The cost of knowing

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The Cost of Knowing: How Obstacle Alerts Reduce Walking Speeds of Augmented White Cane Users

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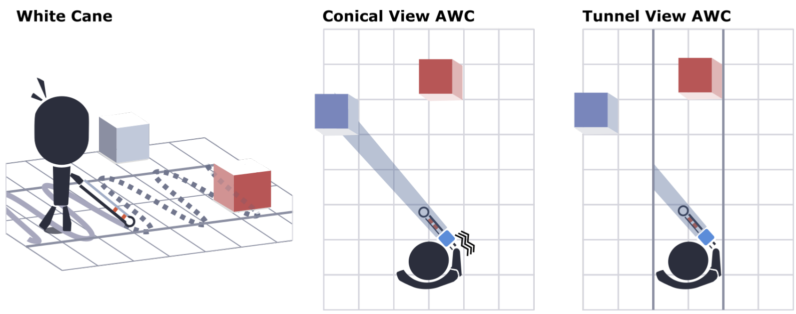

Fig. 1. Left: White cane sampling previews the path for obstacles. Center: AWC with conical view able to alert obstacles outside their path. Right: AWC with tunnel view only able to alert about obstacles inside the path ahead

To ensure safe passage blind travellers utilize mobility aids such as the white cane to preview the space their body will move through. Augmented white canes (AWC) have increased this preview range to reduce collisions, but consequently incurred lower walking speeds. The literature has blamed the slowdown on the AWC provided alerts that are additional to white cane feedback, unnecessary, too complex, and the anticipatory slowdown of their users. Two within-subject studies with six visually impaired and ten blindfolded people compared the white cane to two different AWC preview types (See Figure 1) combined with two ranges to investigate the causes of the slowdowns. The cognitive cost from processing AWC additional and unnecessary alerts and their complexity slowed users down and should be kept to a minimum as they neither helped reduce collisions nor physically detecting obstacles with the cane.

CCS Concepts: • **Human-centered computing → Accessibility design and evaluation methods**; *Accessibility technologies*; *User studies*; *Laboratory experiments*.

Additional Key Words and Phrases: White cane, visually impaired, blind, mobility aid, electronic mobility aid, electronic travel aid, preview range, collisions, walking speed, alerts, haptic interface

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1 INTRODUCTION

For 216 million people [6], the loss of vision severely limits their perceived space, making movement unsafe due to collisions (unintended body contact) with obstacles. To physically detect and be *kinetically* alerted to obstacles, many blind pedestrians *preview* the space ahead by sweeping their white canes from side to side. Despite its popularity, white cane users walk more slowly than those with guide dogs [7] or sighted guides [9]. One explanation is that the white cane's short preview range requires slower walking to allow for stopping in time when detecting obstacles. Augmented white canes (AWCs) provide such *vibration* alerts to obstacles earlier than the cane, but incur even slower walking speeds. Previous research has offered many and sometimes contradicting explanations, such as 1) the quantity of alerts 2) the usefulness of alerts, 3) proactively slowing down, and 4) the complexity of the alert, but provided scant empirical evidence in their support.

To validate these hypotheses, we designed an AWC with two different views: 1) conical - detecting obstacles it was pointing towards and 2) tunnel - detecting obstacles it was pointing towards that resided in the traveled path (see Figure 1). Both were coupled with 2m and 4m preview ranges. As parameters, we relied on the walking speed, alert types (kinetic vs. vibrations), number of alerts and collisions. We employed a physical obstacle course utilizing virtual reality hardware to track six visually impaired and ten blindfolded people. When travelling at nominal speed both kinetic and vibration alerts to an obstacle incurred a temporary reduction in walking speed.

The paper contributes empirical knowledge on the cognitive costs of alerts in terms of walking speed reductions, a comparison between blind people and blind-folded proxy, design guidelines for AWCs, and a testing methodology for running studies using virtual reality hardware setup allowing to track and evaluate novel AWC behaviours without physical prototypes.

