# Studying Physiological Responses of Pedestrians Crossing Uncontrolled Urban Roads using Virtual Immersive Reality

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## Short summary

We studied the physiological responses of pedestrians when crossing an uncontrolled street to quantify the incurred stress. To fulfill research objectives, virtual reality technology was used, which is suitable for eliciting and capturing pedestrian responses, in conjunction with an electrodermal activity sensor. A total of 136 individuals participated in the VR experiment, tasked to cross a two-way street under various experimental manipulations. Variable values were randomly selected to design 12 sessions for each participant. Aggregated arousal levels were measured at different locations when performing the experimental task. Subsequently, two trained analysts independently annotated the arousals to identify different stimulus. The linear mixed-effects models showed that participants incur more stress when they are on the street, compared to the sidewalk. "Crossing" was found to be the most prevalent label and the largest arousals were related to "accidents" and "fear of having an accident" labels, confirming the anecdotal evidence.

**Keywords**: crossing stress, pedestrian safety, skin conductance response, virtual reality, walking behaviour

## 1 Introduction

Pedestrian safety, is constantly cited as one of the priorities for residents, elected officials and staff and no loss of life as a result of traffic collisions is acceptable in a Vision Zero approach. The majority of pedestrian fatalities occur on urban roads and pedestrian collisions more often occur near intersections when pedestrians are crossing a roadway. Additionally, the large block sizes and absence of pedestrian crossovers encourage pedestrians to jaywalk across streets, resulting in mid-block areas becoming the second most common locations for pedestrian fatalities, accounting for 14% (Statistics Canada, 2023).

A major body of literature considered wait time (Kalatian & Farooq, 2021), gap acceptance (T. Wang et al., 19), and time to collision (TTC) (Stadler et al., 2019) as the response variables to study pedestrian's crossing behaviour. Other variables such as road geometry and features, weather conditions, gender, and age were considered as predictors to construct models. Most of the studies have been conducted at unsignalized pedestrian crosswalks. The objective was to find the pedestrian's decision to cross under different conditions. The review of the literature shows that the interactions between traffic participants are treated mechanistically to justify pedestrians' behaviour. There appears to be a need to better understand the variability of pedestrians' behaviour using more advanced methods. In this regard, recent studies suggest frameworks based on cognitive and affective approach of human behaviour (M. Prédhumeau et al., 2023).

Given the complexities of pedestrians' decision-making when negotiating the road with other road users, there is a need to enhance our understanding of pedestrian behaviour when crossing a street. Notably, emotional state, particularly stress level, is proved to influence human cognitive processes and subsequently decision-making (Paschalidis et al., 2018), e.g., decision to select a gap and cross a street. To delve deeper into these aspects, physiological sensors emerge as valuable tools capable of uncovering new knowledge about human emotions. However, it is essential to acknowledge that these sensors perform optimally in controlled laboratory environments. For this purpose, electrodermal activity (EDA) sensors offer quantitative measurements of individuals' affective states when performing different tasks, which is able to reveal causal relationships behind human behaviour (Paschalidis et al., 2018). In an effort to bridge the gap between controlled settings and real-world scenarios, Virtual Reality (VR) stands out as a promising platform. VR provides a suitable and safe platform to simulate interactions between pedestrians and motorized vehicles and prevents any injuries or fatalities (Sottile, 2023).

## 2 Methodology

Toronto's Front Street West near the Union Station was selected as the experiment location in VR. The base simulation was developed in-house in Unity 3D (Farooq et al., 2018) and then outsourced to Annimersion UK Ltd. for features development, generalizability, and creation of a more realistic environment and avatars. A view of the simulated environment is shown in Figure 1. Valve Index headset was used to project the environment for the participants. The play area was expanded to the required 10m by 10m by installing four base stations. Extension cables were used to reach every corner of the play area and a ceiling pulley system was designed to hold the wires above participant's head to avoid tripping. Figure 2 shows the experiment setup in the laboratory.

Figure 1: A view of the simulated environment in VR

The Shimmer3 GSR+ sensor was used to monitor the emotional status of each participant when walking in VR. This is a non-invasive device that measures the EDA of skin. The unit was fastened to the non-dominant arm of the participants with two electrodes connected to their palm to read the EDA. EDA data was sampled at 100 Hz.

