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Three pedestrian phasing with audible pedestrian signals configurations: Experience of blind or visually impaired persons in Quebec City (Canada)

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ABSTRACT

Objective: Audible pedestrian signals are strategically placed in some intersections to enhance safety, independence and accessibility for blind or visually impaired persons. This study appraised the sense and level of safety of blind or visually impaired persons with respect to three types of pedestrian phasing with audible pedestrian signals configurations that exist in Quebec City, Canada. These include: 1) exclusive phasing with non-directional audible pedestrian signals; 2) exclusive phasing with directional audible pedestrian signals; and 3) concurrent phasing with directional audible pedestrian signals.

Methods: Experiments with 18 participants were conducted at six crossing corridors that were carefully selected by members of an advisory committee that included diverse stakeholders. In addition to the three possible pedestrian phasing with audible pedestrian signals configurations, situations involving short and long crossing distances were included. Each corridor was crossed three times by each participant. For each crossing, participants' trajectories were objectively determined using a satellite positioning system which uses a relative positioning mode. Participants' sense of safety was also questioned after each crossing using a visual analog scale.

Results: The results obtained do not allow for the identification of an ideal configuration or even a configuration to avoid based on the level of safety. However, findings suggest that the exclusive

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phasing with directional audible pedestrian signals configuration is perceived to be the safest option by the participants.
Conclusion: This study may have practical implications on the design of intersections (e.g., selection of a type of pedestrian phasing with audible pedestrian signal) and the training of blind or visually impaired pedestrians.

1. Introduction

To move around independently and securely is crucial for active social engagement in any person's life. However, blind or visually impaired persons encounter numerous obstacles and difficulties when crossing intersections, even those equipped with pedestrian signals (Barlow et al., 2005, 2009; Scott et al., 2014; Wall et al., 2004). They must navigate these perilous points with limited or no visual information. They rely on interpreting specific environmental cues, like traffic sounds, to analyze intersections and traffic signal cycles, and to establish and maintain alignment while crossing (Barlow et al., 2005, 2010; Leroux et al., 2014). Relying on these cues does not ensure complete safety, given various vehicle movement types that are allowed, such as turning across pedestrian crosswalks (Leroux et al., 2014; Scott et al., 2014). Promoting autonomy for all is a significant equity objective for many cities.

Audible pedestrian signals (APS) are strategically placed at some intersections to enhance safety, independence and accessibility for blind or visually impaired persons (Bentzen et al., 2006; Leroux et al., 2014; Mailhot et al., 2014; National Academies of National Academies of SciencesEngineeringand Medicine, 2011; Scott et al., 2008; Wall et al., 2004). The observed benefits of APS include an increase in independence in locating the crosswalk, as well as a reduction in the starting delay for crossing and an increase in the number of crossings completed within the allotted time (Scott et al., 2008). APS have been commonly implemented in many countries. In the province of Quebec (Canada), the provincial transport department established a standard in 2003 that outlined the operational guidelines for these types of devices (Hall et al., 1996; Ministère des transports du Québec, 2011; Ratelle et al., 1999). It specified a set of criteria, including the utilization of directional sound sources with alternating APS positioned at each end of a crosswalk. The aim is to assist blind or visually impaired pedestrians in establishing and maintaining a straight line while crossing (Laroche et al., 2000; Stevens, 1993). Literature have documented the effectiveness and utility of these alternating APS from one side of the intersection to the other in guiding blind or visually impaired pedestrians in the correct direction before and during street crossings (Tauchi et al., 1998). The standardized system in the province of Quebec also mandates that a pushbutton locator tone must be set to activate and confirm the signal. This type of device has been implemented in various countries, including Australia, New Zealand and Sweden (Barlow et al., 2009; National Academies of Sciences, Engineering, and Medicine, 2011; Noyce and Bentzen, 2005; Wall et al., 2005), and seems to help finding the pushbutton and to decrease veering tendencies when added after the end of the "walk" signal (Barlow et al., 2009; Wall et al., 2005). The newly revised Pedestrian Right-of-Way Accessibility Guidelines in the United States also sets out similar requirements, being explicit about the need for APS to address pedestrian safety (Architectural and Transportation Barriers Compliance Board, 2023).

APS are typically set up at specific intersections along pedestrian crosswalks and are paired with traffic signals. Several years ago, Quebec City, the capital of the province of Quebec, Canada, with around 540,000 residents, adopted a traffic management system featuring exclusive pedestrian phases. A phase denotes a portion of a traffic light signal dedicated to specific traffic movements, such as East-West traffic and then North-South traffic in a two-phase system. During exclusive phasing, automobile traffic is completely halted for one phase, allowing only pedestrians to move. Most intersections in Quebec City do not technically apply a true exclusive phase, as vehicles are allowed to turn right on a red vehicle signal. However, turning right on a red is not permitted in Quebec City during the day in crossing corridors with APS. The duration of exclusive phases is determined based on the length of the longest direct (not diagonal) crosswalk at the intersection, encompassing both the "walk" and "don't walk" signal indications. Before the 2003 standard, non-directional APS were deployed at several intersections (i.e., those with exclusive pedestrian phases), which still remain operational.

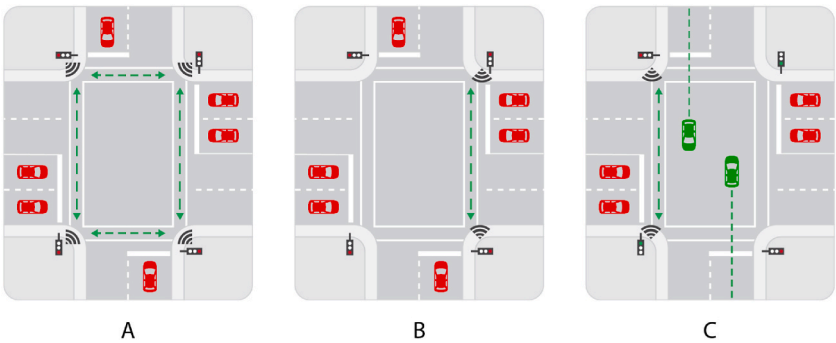

Fig. 1. Three different types of pedestrian phasing with audible pedestrian signal configurations found in Quebec City, Canada: A) exclusive phasing with non-directional audible pedestrian signals; B) exclusive phasing with directional audible pedestrian signals; and C) concurrent phasing with directional audible pedestrian signals.