2 BACKGROUND

Apart from increasing safety by reducing collisions and ensuring efficient mobility, the white cane provides tremendous (direct and indirect) benefits with keeping balance [38, 46], detecting drop-offs (e.g. curbs) [22, 24], echolocation [43], alerting other travelers (visually and audibly), and maintaining orientation by detection and following of continuous edges e.g. tactile paving and walls (shorelining) [42]. During the orientation and mobility (O&M) detection technique 'constant touch' (CT), users hold the cane with their preferred hand, extending the preview of their path by around one meter at ground level. They sweep the cane from side to side, synchronized with the gait cycle, keeping the cane tip in front of the back-most foot, which can then be safely placed into the previewed spot the cane tip just sampled [27]. While sampling the path, the cane works as a physical bumper for obstacles (providing haptic and kinetic feedback), often enabling the user to terminate their gait before collisions. However, the sweeping frequency combined with a forward momentum of the user, results in sampling only 70% of the ground in the travelled path [4, 29, 47]. Consequently, 30%-40% of ground obstacles taller than 18 cm go undetected and more so for smaller ones due to the angle of the cane [20, 21, 23]. Likewise, obstacles elevated above knee level are not detected in time to terminate gait [32].

On ideal controlled routes with no obstacles, blind travelers walked more slowly with white canes (0.9m/s) [12, 19] than guide dogs (1.45m/s) [7] or sighted guides (1.8m/s) [9]. Routes with narrower width, ill-defined shorelines, and high obstacle densities on the shoreline, reduced walking speeds with white canes to around 0.6m/s [7]. Hollins suggested that the cane's short preview range might require users to constantly be prepared to quickly correct course or terminate gait on obstacle detection, hence forcing a slower pace [16]. Conversely, Kim et al. conjectured that longer preview ranges should support faster walking by alerting to obstacles earlier [25]. However, increasing the physical length of the cane has its drawbacks as, add weight, make sweeping harder, and decreases drop-off detection [23]. Hence, designers have created a variety of electronic mobility/travel aids (EMA/ETA), utilizing electronic distance sensors to increase the range of the preview while also covering the users entire body by alerting to elevated obstacles. Thereby, in theory, improving both safety and walking speeds compared to the white cane.

2.1 Augmented White Canes

We reviewed the literature on a category of EMAs - augmented white canes (AWC), which provide standard O&M technique benefits (e.g. detecting drop-offs and shorelining). The review only included studies reporting on walking speeds, preview ranges, collisions, obstacle densities, training times, and provided baseline comparisons to a traditional white cane, see Table 1. To alert to obstacles ahead of the cane's sweeping range, AWCs utilized distance sensors with ranges varying between 1m to 3m, either due to sensor limitations or undocumented design decisions. The sensor(s) field of view (FoV), in which they detected obstacles, differed between 18° and 60°. However, during O&M sweeping, the total area sampled by the movable sensor(s) provided an additional 50-60°of coverage to the field of regard (FoR) [25]. Combined with the longer detection range this alerted to obstacles outside of the path ahead. Furthermore, the sensors alerted to obstacles above knee level.

As hoped by their designers, the increased preview reduced obstacle collisions when elevated obstacles - undetectable by the white cane alone - were included in the course [25, 28, 41]. Without obstacles elevated above the white cane, AWCs did not help in reducing collisions [10, 36]. Given that collisions slow down walking and AWCs reduced collisions with elevated obstacles, one would expect faster walking with AWCs [25, 28, 41, 44]. Surprisingly, all of the AWCs yielded slower walking speeds (see Table 1). We categorized the lines of explanation given by previous studies for this slowdown into four hypotheses:

- H1: **Additional alerts**: Kuchenbecker et al. blamed the cognitive burden from mentally processing the additional alerts compared to the white cane, i.e. by providing multiple alerts per obstacle [28].
- H2: **Unnecessary alerts**: Clark-Carter et al. criticized AWCs for creating unnecessary alerts to irrelevant obstacles outside the travelers' path, that do not help with reducing collisions [8].
- H3: **Anticipatory slowdown**: Kuchenbecker et al. attributed it to walking more slowly to avoid or stop in time for obstacles alerted to [28].
- H4: **Feedback complexity**: Santos et al. faulted unfamiliarity and complexity of the vibration modality contributing to a higher cognitive cost for interpreting obstacle distances from vibration patterns [10].