***Experiment design***

The research incorporated five distinct factors aimed at manipulating diverse environments for participants. Table 1 shows all factors, the associated variables, and variable levels. Several vehicle types and vehicle appearances were designed, including autonomous vehicles (AVs) with external human-machine interfaces (eHMIs). An avatar was positioned on the tactile paving facing the street. This avatar had either of these three behaviours: 1. A standing avatar simply waiting on the sidewalk, 2. A conservative avatar crossing the street in a cautious manner at a regular walking pace, and 3. An adventurous avatar who chose a more daring approach of running to cross the street. The remaining design elements were influenced by street medians and various environmental factors.
The experimental design was executed with consideration of all research variables and practical factors, including the maximum VR immersion duration and the overall experiment duration. In total 12 different sessions were constructed for each participant to go through. The initial combinations were tested with pilot participants to evaluate the performance of the VR experiment

Figure 2: Experiment setup

Table 1: Experiment factors, variables, and variable levels

| Factor | Variable | Levels | | | |
|---|---|---|---|---|---|
| Vehicle type | Vehicle appearance | Normal car | AV with roof sign | AV with signal boards | |
| Social influence | Avatar behaviour | No avatar | Standing avatar | Conservative avatar | Adventurous avatar |
| Traffic characteristics | Traffic flow | High arrival rate + low speed (20 km/hr) | Low arrival rate + high speed (40 km/hr) | | |
| | Vehicle distance | 2.5 m | 3 m | | |
| | Vehicle share | 0% AV | 100% AV | | |
| Road type | Street design | No median | With median | | |
| Environmental characteristics | Time of day | Day | Night | | |
| | Weather | Clear | Rain | Snow | |

and observe participants' reaction to different environments. All variable levels were incorporated in the final experimental design randomly, having avatar behaviour levels being repeated equally for each participant. Random sampling of the variable levels were performed by an R script. The script was run multiple times and the experimental designs were compared based on the number of repeated scenarios. Finally, the experimental design having the least number of repetitions was selected, to increase the diversity of sessions.

### *Experimental task*

Participants were placed on a sidewalk and they were instructed to go to the tactile paving and then find a safe and suitable moment to cross the street. Participants were given a 60-second time limit to complete the task, and if they did not finish within that time frame, the session would be terminated and the next session would be automatically loaded. To prevent participants from experiencing discomfort, the screen was programmed to black out just before the moment of impact in the event of a vehicle accident and a message was shown to the participants indicating that they had an accident. Figure 3 shows the details of the experimental task.

### *Participants*

Out of a total of 136 participants, 5 had failed VR data, and 38 had failed physiological data, resulting in a total of 95 valid observations. The majority of participants were recruited by a panel provider and they were compensated a $50 Amazon gift card. The rest of the participants were invited by posting advertisement in social media and they were compensated a $25 Amazon gift card. The participation criteria were as follows.

- Being fully vaccinated or have received an approved exemption from the university in accordance with Toronto Metropolitan University's COVID-19 vaccination protocols.
- Aged between 18 and 65 years old.
- Not having any head, eye, brain, or heart illness.

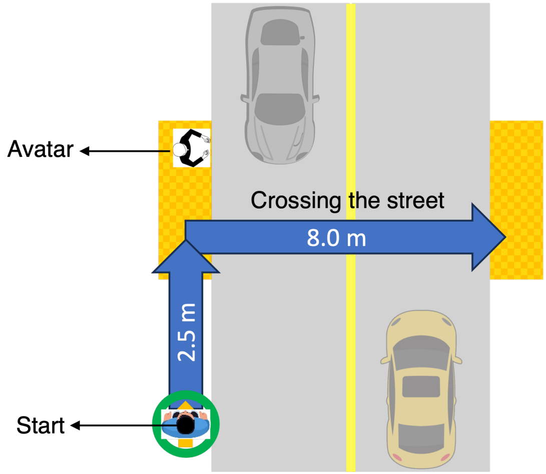



Figure 3: Details of the experiment task

- Never had a feeling of nausea or fatigue when playing video games.
- To live in the Greater Toronto Area.