Unlike directional APS, non-directional APS emits sound from a single source situated at one corner, providing audible cues akin to the visual "walk" (continuous sound) and "don't walk" (intermittent sound) signal indications. With evolving standards, there are currently three distinct configurations of pedestrian phasing with APS for blind or visually impaired pedestrians in Quebec City. These configurations encompass: 1) exclusive phasing with non-directional APS; 2) exclusive phasing with directional APS; and 3) concurrent phasing (where pedestrians are served concurrently with adjacent traffic movement through an on-demand pushbutton) with directional APS (Fig. 1).

During a consultation process regarding the upgrade of APS in Quebec City, advocacy groups representing the rights of individuals with disabilities voiced apprehensions regarding the implementation of signals that comply with the 2003 standard. They were primarily concerned with the challenges related to adaptation faced by blind or visually impaired persons. Due to such changes, additional intensive training with orientation and mobility specialists was required. Additionally, the advocacy groups questioned the effective safety of the non-standardized system, particularly in an area with highly variable configurations, and were ready to commit to a research project. The lack of trust in the existing systems among blind or visually impaired individuals can significantly hinder their daily mobility, preventing them from traveling independently and potentially affecting their overall quality of life. Even though Canada and other countries have been using various types of pedestrian phasing with APS for some years now, there is limited available evidence on the behavior and perception of blind or visually impaired individuals regarding these different configurations.

In this respect, the overall purpose of this exploratory study was to investigate the three types of pedestrian phasing with APS configurations found in Quebec City area with the aim of improving the safety and autonomy of blind or visually impaired persons. As a first step, through an online survey and individual interviews, we appraised the preferences, expectations, and sense of safety of blind or visually impaired persons regarding the three types of pedestrian phasing with APS configurations that exist in Quebec City. Thirty-two blind or visually impaired persons were asked to complete the survey which contained a series of simulations. Subsequently, semi-directed, individual interviews with 11 of the individuals who had completed the survey were conducted to complement the collected information. No formal consensus regarding many of the issues discussed were established as participants' responses varied too significantly. However, the results tend to demonstrate that the addition of APS to pedestrian signals heightens the sense of safety of blind or visually impaired persons (Routhier et al., 2023). Findings also suggest that the exclusive phasing with directional APS configuration is perceived to be the safest option by the participants (Routhier et al., 2023). Findings are reported in another paper (Routhier et al., 2023).

As a second step, following concerns raised by various partners, our research also sought to evaluate the objective level of safety of the three types of configurations found in Quebec City. Findings from this last phase of the project are reported in this paper. In this study, the level of safety refers to the characteristics of the trajectory followed (e.g., deviation, duration). The sense of safety was also reassessed in this last phase. It refers to the participants' perceived level of safety (based on their profile and personal experiences) and comfort (e.g., ease of mobility, accessibility, traffic noise, audible signal volume) (Ovstedal and Olaussen, 2002; Roussel, 2014; Thomas et al., 2015).

2. Methods

An advisory committee was set up to support the completion of this exploratory study. It was made up of community stakeholders advocating for the rights of people with disabilities (n = 3), orientation and mobility specialists (n = 2), and municipal and provincial agents (n = 2). The advisory committee's role consisted of validating the project milestones, advising on the content of the data collection tools, participating in the recruitment process, monitoring project progress, and proposing courses of action. The study was approved by the Research Ethics Board in rehabilitation and social integration at the *Centre intégré universitaire de santé et de services sociaux de la Capitale-Nationale* (REB number: 2018-435, RIS_2017-571). All participants provided written informed consent.

2.1. Recruitment

Blind or visually impaired persons were recruited: 1) with the help of a regional non-profit organization, the *Regroupement des personnes handicapées visuelles* (RPHV; roughly translates to "Association of people who are visually impaired"), in particular via their newsletter; 2) with the help of the Blindness and Visual Impairment Program of the *Centre intégré universitaire de santé et de services sociaux de la Capitale-Nationale,* specifically program stakeholders provided project information to their clients; and 3) through snowball sampling.

We aimed to include a diverse range of participants, taking into consideration factors such as the degree of visual impairment and the types of assistive technologies employed, as well as their level of independence in navigating both familiar and unfamiliar surroundings, and their prior experience with APS. To be eligible for inclusion, individuals were required to meet the following criteria: 1) be between the ages of 18 and 65 (inclusively); 2) be visually impaired as defined by Quebec legislation; 3) be familiar with pedestrian crossing signals; 4) use audible pedestrian crossings; 5) live in the eastern part of the province of Quebec; 6) have no significant auditory asymmetry; 7) use or be able to use a long detection cane as a mobility aid (not a guide dog that can correct the trajectory); and 8) have no cognitive or communication impairments that might affect understanding of instructions, completion of tasks and communication with research staff.

2.2. Participants

Eighteen individuals took part in the experiments. Most participants were between 46 and 65 years of age (n = 14; 77.8%) and

women made up 61.1% of the sample pool (n = 10). A large majority of participants had been living with visual impairments since birth (n = 15; 83.3%) and had a residual sight (n = 14; 77.8 %). Considering the exploratory nature of the study, it was decided to limit the sample size to 18 participants. Discussions with project partners suggested that this was a realistic number based on the pool of potential participants from the involved organizations.

2.3. Variables

To assess the sense and level of safety with respect to the three types of pedestrian phasing with APS configurations found in Quebec City, six crossing corridors within four intersections were selected by the advisory committee to ensure a representation of the situations and environments encountered by individuals with visual impairments. In addition to the three possible configurations, we were looking for situations involving: 1) short crossings, i.e. 15 ± 2.5 m, and 2) longer crossings, i.e. 25 ± 2.5 m. Due to technical issues related to the sound emission of APS during the data collection conducted with the first four participants, it was decided to replace one crossing corridor (i.e., concurrent phasing with directional APS, long crossing) with another very similar one.

The sociodemographic and clinical data of the participants were collected using a questionnaire developed for the project. Through direct observations, various items were documented using an observation grid developed for each crossing corridor, including: ease of locating the pedestrian pushbutton, activation of the audible signal (if applicable, the tone confirming signal activation), alignment with the pedestrian crosswalk in preparation for the crossing, moment of initiation of the crossing (in relation to the beginning of the audible signal), contact with obstacles, and location of the end of the crossing. The information collected using these observation grids enabled us to validate some of the results obtained. Each crossing was also recorded on video, which enabled the visual validation of several aspects related to the participants' trajectory. Finally, participants' sense of safety was questioned after each crossing using a visual analog scale ranging from 1 ("not safe at all") to 5 ("completely safe"). It is a tool generally used to assess subjective experiences in a simple and effective way.