All four explanations suggested that alerts imposed a cost reducing walking speeds. None of the surveyed studies tried to quantify the cost of physical or augmented alerts from AWCs. Instead, they reported the number of detected obstacles - often as percentages of the total number of obstacles [10]. However, participants might have received multiple alerts about the same obstacle and therefore the number of detected obstacles combined the cost of all alerts for a given obstacle, which would overestimate the cost of individual alerts.

Our review identified three control variables for the evaluation and comparison of AWCs that increased walking speeds: prior white cane familiarity, amount of training during the experiment, and lower obstacle densities. Novice white cane users (e.g. blindfolded) walked more slowly (avg. 0.30m/s [10, 28]) than experienced ones (avg. 0.44m/s [10, 25, 41]) indicating that the absolute

Table 1. Seven studies evaluated AWCs (best result **bolded**) and a white cane. Sub-studies within publications appear on separate lines. Symbols = and > represent the relationship where exact number were not reported.

Author	**range**	**FoV** †	**obstacles per meter**	**p** ‡		**collisions**		**walking speed (m/s)**	
				b	bf	white cane	AWC	white cane	AWC
O'Brien et al. [36]	1	60°	0.25		16	=		=	
Kuchenbecker [28]	2	18°	0.33		15	>		**0.33***	0.19
Santos et al. [10, 11]	1.5	30°	0.24		31	2.2	**1.9**	**0.26***	0.20
	1.5	30°	0.24	10		0.8	**0.7**	**0.40***	0.33
Kim & Cho [25]	2	30°	0.70	20		8	**6.5***	**0.31**	0.30
Roentgen et al. [41]	2	–	0.48	8		7.8	**4.2***	**0.62***	0.49
Vaibhav et al. [44]	3	50°	0.82	28		5.6	**0.4***	>	
This study: conical view	2-4	5cm	0.86	6		1.2	**1.1**	**0.54***	0.50
tunnel view	2-4	5cm	0.86	6		1.2	1.2	**0.54***	0.50
conical view	2-4	5cm	0.86		10	**1.4**	1.6	**0.33***	0.28
tunnel view	2-4	5cm	0.86		10	1.4	**1.2**	**0.33**	0.31

* *Significant difference between white cane and AWC* † *Field of View* ‡ *(P)articipants: (b)lind and blindfolded (bf)*

results from proxy groups do not generalize to blind users [10]. However, given the group-based average values reported by Santos et al. both blind- and proxy participants walked 20% more slowly and experienced 14% fewer collisions using an AWC [10]. Indicating, proxy groups might be used to evaluate relative differences between conditions, however, further compassion studies need to verify whether this is the case. Training times for participants varied between five minutes to a few hours. Participants who received more training walked faster (0.62m/s) [41] than those with less training (0.33m/s) [10, 25, 28]. Obstacle courses that participants traversed varied in length (17m to 30m), tactile support (with or without shorelines), and the number and types of obstacles included (ground level, elevated above waist level, or a mixture of both). Obstacle densities varied between 0.2 to 0.8 obstacles per meter. Higher obstacle densities increased collisions and reduced walking speeds [10, 25, 28, 36, 41].

In summary, AWCs alerts to distant obstacles reduced collisions at the cost of slower walking speeds, compared to the white cane. But no study has systematically investigated the cost of alerts.

3 STUDY 1

To understand to what degree the hypotheses (H1-4) can explain the AWC slow down we designed a study that allowed for correlating received alerts with walking speeds (H1), compared unnecessary to relevant alerts (H2), different ranges that allowed for investigating the anticipatory slowdown (H3), and included feedback with higher and lower complexity (H4). To do so our experimental setup compared three different mobility aids in a within subject study: a traditional white cane as baseline and an AWC with two different view types (see Figure 1):

(1) The conical view alerted to the nearest obstacle in the AWC's direction within the FoV and range providing alerts to obstacles outside the path ahead. It served as a comparison baseline representing typical AWC designs.
(2) The tunnel view only alerted to the nearest obstacle in the AWC's direction when it was located within the straight path ahead of the user's torso orientation.