***Continuous decomposition analysis***

In order to conduct the analysis, it was essential to synchronize the VR data and the physiological sensor data. Both times were converted into Epoch times to facilitate this process. All EDA data were visually inspected to remove the artifacts and failed readings. The next stage was the extraction of phasic and tonic components from the recorded signal. Ledalab package was used for signal decomposition in MATLAB. Details of the continuous decomposition algorithm used in this package can be found in Benedek & Kaernbach (2010). Considering the ambulatory nature of the experiment, a threshold of 0.1 was selected for skin conductance response (SCR) detection. The data were downsampled to 10 Hz to speedup the analysis. Smoothing methods were applied on the whole dataset to remove the small shakes of the signal, which largely corresponded to low-pass filtering of the data. This pre-processing step is crucial in addition to artifact correction. Due to the long and non-stationary behaviour of the signals, a Gaussian filter was applied with window size equal to 30, which is three times the downsampled data collection frequency of 10 Hz (Nazemi, 2020).
Several transformation methods have been suggested for SCR amplitude, due to inter-individual variations in response range, prior to performing any statistical analysis (Ben-Shakhar, 1985). Transformation into standard values was selected for this study, which considers each particular individual mean and standard deviation of SCRs. Standardized SCRs are calculated as follows.

$$z_{ik} = \frac{SCR_{ik} - \overline{SCR_i}}{s_i} \tag{1}$$

where
$z_{ik}$ = $k$th SCR standardized value for individual $i$,
$SCR_{ik}$ = $k$th raw SCR score for individual $i$,
$\overline{SCR_i}$ = mean of all SCRs for individual $i$, and
$s_i$ = standard deviation of all SCRs.

The normally distributed z scores are transformed to T scores with a mean of 50 and standard deviation of 10 to drop out the minus signs and perform statistical tests (Boucsein, 2012).

$$T_{ik} = 50 + 10z_{ik} \tag{2}$$

where
$T_{ik}$ = $k$th SCR T score for individual $i$, and
$z_{ik}$ = $k$th SCR standardiszed value for individual $i$.

### *Contextual annotation*

Qualitative coding process was performed on 60 participants (given project resources) to explore the stimuli causing arousals and hopefully, identify the stress associated to crossing the street. Coding in this context refers to labelling or categorizing excerpts and organizing them according to their content. Given that the study was exploratory, a hybrid deductive and inductive approach was adopted in this research, as shown in Figure 4 The screen for each participant performing the task in VR was recorded, displaying the participant's EDA level simultaneously in the corner of the screen. At the same time, participant's voice was recorded using the microphone on the VR headset. These were the input data to perform the contextual analysis.

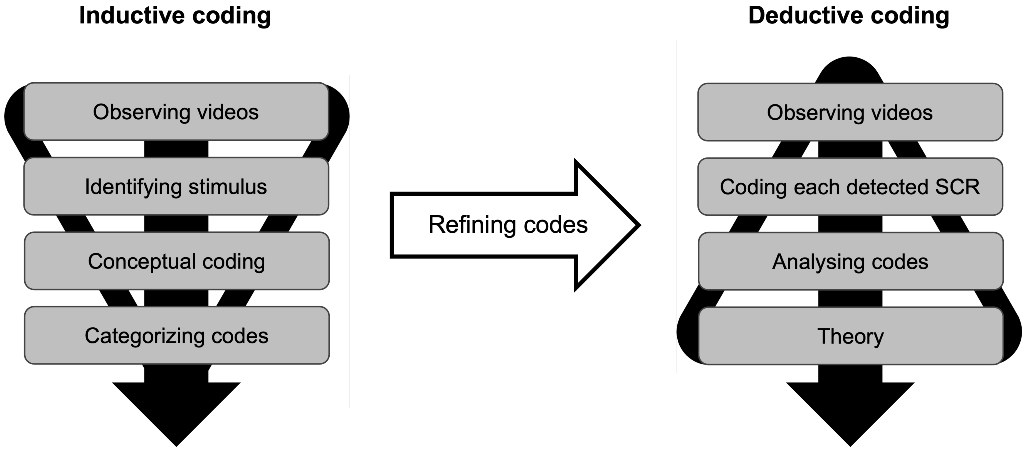



Figure 4: Annotation process diagram

## 3 Results and discussion

### *Location-based analysis*

The walking manoeuvre of participants during the experiment task was divided spatially into four different segments (refer to Figure 3).