For each crossing, participants' trajectories were objectively measured using a satellite positioning system, employing *Trimble R8* type receivers. This is a GPS system that uses a relative positioning mode, meaning that positioning is measured using two receivers. The first receiver is fixed and its position is known, while the second receiver is mobile and its position is determined relative to the first. This system allows for achieving a positional accuracy of at least 2 cm, once the corrections required by the method are applied *a posteriori*. This level of accuracy is more than sufficient for the study's needs (Santerre et al., 2012; Van Sickle and Dutton). Such an approach has been used in much more demanding conditions, such as for sports performance analysis (Lambert, 2002; Waegli et al., 2007). In the context of the current study, the fixed receiver was located at the building of the Ministry of Natural Resources and Forests in Quebec City, while the mobile receiver was attached to a support that participants carried on their back while crossing the intersections (Fig. 2).

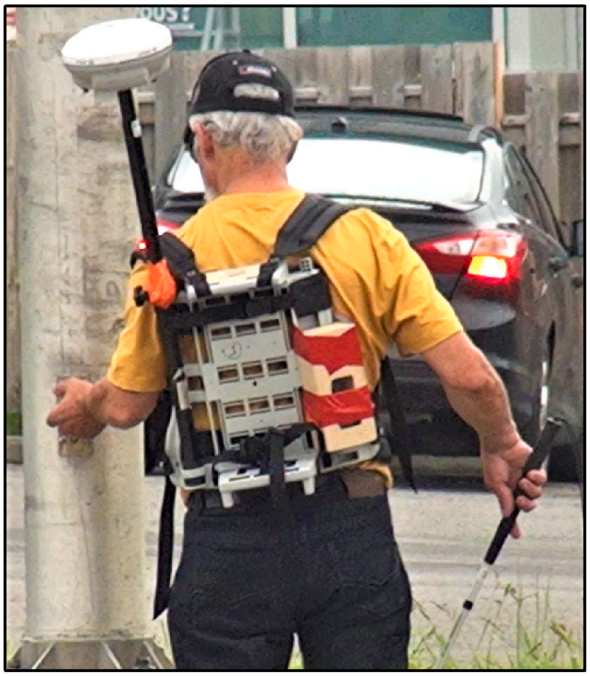

Fig. 2. The mobile GPS receiver carried by one of the participants in this study.

2.4. Data acquisition procedure

Each participant was met during an individual session lasting about 3 h. To mitigate the impact of variability in external and environmental factors on participants' performance, data collection was generally conducted at the same time of day and under similar climatic and acoustic conditions for each participant. Indeed, most of the experiments (n = 15; 83.3%) were carried out during summer 2018 in fair weather periods. Three experiments (16.7%) took place in autumn, but only one of them was carried out in light rain. Before starting the experiment, a sociodemographic and clinical questionnaire was completed with the participant. Subsequently, the research team and the participant moved to the field, where the participant was invited to cross the six previously identified crossing corridors. Each corridor was crossed three times (i.e., three trials at each crossing corridor, always in the same direction). During the experiments, a research assistant provided explanations and starting instructions, including the following information: name of the intersection and crossing corridor, type of configuration, length of the crossing corridor, number of lanes in each direction, time allowed for the crossing, presence of a raised median and/or of a bicycle path. This assistant, along with a second assistant, ensured the participant's safety during the crossing by positioning themselves on either side of the participant. A third assistant, positioned at the opposite end of the corridor, recorded the crossing on video. Once the crossing was completed, the second assistant was responsible for filling out an observation grid and questioning the participant about their sense of safety. For logistical reasons, all participants experienced the crossing corridors in the same order.

2.5. Data analysis

The participants' characteristics obtained through the sociodemographic and clinical questionnaire were compiled using descriptive statistics (frequencies). The sense of safety expressed by participants on a visual analog scale was also analyzed using descriptive statistics (means, standard deviations). For this ordinal variable, statistical differences between crossing corridors and trials were analyzed using a non-parametric ANOVA-type test (*R software, package nparLD, version 2.1*) (Noguchi et al., 2012). This test is more robust when dealing with small sample sizes and is suitable for ordinal data. A significance level of 0.05 was set. The collected GPS data were extracted, and the percentage of participants located within a safety corridor according to the percentage progression across the pedestrian crosswalk was calculated for each corridor and each trial. The safety corridor was predetermined for each crossing corridor by two orientation and mobility specialists based on the location of curb cuts and road markings. It is the widest area encompassed by the road-painted pedestrian crosswalk and the rise in the sidewalk at the end of the curb cut. Since the software did not allow for a single analysis, three separate nparLD ANOVA-type tests were conducted, one for each trial. When a significant interaction was observed (trial x crossing corridor), the crossing corridors by portion of the route were compared. To determine which corridors differed from each other, pairwise comparisons using a two-sided equality of proportions test (with continuity correction, due to the small sample size) were performed. The percentage of participants located on the inner and outer side of the safety corridor according to the percentage progression across the pedestrian crosswalk was also calculated for each corridor and each trial.

3. Results

3.1. Sense of safety

After each trial (three per crossing corridor), participants were asked to evaluate their sense of safety on a scale ranging from 1 ("not at all safe") to 5 ("completely safe"). Table 1 presents descriptive statistics for the three trials conducted at each of the six crossing corridors. The trials × crossing corridors comparison was performed using a nparLD ANOVA-type test. Referring to Fig. 3, significant differences are observed between the trials ($p < 0.001$) and between the crossing corridors ($p < 0.001$), but without a significant interaction ($p = 0.455$) for the trials × crossing corridors. In short, the colored curves are statistically parallel. The ordinate of the graph represents a statistic called Relative Treatment Effect (RTE), which is interpreted similarly to the Vargha and Delaney's A (VDA) statistic (Vargha and Delaney, 2000). If there were no differences between the trials and the crossing corridors, all points would have a RTE equal to 0.5. A RTE greater than 0.64 or less than 0.36 indicates an appreciably higher or lower sense of safety (Vargha and Delaney, 2000). It is observed that participants feel safer during a short crossing at a crossing corridor with exclusive phasing and a directional APS (crossing corridor 5). Conversely, participants feel less safe during a long crossing at a crossing corridor with exclusive phasing and a non-directional APS (crossing corridor 2). Additionally, participants' sense of safety is consistently lower during the first

Table 1
Participants' sense of safety for each crossing corridor at each trial.