These views allowed us to evaluate two hypothesis - additional (H1) and unnecessary alerts (H2). By measuring how many additional vibration alerts the AWCs provide compared to the white cane and whether some of them are unnecessary, i.e. do not reduce the number of collisions. To evaluate the final two hypothesis - anticipatory slowdown (H3) and alert complexity (H4) - we combined the two different AWC views with 2m and 4m preview ranges. The 4m preview range

Table 2. Black dots represent the activated actuator providing vibrating alerts for obstacle detected within the given preview range. Obstacles alerted within one meter were kinetic alerts from the white cane marked by X.

	< 1 meters	1 to 2 meter	2 to 3 meters	3 to 4 meters
White cane	X -	-	-	-
tunnel & conical AWC	X ○ ○ ○	● ○ ○	○ ● ○	○ ○ ●

matched the maximum range of the UltraCane - a commonly used AWC benchmark [17, 41]. To communicate the distance to the obstacle, we embedded three vibration motors, into the handle under each of the user's index-, middle-, and ring fingers (see Figure 3). Each actuator only provided *vibration alerts* about obstacles within their range of 1-2m, 2-3m, and 3-4m (see Table 2). Mapping obstacle distance to vibration location, i.e. actuators under separate fingers reduce cognitive load over e.g. different intensities of a single vibrator and improve the accuracy of identifying the correct distance [26]. To avoid (re-)learning different distance mappings for each preview range, we disabled the actuators above the target detection range - e.g. for the detection range of 2m the two other actuators were disabled - thereby ensuring the same alert mappings for obstacle distances across the preview ranges. Furthermore, the mapping provide two different levels of alert complexity: 1) the 2m condition conveyed binary feedback - either vibrator 1 was active or not, 2) in the 4m condition users had to distinguish between three actuators to determine obstacle distances. Hick-Hyman's law [18] predicts increasing the number of possible stimuli logarithmically increases the cognitive processing time when taking specific actions. The system did not provide any additional vibration alerts for obstacle detected closer than 1m. Instead, it relied on the *kinetic alerts* from the white cane as all obstacles resided at ground level (see Figure 2). The white cane baseline plus the two different AWCs views each with two different ranges resulted in five different conditions.

To measure how these conditions affected alerts and thereby users walking speed, we used Virtual Reality sensors (HTC Vive) to track the positions and speeds of people and the cane in relation to physical obstacles. The position accuracy varying from a few millimeters to a few centimetres during movements [5].

3.1 Apparatus

Our physical obstacle course was 7m long, 2.8m wide, and contained a 4mm wide and tall wooden shoreline down the middle for orientation (see Figure 2). For simplified placement of cardboard box (70x40x40 cm) obstacles, each meter, seven squares (40x40 cm) were marked perpendicular to the shoreline, for a total of 42 squares. Each scenario included six obstacles placed in different squares,

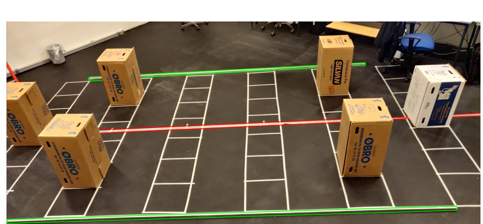

Fig. 2. Real-world 7m obstacle course including the shoreline to keep direction (red line) and outer boundaries consisting of metal bars (green lines).

for an obstacle density of 0.86 obstacles per meter. The physical setups were replicated in a virtual environment (VE) to track and deliver the appropriate feedback (see Figure 2).

We logged movement, speed, and orientation of the participant and AWC, using two HTC Vive trackers. One attached to the participant's shoulder using a 3D-printed mount, ensuring visibility for the base stations. The other tracker was attached to a real white cane with a 3D-printed mount. Since, the uneven surface of the obstacle course caused vibrations in the trackers, resulting in drift. A cloth shock absorber at the tip of the cane removed these drifts (see Figure 3). The trackers controlled two virtual bounding boxes within the VE scene. The participant's bounding box was the equivalent of 45cm wide, 200cm high, and 25cm deep. The AWC's bounding box was the equivalent of 5cm wide, 200cm high, and had a varying length (range) of either 1, 2, or 4m. Each obstacle had a bounding box matching their physical counterpart.