1. Sidewalk
2. Waiting to cross (on the tactile paving)
3. Crossing lane 1
4. Crossing lane 2

The detected SCRs within each segment are shown in Figure 5.
The differences in the detected SCRs for each segment is further explored by means of mixed effects model on the panel data. The mean T scores of the detected SCRs are taken as the dependent variable. The segments were included as independent variables with "Sidewalk" as the reference factor. The model results are presented in Table 2. The estimated coefficient for Sidewalk is placed in the intercept row. The estimated coefficients for other segments show the difference between each segment and the reference segment, i.e., Sidewalk. The t-value is showing if the absolute difference between, say the segment X coefficient, and sidewalk is different than zero. As the results show, participants' stress levels were significantly higher when they were on the street, compared to the time when they were on the sidewalk ($p < 0.001$).

### *Contextual analysis*

Two trained analysts independently annotated the detected SCRs to explore different stimuli that could be associated with the detected arousals. The objective was to conduct a disaggregated analysis of the data and identify the stress associated to crossing the street. The first researcher viewed the videos of the first 10 participants and openly developed a set of labels for each detected major arousal. Labelling was based on what participant had observed in VR, their behaviour, and

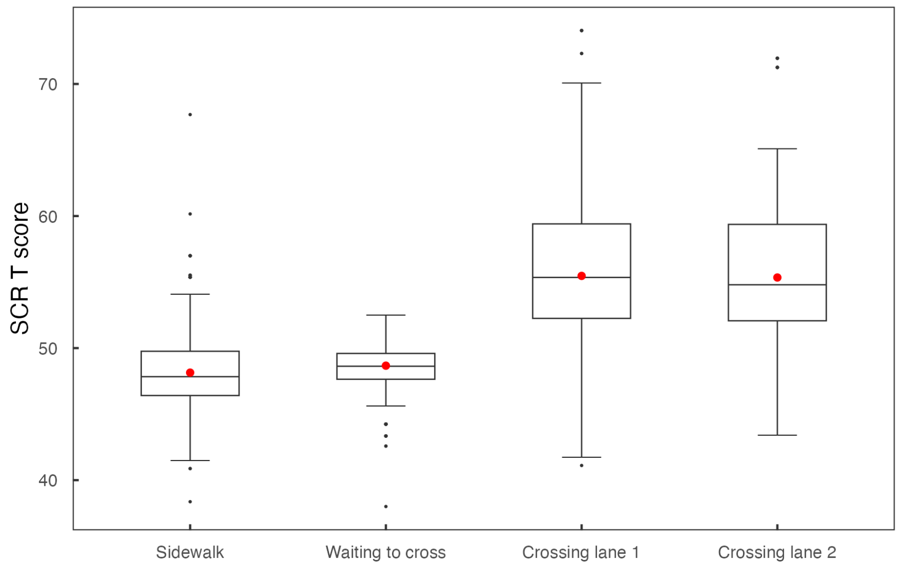



Figure 5: Detected SCRs within each walking segment

Table 2: Regression results for T scores of detected SCRs in different segments

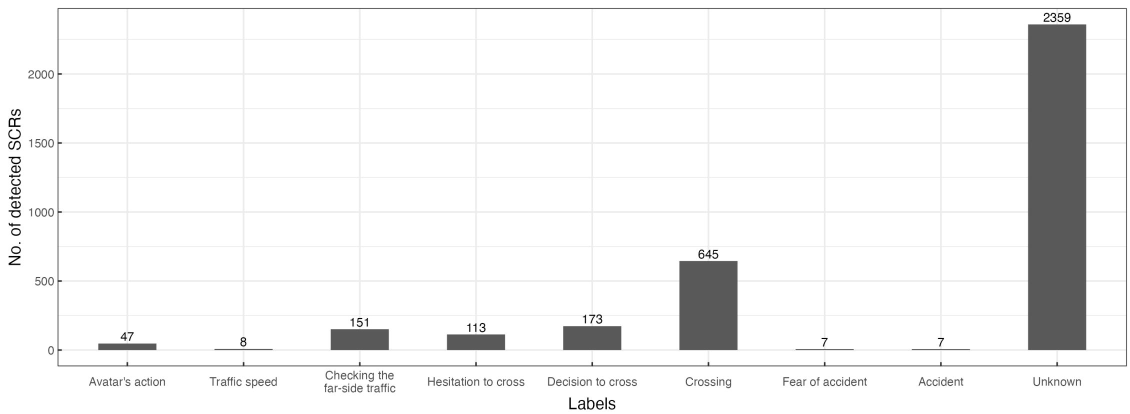
| Coefficients | SCR T score | | |
|---|---|---|---|
| | Estimate | t-value | Sign. |
| (Intercept) | 48.14 | 186.91 | *** |