Crossing corridors	Trial 1	Trial 2	Trial 3
	Mean ± SD	Mean ± SD	Mean ± SD
1. Exclusive phasing with **non-directional** APS, **short** crossing	4.1 ± 1.1	4.4 ± 0.7	4.6 ± 0.6
2. Exclusive phasing with **non-directional** APS, **long** crossing	3.3 ± 1.1	3.8 ± 1.0	4.1 ± 0.6
3. Concurrent phasing with **directional** APS, **short** crossing	4.1 ± 0.9	4.4 ± 0.7	4.4 ± 0.7
4. Exclusive phasing with **directional** APS, **long** crossing	4.2 ± 0.8	4.3 ± 0.9	4.3 ± 0.8
5. Exclusive phasing with **directional** APS, **short** crossing	4.6 ± 0.5	4.8 ± 0.4	4.8 ± 0.4
6. Concurrent phasing with **directional** APS, **long** crossing	3.7 ± 1.2	4.1 ± 1.3	4.1 ± 1.2

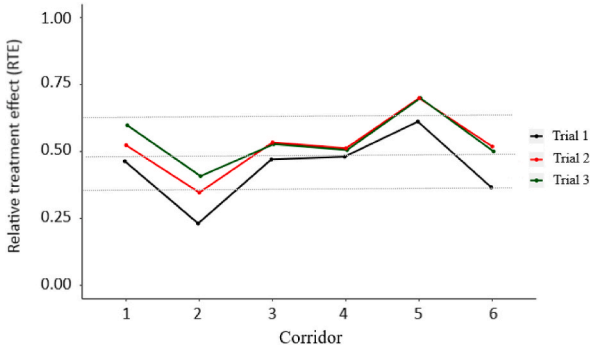

Fig. 3. Effect of crossing corridors on participants' sense of safety at each trial.

trial, which could correspond to a learning effect. It should be noted that 27.8% (n = 5 out of 18) of participants were familiar with the first crosswalk, 33.3% (n = 6 out of 18) with the second, 38.9% (n = 7 out of 18) with the third, 5.6% (n = 1 out of 18) with the fourth, 5.6% (n = 1 out of 18) with the fifth, and 71.4% (n = 10 out of 14) with the sixth. Although this variable might impact the sense of safety, it was not considered in the analyses due to the unknown extent of familiarity with the crossing corridors (e.g., whether a crossing corridor was crossed only once or on a daily basis).

3.2. Level of safety

From the raw data collected using the GPS system, it is possible to illustrate the route taken and to calculate, for each trial, each crossing corridor and each 5% of the route, the percentage of participants situated within the safety corridor (see Table 2). Supplemental material provides examples of the trajectories taken by participants. The analysis of GPS trajectories does not allow for the consideration of an average route for the three trials. From one trial to another, participants followed routes that differ considerably. For this reason, GPS data must be analyzed separately for each trial. No clear trends emerge from the ANOVA to identify statistical differences between the six crossing corridors. As can be observed in Figs. 4–6, from trial to trial, the differences between the crossing corridors are not located at the same portions of the route. For instance, in trial 2, the differences between crossing corridors (trial x crossing corridor interaction: $p = 0.019$) occur between 90% and 100% of the route, whereas in trial 3, the differences (interaction: $p = 0.003$) are mostly present at the beginning of the route. For trial 1, no significant interaction was observed ($p = 0.116$).

In *post-hoc* tests, when pairwise comparisons are made between the crossing corridors using equality of proportions tests, very few significant differences are obtained, and no clear trend emerges among the three trials. For instance, the significant differences between two crossing corridors for one trial are not similarly observed for the other two trials. The significant differences observed in trial 2 between crossing corridors 2 and 6 from 65% to 100% of the route, and between crossing corridors 5 and 6 from 85% to 100% of the route, are the only ones that stand out. Therefore, for these end portions of the route, it can be noted that the percentage of participants within the safety corridor for crossing corridors 2 and 5 is significantly lower than that for crossing corridor 6.

Using the raw data collected through the GPS system, the percentage of participants situated outside the safety corridor was also calculated for each trial, each crossing corridor, and each 5% interval of the route. In these cases, it was also determined whether the participants were positioned on the inner or outer side of the safety corridor (Tables 3 and 4). Although several nuances exist due to environmental characteristics specific to each of the six studied crossing corridors, participants were generally considered to be in a risk zone when they were on the inner side of the safety corridor (i.e., towards the stopped cars with a red light) and generally in a danger zone when they were on the outer side of the safety corridor (i.e., in the open intersection zone). It is noticeable that the percentage of participants located on the inner side of the safety corridor, hence in a risk zone, is higher for crossing corridors 2 and 6, which are two of the three long crossings. For crossing corridor 2, this percentage is higher at the beginning and at the end of the route, whereas for crossing corridor 6, it is higher only at the beginning of the route. These results are likely attributable to the location of the poles with pedestrian pushbuttons, which are in line with the risk zones, and therefore outside the safety corridors. It is also observed that the percentage of participants located on the outer side of the safety corridor, thus in a danger zone, is higher for crossing corridor 5, as well as for crossing corridors 1 and 3, but to a lesser extent. It is important to note that these are all short crossings, and that it is mainly in the second half of the route that participants find themselves in this danger zone. These results can be interpreted in two different ways regarding the degree of danger. On one hand, in the case of crossing corridors 1 and 5, where exclusive phasing is present, vehicles do not circulate during the crossing. Therefore, pedestrian deviations should not result in collisions. However, they might deviate enough to still be on the road when the pedestrian phase ends and vehicles start moving again, which can become a source of insecurity and danger. On the other hand, the parallel traffic alongside crossing corridor 3 might pose a risk of collision with vehicles traveling in parallel. However, their presence provides an auditory cue for pedestrians to adjust their trajectory during the crossing.

The number of participants who came into contact with a raised median, an obstacle only present in the case of long crossings (i.e., crossing corridors 2, 4, and 6), was recorded for each trial. This contact was generally made with their cane or their feet. When all trials are combined, it is observed that four participants came into contact with the raised median at crossing corridor 2. None of these

Table 2
Percentage of participants in safety according to crossing progression for each crossing corridor and at each trial[a].

