07 (0.35)	–	1.47 (0.34)	2.30 (0.39)	3.12 (0.55)	3.50 (0.71)

Note. IT: initiation time (s); CD: crossing duration PET: post encroachment time (s)

Table A3
Proportion of crossing decision categories for time gaps and tasks.

		Baseline		Timer		Arrows		*N*-back	
Time gap (s)	Decision category	Freq.	Pct.	Freq.	Pct.	Freq.	Pct.	Freq.	Pct.
2	Near-collision (PET < 0)	3	100	4	100	5	100	2	100
	Unsafe (0 < PET < 1.5)	0	0	0	0	1	0	0	0
	Safe (PET > 1.5)	0	0	0	0	0	0	0	0
3	Near-collision	96	54.2	43	18.5	84	48.8	85	44.0
	Unsafe	81	45.7	190	81.5	88	51.2	108	56.0
	Safe	0	0	0	0	0	0	0	0
4	Near-collision	0	0	0	0	1	16.7	0	0
	Unsafe	0	0	0	0	5	83.3	0	0
	Safe	0	0	0	0	0	0	0	0
5	Near-collision	0	0	0	0	2	1.4	0	0
	Unsafe	57	41.9	20	18.3	58	50.4	61	50
	Safe	79	58.1	89	81.7	57	49.6	61	50
6	Near-collision	0	0	0	0	0	0	0	0
	Unsafe	0	0	1	1.8	6	6.8	4	5.0
	Safe	73	100	56	98.2	69	93.2	68	95.0
7	Near-collision	0	0	0	0	0		0	
	Unsafe	0	0	0	0	1	1.3	1	1.3
	Safe	81	100	67	100	80	98.7	76	98.7
Overall	Near-collision	99	20.7	47	9.9	92	19.6	87	18.2
	Unsafe	138	28.9	211	44.3	159	34.0	174	36.4
	Safe	241	50.4	218	45.8	217	46.4	217	45.4

Note. PET: post encroachment time (s); Freq.: frequency; Pct.: percentage (%)

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