| *Segment* | | | |
| Sidewalk | – | – | – |
| Waiting to cross | 0.53 | 1.76 | . |
| Crossing lane 1 | 7.32 | 14.21 | *** |
| Crossing lane 2 | 7.20 | 18.00 | *** |

their interjections and comments during their VR interaction. Inductive coding yielded 16 codes in the first round of coding. A second round of coding involving a second researcher consolidated the labels into 13 codes. The labels were then reviewed and revised by an expert researcher which resulted in 10 codes after negotiation. The rest of the dataset was annotated deductively with the 10 available codes. Those arousals that could not be associated to any stimulus were labelled as *Unknown*. The list of the labels and their definitions are presented as follows. The "Immersion" label was omitted from the analysis as it did not align with the research objectives.

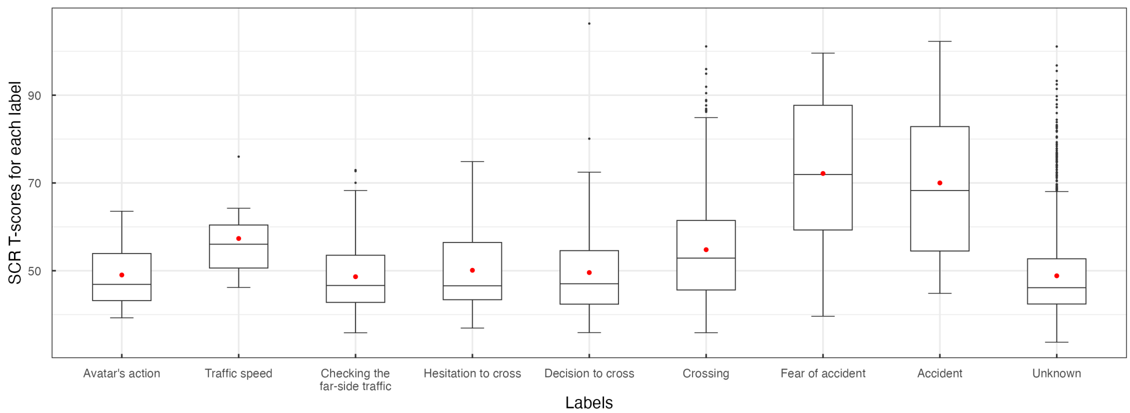
1. Immersion: the arousal associated with being immersed in a new VR environment
2. Avatar actions: the arousal associated with observing the avatar's behaviour
3. Traffic speed: the arousal associated with high traffic speed, when the participant perceives it as high and verbally expresses it
4. Checking far-side traffic: the arousal associated with checking the far-side traffic
5. Hesitation to cross: the arousal associated with uncertainty in making the choice of crossing, when the participant is checking for the near-side and far-side traffic
6. Decision to cross: the arousal associated with making the decision to cross the street, usually followed by moving forward
7. Crossing: the arousal associated with crossing the street
8. Fear of accident: the arousal associated with the situation when the participant thinks that there is a high chance of having an accident
9. Accident: the arousal associated with having an accident