Crossing corridor[b]	Progression in % of completed crossing																				
	0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%	100%
TRIAL 1																					
1	94.1	94.1	100	100	100	94.1	94.1	94.1	88.2	82.4	82.4	82.4	76.5	76.5	76.5	76.5	76.5	76.5	75.0	75.0	81.3
2	68.8	75.0	75.0	81.3	81.3	87.5	87.5	93.8	93.8	93.8	93.8	81.3	75.0	75.0	75.0	75.0	68.8	62.5	62.5	62.5	62.5
3	94.4	94.4	94.4	94.4	94.4	94.4	88.9	94.4	66.7	72.2	72.2	72.2	72.2	72.2	72.2	72.2	72.2	66.7	66.7	72.2	72.2
4	94.4	94.4	94.4	88.9	77.8	77.8	77.8	77.8	72.2	72.2	77.8	77.8	83.3	83.3	83.3	83.3	77.8	83.3	83.3	83.3	83.3
5	87.5	87.5	87.5	87.5	100	100	100	100	100	100	87.5	81.3	81.3	68.8	68.8	62.5	62.5	62.5	56.3	62.5	62.5
6	71.4	85.7	92.9	92.9	92.9	85.7	85.7	85.7	85.7	100	92.9	92.9	92.9	92.9	92.9	92.9	85.7	85.7	85.7	85.7	78.6
TRIAL 2																					
1	94.4	94.4	88.9	88.9	88.9	88.9	88.9	88.9	83.3	66.7	66.7	72.2	72.2	72.2	72.2	72.2	72.2	72.2	72.2	77.8	72.2
2	76.5	82.4	82.4	82.4	82.4	88.2	88.2	82.4	82.4	82.4	70.6	70.6	70.6	58.8	58.8	52.9	52.9	58.8	52.9	47.1	50.0
3	94.4	94.4	94.4	94.4	88.9	88.9	83.3	77.8	77.8	77.8	72.2	72.2	72.2	72.2	72.2	66.7	61.1	72.2	66.7	72.2	66.7
4	94.4	94.4	94.4	94.4	77.8	77.8	77.8	83.3	77.8	77.8	77.8	77.8	77.8	77.8	77.8	72.2	77.8	77.8	83.3	83.3	88.9
5	88.9	94.4	94.4	94.4	94.4	94.4	94.4	94.4	100	94.4	83.3	77.8	77.8	77.8	77.8	77.8	77.8	61.1	55.6	55.6	55.6
6	69.2	76.9	76.9	76.9	76.9	76.9	84.6	84.6	100	100	100	100	100	100	100	100	100	100	100	100	100
TRIAL 3																					
1	94.4	94.4	94.4	88.9	88.9	88.9	88.9	88.9	88.9	88.9	88.9	88.9	88.9	88.9	83.3	83.3	83.3	83.3	83.3	83.3	88.9
2	73.3	68.8	70.6	76.5	76.5	76.5	82.4	82.4	82.4	88.2	82.4	82.4	88.2	88.2	88.2	88.2	88.2	70.6	70.6	64.7	64.7
3	94.4	100	88.9	88.9	88.9	88.9	88.9	88.9	88.9	83.3	83.3	83.3	83.3	77.8	83.3	77.8	77.8	72.2	66.7	66.7	72.2
4	100	100	100	94.4	94.4	94.4	94.4	88.9	88.9	88.9	88.9	88.9	88.9	88.9	88.9	88.9	88.9	88.9	88.9	82.4	82.4
5	88.9	88.9	94.4	94.4	94.4	94.4	94.4	94.4	88.9	88.9	83.3	77.8	72.2	72.2	66.7	72.2	66.7	55.6	44.4	61.1	61.1
6	50.0	57.1	71.4	71.4	71.4	71.4	71.4	71.4	92.9	100	100	100	100	92.9	85.7	85.7	85.7	85.7	85.7	85.7	92.9

In green: 100% of participants are in the safety corridor. In yellow: 75 to 99.9% of participants are in the safety corridor.

[a] Generally, the total number of participants is 18 for crossing corridors 1 to 5, and 14 for crossing corridor 6. However, there are missing data. This is essentially attributable to the fact that some of the signals emitted by satellites could not be captured by the GPS receiver due to the presence of tree leaves.

[b] 1) exclusive phasing with non-directional APS, short crossing; 2) exclusive phasing with non-directional APS, long crossing; 3) concurrent phasing with directional APS, short crossing; 4) exclusive phasing with directional APS, long crossing; 5) exclusive phasing with directional APS, short crossing; 6) concurrent phasing with directional APS, long crossing.

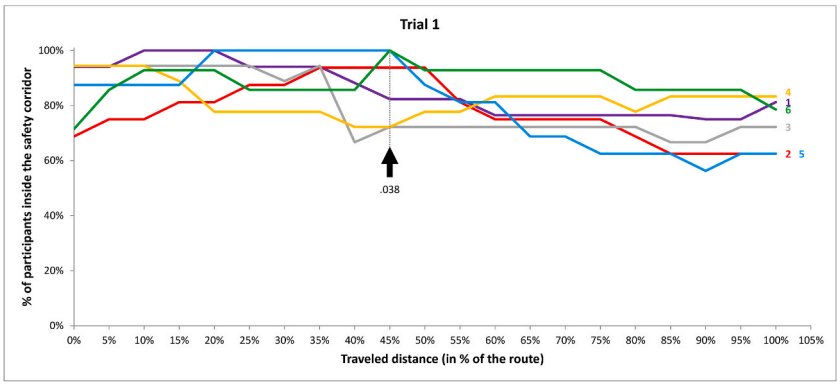

Fig. 4. Percentage of participants in safety at trial 1 according to crossing progression. A black arrow indicates the presence of a statistically significant difference between the crossing corridors at a specific portion of the route. Crossing corridors: 1) exclusive phasing with non-directional APS, short crossing; 2) exclusive phasing with non-directional APS, long crossing; 3) concurrent phasing with directional APS, short crossing; 4) exclusive phasing with directional APS, long crossing; 5) exclusive phasing with directional APS, short crossing; 6) concurrent phasing with directional APS, long crossing.

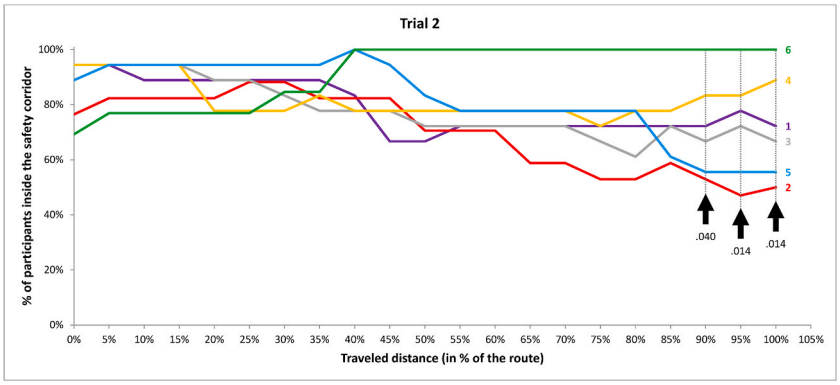

Fig. 5. Percentage of participants in safety at trial 2 according to crossing progression. A black arrow indicates the presence of a statistically significant difference between the crossing corridors at a specific portion of the route. Crossing corridors: 1) exclusive phasing with non-directional APS, short crossing; 2) exclusive phasing with non-directional APS, long crossing; 3) concurrent phasing with directional APS, short crossing; 4) exclusive phasing with directional APS, long crossing; 5) exclusive phasing with directional APS, short crossing; 6) concurrent phasing with directional APS, long crossing.

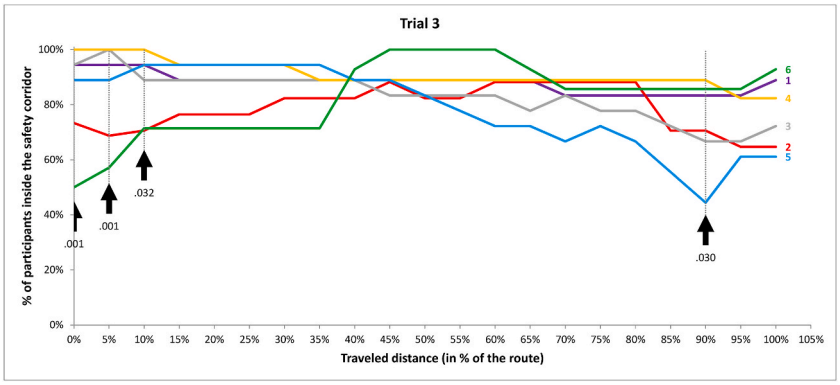

Fig. 6. Percentage of participants in safety at trial 3 according to crossing progression. A black arrow indicates the presence of a statistically significant difference between the crossing corridors at a specific portion of the route. Crossing corridors: 1) exclusive phasing with non-directional APS, short crossing; 2) exclusive phasing with non-directional APS, long crossing; 3) concurrent phasing with directional APS, short crossing; 4) exclusive phasing with directional APS, long crossing; 5) exclusive phasing with directional APS, short crossing; 6) concurrent phasing with directional APS, long crossing.

Table 3
Percentage of participants in a risk zone[a] according to crossing progression for each crossing corridor and at each trial[b].

Crossing corridor[c]	Progression in % of completed crossing																				
	0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%	100%
TRIAL 1																					
1	5.9	5.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.9	5.9	5.9	5.9	5.9	5.9	6.3	6.3	6.3
2	31.3	25.0	25.0	18.8	18.8	12.5	12.5	6.3	6.3	6.3	6.3	12.5	18.8	18.8	18.8	18.8	25.0	31.3	31.3	31.3	31.3
3	5.6	5.6	5.6	5.6	5.6	5.6	11.1	5.6	22.2	16.7	16.7	16.7	16.7	16.7	16.7	16.7	22.2	22.2	22.2	16.7	16.7
4	5.6	5.6	5.6	5.6	11.1	11.1	11.1	11.1	16.7	16.7	16.7	16.7	11.1	11.1	11.1	11.1	16.7	16.7	16.7	16.7	16.7
5	12.5	12.5	12.5	12.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	28.6	14.3	7.1	7.1	7.1	14.3	14.3	14.3	14.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.1	7.1	7.1	7.1	14.3
TRIAL 2																					
1	5.6	5.6	11.1	11.1	11.1	11.1	11.1	11.1	11.1	16.7	16.7	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1
2	23.5	17.6	17.6	17.6	17.6	11.8	11.8	11.8	11.8	11.8	11.8	11.8	17.6	29.4	29.4	35.3	35.3	35.3	41.2	47.1	43.8
3	5.6	5.6	5.6	5.6	5.6	5.6	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	16.7	16.7	11.1	11.1	11.1	16.7
4	0.0	0.0	0.0	0.0	16.7	16.7	16.7	11.1	16.7	16.7	16.7	16.7	16.7	16.7	16.7	22.2	16.7	16.7	11.1	11.1	5.6
5	11.1	5.6	5.6	5.6	5.6	5.6	5.6	5.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6	5.6	5.6	5.6
6	30.8	23.1	23.1	23.1	23.1	23.1	15.4	15.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TRIAL 3																					
1	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	11.1	11.1	11.1	11.1	11.1	11.1	11.1
2	26.7	31.3	29.4	23.5	23.5	23.5	17.6	17.6	17.6	11.8	17.6	11.8	5.9	5.9	5.9	5.9	5.9	17.6	17.6	23.5	29.4
3	5.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6	5.6	5.6	5.6	5.6	5.6
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	11.1	11.1	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6
6	50.0	42.9	28.6	28.6	28.6	28.6	28.6	28.6	7.1	0.0	0.0	0.0	0.0	0.0	7.1	7.1	7.1	7.1	7.1	7.1	7.1

In red: $\geq$ 20% of participants are in a risk zone.
[a] The risk zone corresponds, within this table, to the inner side of the safety corridor.
[b] Generally, the total number of participants is 18 for crossing corridors 1 to 5, and 14 for crossing corridor 6. However, there are missing data. This is essentially attributable to the fact that some of the signals emitted by satellites could not be captured by the GPS receiver due to the presence of tree leaves.
[c] 1) exclusive phasing with non-directional APS, short crossing; 2) exclusive phasing with non-directional APS, long crossing; 3) concurrent phasing with directional APS, short crossing; 4) exclusive phasing with directional APS, long crossing; 5) exclusive phasing with directional APS, short crossing; 6) concurrent phasing with directional APS, long crossing.

Table 4
Percentage of participants in a danger zone[a] according to crossing progression for each crossing corridor and at each trial[b].