10. Unknown: the arousals that could not be unequivocally linked to any of the aforementioned labels

Figure 6 shows the frequency and the average arousal level of each label. Participants were evaluating the traffic flow when they were standing on the sidewalk and the process of checking the incoming traffic, finding a suitable gap, and sometimes hesitation to cross, stimulated arousal and subsequently, increased arousal levels. However, when they actually performed the crossing task, the arousal level reached to much higher states due to the unsecured feeling of being on the road and the potential possibility of having an accident. Therefore, it was fairly easy for analysts to identify arousals associated with crossings and that is why “Crossing” is the most frequently observed label. In several cases it noticed that crossings are preceded by a “Decision to cross” arousal, which happens right before the participant selects a gap and crosses the street.
Since the traffic was initially only coming from one side of the road and after a while from the opposite direction, it happened that the participants did not expect vehicles when crossing the second lane, which sometimes resulted in having accidents and large arousal levels due to shocking. “Fear of accident”, “Accident”, and “Traffic speed” are the less frequently observed labels, yet the highest arousal levels are related to them. Participants were also experiencing high arousal levels when standing insecurely in the middle of the road checking the traffic stream that was coming from the opposite direction.




(a) Number of detected SCRs for each label




(b) Box plot of SCR amplitudes for each label

Figure 6: Number of detected SCRs and SCR amplitudes for each label

Similar to the previous analysis, the differences in the mean detected SCRs for each label is further explored by means of mixed effects model on the panel data. The mean T scores of the detected SCRs are taken as the dependent variable. The labels were included as independent variables with “Crossing" as the reference factor. The model results are presented in Table 3. The estimated coefficient for “Crossing" is placed in the intercept row. The estimated coefficients for other labels show the difference between arousal amplitude of each label and the reference label, i.e., “Crossing". The t-value is showing if the absolute difference between, say the label X coefficient, and “Crossing" label is different than zero.
Crossing would cause 54.79 The stress level associated to the “Fear of accident" and “Accident"

Table 3: Regression results for T scores of detected SCRs for different labels

| Coefficients | SCR T score | | |
|---|---|---|---|
| | Estimate | t-value | Sign. |
| (Intercept) | 54.79 | 144.16 | *** |
| *Label* | | | |
| Crossing | – | – | – |
| Avatar's action | -5.76 | -3.95 | *** |
| Traffic speed | 2.55 | 0.74 | |
| Checking the far-side traffic | -6.16 | -7.05 | *** |
| Hesitation to cross | -4.69 | -4.76 | *** |
| Decision to cross | -5.21 | -6.31 | *** |
| Fear of accident | 17.36 | 4.73 | *** |
| Accident | 15.21 | 4.15 | *** |
| Unknown | -5.95 | -13.88 | *** |
| Number of participants | 60 | | |
| Number of observations | 3509 | | |

Sign. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

labels found to be significantly larger than the "Crossing" label ($p < 0.001$). It should be noted that in certain accident scenarios, individuals did not see that a car collided with them; they only saw the dark screen and a message that informed them that they had an accident. The incurred stress associated to "Crossing" is significantly higher than the emotional responses occurred when the participant was on the sidewalk, i.e., Avatar's action, Checking the far-side traffic, Hesitation to cross, and Decision to cross ($p < 0.001$). This difference highlights how street crossing task is relatively more demanding and stressful that the other processes.

## 4 Conclusions

The results of the aggregate and disaggregate statistical analyses indicated a significant impact of crossing the incurred stress of pedestrians. The stress level associated to crossing a two-way street was quantified and it was compared to the other arousals that a pedestrian experiences when they want to cross a street. Through this research, the stress associated to fear of having an accident and having an accident was also quantified; it was identified that fear of having an accident and having an accident would cause 17.36 and 16.21 units more stress than the "Crossing" stress, respectively. The results indicate the significantly high stress level that pedestrian have to deal with when crossing an uncontrolled urban road and signify the inclusion of having pedestrian crossovers to ease the pressure. Furthermore, the findings suggest inclusion of emotional responses of pedestrians, in addition to the objective safety measurements (i.e., number of crashes, injuries, and fatalities involving pedestrians) to measure the level of safety of a facility.

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