Crossing corridor[c]	Progression in % of completed crossing																				
	0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%	100%
TRIAL 1																					
1	0.0	0.0	0.0	0.0	0.0	5.9	5.9	5.9	11.8	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	18.8	18.8	12.5
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	5.6	11.1	11.1	11.1	11.1
4	0.0	0.0	0.0	5.6	11.1	11.1	11.1	11.1	11.1	11.1	5.6	5.6	5.6	5.6	5.6	5.6	5.6	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.5	18.8	18.8	31.3	31.3	37.5	37.5	37.5	43.8	37.5	37.5
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1
TRIAL 2																					
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	11.1	16.7
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.9	5.9	5.9	17.6	17.6	11.8	11.8	11.8	11.8	11.8	5.9	5.9	5.9	6.3
3	0.0	0.0	0.0	0.0	5.6	5.6	5.6	11.1	11.1	11.1	16.7	16.7	16.7	16.7	16.7	16.7	22.2	16.7	22.2	16.7	16.7
4	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6	16.7	22.2	22.2	22.2	22.2	22.2	22.2	33.3	38.9	38.9	38.9
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TRIAL 3																					
1	0.0	0.0	0.0	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.9	5.9	5.9	5.9	5.9	5.9	11.8	11.8	11.8	5.9
3	0.0	0.0	11.1	11.1	11.1	11.1	11.1	11.1	11.1	16.7	16.7	16.7	16.7	22.1	16.7	16.7	16.7	22.2	27.8	27.8	22.2
4	0.0	0.0	0.0	5.6	5.6	5.6	5.6	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	17.6	17.6
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6	5.6	11.1	16.7	22.2	22.2	27.8	22.2	27.8	38.9	50.0	33.3	33.3
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.1	7.1	7.1	7.1	7.1	7.1	7.1	0.0

In red: $\geq$ 15% of participants are in a danger zone.
[a] The danger zone corresponds, within this table, to the outer side of the safety corridor.
[b] Generally, the total number of participants is 18 for crossing corridors 1 to 5, and 14 for crossing corridor 6. However, there are missing data. This is essentially attributable to the fact that some of the signals emitted by satellites could not be captured by the GPS receiver due to the presence of tree leaves.
[c] 1) exclusive phasing with non-directional APS, short crossing; 2) exclusive phasing with non-directional APS, long crossing; 3) concurrent phasing with directional APS, short crossing; 4) exclusive phasing with directional APS, long crossing; 5) exclusive phasing with directional APS, short crossing; 6) concurrent phasing with directional APS, long crossing.

participants completed their crossing within the safety corridor. At crossing corridor 4, two participants came into contact with the raised median. The impact resulted in one participant falling (no injuries were reported or observed), who was subsequently accompanied by the research assistants to the finish point. The other participant did not complete their crossing within the safety corridor. Nine participants came into contact with the raised median at crossing corridor 6. Among them, seven were able to complete the crossing within the safety corridor.

It should be noted that information regarding the success or failure of crossing within the allotted time for the pedestrian phase was not systematically recorded, making it impossible to draw any conclusions in relation to this aspect of the crossing.

Table 5 presents the number of instances where participants initiated their crossing outside the safety corridor and, among them, those where participants completed their crossing within the safety corridor. Across all crossing corridors, it is notable that for a small proportion of instances, participants begin their crossing outside the safety corridor (9.9%), and that for the vast majority of them participants are positioned on the inner side of the corridor, thus within a risk zone and not a danger zone. This is generally attributable to the location of the pole with the pedestrian pushbutton, which are directly in line with the risk zone in some crossing corridors. The proportion of instances where participants were successfully aligning themselves to complete their crossing in the safety zone varies from trial to trial and from one crossing corridor to another. Of the 29 instances where a participant started their crossing from the inner side of the safety corridor, thus within a risk zone, 15 (51.7%) were completed within the safety corridor, 13 (44.8%) were completed within a risk zone, and one (3.5%) was completed within a danger zone. For the two instances where participants initiated their crossing from the outer side of the safety corridor, thus within a danger zone, participants completed their crossing in that same danger zone. Consequently, even though in only 48.4% of the instances participants correctly adjusted their trajectory to enter the safety zone, very few dangerous trajectories were observed, regardless of the type of configuration or trial. However, it is noteworthy that the percentage of instances where participants correctly adjusted their trajectory is higher for crossing corridor 6.

4. Discussion

Through experiments conducted at six crossing corridors, this research appraised the sense of safety and level of safety of blind or visually impaired persons regarding the three types of pedestrian phasing with APS configurations that exist in Quebec City, Canada.

4.1. Sense of safety

Looking separately at long crossings and short crossings, the traffic control system with an exclusive pedestrian phase that uses the directional APS appears to provide a higher sense of safety during the experiments than the other two types of configurations (i.e., exclusive phasing with non-directional APS and concurrent phasing with directional APS). This is in line with the existing literature (Bentzen et al., 2006; Ivan et al., 2017) and the findings from the first two phases of this study where many participants indicated that they had a heightened sense of safety when there is: a) an absence of car movement, b) a pushbutton locator tone, c) the emission of a sound confirming that the sound signal command has been activated, and d) an alternating APS at either end of the intersection (Routhier et al., 2023).

The exclusive phasing with non-directional APS configuration has the advantage of being widely familiar; participants are accustomed to it since it has been common in the Quebec City area for a long time. However, in these experiments, participants' sense of safety was at its lowest during a long crossing at a corridor with this type of configuration. This is consistent with the results from the interviews conducted as a first step of this project, where almost half of the participants pointed out the disadvantages of the non-directional APS, namely due to the challenges maintaining proper alignment when crossing (Routhier et al., 2023). Overall, in the current experiments, participants' sense of safety with this type of configuration is similar to that expressed with the concurrent phasing with directional APS configuration. This observation differs from that made following our online survey, where it was found that this last configuration (i.e., concurrent phasing with directional APS) was perceived as the least safe (Routhier et al., 2023). Actually, opinions expressed on the concurrent phasing with directional APS configuration were polarized. Nearly 50% of the interviewed participants expressed a sense of insecurity due to the simultaneous presence of vehicles and pedestrians on the road.

Table 5
Arrival location for instances where participants started their crossing outside the safety corridor.

Crossing corridor[a]	Departure[b] from outside the safety corridor		Arrival inside the safety corridor when the departure is outside the safety corridor
	Inner side	Outer side	
1	3	0	1 (33.3%)
2	11	0	5 (45.5%)
3	2	2	0 (0.0%)
4	2	0	0 (0.0%)
5	3	0	2 (66.7%)
6	8	0	7 (87.5%)
TOTAL	29	2	15 (48.4%)

[a] 1) exclusive phasing with non-directional APS, short crossing; 2) exclusive phasing with non-directional APS, long crossing; 3) concurrent phasing with directional APS, short crossing; 4) exclusive phasing with directional APS, long crossing; 5) exclusive phasing with directional APS, short crossing; 6) concurrent phasing with directional APS, long crossing.

[b] The departure zone here comprises the first two 5% sections of the crossing, i.e. the first 10% of the crossing.

Nonetheless, individuals who were accustomed to this configuration and had a higher tolerance for risk appreciated it. Existing literature highlights some benefits of concurrent phasing, including shorter disruptions to both pedestrian and vehicular flow and the potential for blind or visually impaired individuals to use parallel traffic sounds to initiate and maintain their crossing alignment (Bentzen et al., 2004; Ivan et al., 2017).

4.2. Level of safety

While no clear trend emerges from the analyses conducted using the GPS data collected to identify statistically significant differences among the six selected crossing corridors with respect to the participants' level of safety, one point does draw attention. Among the few statistical differences that stand out, it can be observed that in trial 2, the percentage of participants located within the safety corridor in crossing corridor 5 (exclusive phasing with directional APS, short crossing) is significantly lower than that in crossing corridor 6 (concurrent phasing with directional APS, long crossing) at the very end of the route (85% vs. 100%). The objective level of safety is, therefore, different in this case from the sense of safety expressed by the participants. Indeed, participants' sense of safety was highest in crossing corridor 5. For crossing corridor 5, the exclusive phasing means that all car movements are prohibited while in crossing corridor 6, parallel movement of vehicles is permitted. Thus, although individuals in crossing corridor 5 may have finished outside of the designated safety corridor, the fact that vehicle movement is absent might help explain why participants rated it safer despite the problems of crossing within the safety corridor. However, as this statistical difference in trial 2 is not observed in the other two trials, it may only be "noise". It is difficult to determine whether the near absence of statistically significant differences obtained between the crossing corridors regarding level of safety can be attributed to methodological/contextual factors (e.g., the impact of the GPS system on participants' trajectories, the presence of buses, the presence of cyclists) or if the level of safety is genuinely not significantly different between configurations. The results obtained do not allow for the identification of an ideal configuration or even a configuration to avoid.

Regardless of the type of configuration, participants consistently feel safer during a short crossing than during a long crossing. Indeed, the results suggest that a short intersection seems to reduce the risk of losing one's alignment, thereby increasing participants' sense of safety. However, it is surprising to note that this is not necessarily confirmed by the collected GPS data, while the percentage of participants within the safety corridor is not systematically higher in the case of short crossings. Furthermore, participants were more likely to find themselves in a danger zone (i.e., on the outer side of the safety corridor) in the case of short crossings than in the case of long crossings. Obviously, it is impossible to prioritize the sense of safety at the expense of the level of safety, and vice versa. Although the level of safety cannot be set aside for clear reasons, the sense of safety is equally important as it is a prerequisite for participation (i.e., being independently mobile). However, since the results related to the level of safety do not identify a preferred or prohibited configuration, but the results regarding the sense of safety are clear (preference for the configuration of exclusive phasing with directional APS), it is recommended, as a future step, that a larger-scale evaluation of the level of safety allowing for more detailed analyses (e.g., according to visual profiles) be conducted. Such a study should be carried out in a real use context and could include cities other than just Quebec City.

4.3. Study limitations

The GPS system receiver that participants had to carry on their backs was quite bulky, and despite efforts to minimize its inconvenience, it is possible that it influenced the participants' trajectories. Additionally, for logistical reasons, all participants experienced the six selected crossing corridors in the same order. A fatigue effect may have had an impact on the results. Furthermore, due to the small sample pool, it was impossible to perform separate analyses comparing participants with functional residual sight to those without or socio-demographic factors such as gender, age, or years of experience. Unfortunately, a detailed description of visual impairments (e.g., characteristics such as visual acuity and visual field) was not collected. However, considering the small sample pool, we would not have been able to conduct analyses documenting the impact of these difficulties on the participants' sense of safety and level of safety. Similarly, older adults were excluded from the study due to their often distinct walking behaviors, including variations in gait patterns and balance. This decision aimed to manage the already significant variability within our sample. Additionally, given our small sample size, conducting specific analyses for older adults would not have been feasible. Although generalizability is limited because the study was conducted in only one city, the unique experimental context of this area, including the use of the rather unique exclusive phasing with non-directional APS configuration, provides valuable contribution for documentation of advantages and disadvantages of different types of pedestrian phasing with APS configurations from the perspective of blind or visually impaired persons. This study highlights the complexity of this type of evaluation, as multiple factors must be considered to gain a comprehensive understanding of the phenomenon. Given the numerous parameters and variables involved in this project (configuration type, intersection characteristics, participant characteristics, etc.), a larger sample would have allowed for more extensive analyses. However, conducting such a large-scale experiment is expensive and logistically challenging. While it is difficult to expand further in a real-world setting, controlled environment experiments (e.g., virtual reality laboratories) also have limitations, particularly in terms of generalizing the results. Finally, future studies might examine how the speed, volume of traffic, or vehicles types impact perceptions of safety. For instance, cyclists and electric vehicles may impacts some individuals' sense of safety, as they do not make much noise.

5. Conclusion

Through this study, it was possible to investigate, in a real-world setting, within the same population and on the same territory, the

sense and level of safety of 18 blind or visually impaired persons regarding three different types of pedestrian phasing with APS configurations. Due to the small sample size, the results must be interpreted with caution, but they do address a gap in knowledge with respect to APS paired with traffic signals and perceived safety and objective safety experienced by their target users. The results obtained do not allow for the identification of an ideal configuration or even a configuration to avoid with regard to the level of safety. However, the findings suggest that the exclusive phasing with directional audible pedestrian signals configuration is perceived to be the safest option by the participants. The results from this project will enhance the existing body of knowledge and expertise related to accessibility for individuals with disabilities. In particular, this research could have practical applications in shaping the design of intersections equipped with APS, determining the most suitable APS type based on intersection features, providing guidance for the training of blind or visually impaired pedestrians by orientation and mobility specialists (e.g., familiarization with different types of configurations, description of the issues associated with each configuration, follow-up over time), and emphasizing the significance of educating road users about pedestrians who are blind or visually impaired. Interestingly, this study led one of our partners to take things a step further and carry out a comparative analysis of the various APS implemented in other countries, as well as their deployment and maintenance strategies, in order to identify innovation opportunities for Quebec (Regroupement des personnes handicapées visuelles).

CRediT authorship contribution statement

François Routhier: Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Josiane Lettre:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Caroline Pigeon:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Valérie Martel:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **René Binet:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Véronique Vézina:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Olivier Collomb d'Eyrames:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **E. Owen Waygood:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Mir Abolfazl Mostafavi:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Ernesto Morales:** Writing – review & editing, Methodology, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors do not have any conflicts of interest to declare.

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Appendix ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jth.2024.101938.

Data availability

Data will be made available on request.

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