When participants, in the physical world, walked into an obstacle making bodily contact, their bounding boxes overlapped in the virtual environment - logged as a collision. When participants, in the physical world, made direct contact or pointed the AWC towards an obstacle within range, the AWCs and obstacles bounding box overlapped in the virtual environment - logged as an obstacle detection and issued an associated alert (see Table 2). This triggered (using bluetooth) an Arduino Uno micro-controller mounted to the white cane to turn on the vibrotactile alerts through one of the three eccentric rotating mass (ERM) vibration motors embedded into the handle.

3.2 Procedure

We followed Santos' familiarization procedure [10] in which participants first walked the distance of the obstacle course with neither obstacles, nor blindfolds, nor cane until feeling familiar with the course's length. After instructions, the participants practiced the use of the white cane with constant touch and shorelining while walking the course first without then with blindfolds. Once comfortable, they walked a training scenario with added obstacles five times blindfolded. In total, the familiarization took between five to ten minutes.

During the test, the blind-folded participants, equipped with calibrated body- and the AWC-trackers, were guided to the starting position of the course. Aware of the condition (view type and range), they followed the shoreline and circumvented obstacles using the constant touch technique. On completion of a *walk*, a facilitator guided them back to a waiting-point for relaxation (remaining blindfolded), while the next obstacle scenario was setup. After setting up the virtual and physical scenario, the facilitator guided the participant to the starting position. The process was repeated for a total of five different scenarios for a given condition. Scenario order was counterbalanced across conditions within and across participants. The participants completed five scenarios in each

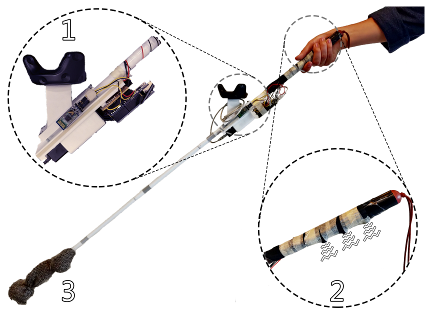

Fig. 3. The AWC. 1: HTC Vive tracker, Arduino Uno and bluetooth-module bolted to the 3D-printed mount. 2: Handle with three embedded eccentric rotating mass (ERM) vibration motors. 3: Shock absorber

of the five conditions for a total of 25 walks. The entire test took between 45 and 60 minutes per participant.

3.3 Participants

Ten (9 male, 1 female) adults (*m*=24, *SD*=3) from a campus population volunteered their time. None were visually impaired or had prior white cane experience.

3.4 Measurements

During each walk, the system logged speed and position of the body/cane at 100 Hz. The system logged obstacle collision(s) (bodily contact with obstacle) and alerts. This included both *kinetic* alerts - from the cane touching obstacles - or *vibration* alerts issued on detection of obstacle within the designated range. When referring to alerts in general this indicates the combined number of kinetic and vibration alerts.

3.5 Analysis

For each walk, we calculated its completion time, average walking speed, and the total numbers of alerts and collisions by grouping the data by participants (n=10), conditions (n=5), and scenarios (n=5). This resulted in 250 degrees of freedom.

We checked these walking speeds for normality using qq-plots and a Shapiro–Wilk test. While they were not normally distributed across participants, they were normally distributed within participants. We therefore relied on linear mixed effect models (LMM) [2, 50] to account for individual baseline differences in walking speeds (dependent variable) and added independent variables (IV) such as aid type, alerts, collisions, etc. as fixed effects. Adding random slopes for the IVs resulted in over-fitting errors for the average walking speeds [2]. We therefore included participants only as random intercepts for the mixed effect models. Table 3 details each of the four successive LMMs adding one fixed effect until the final best fitted model. To pick the model that fit the data best, we relied on Akaike's information criterion (AIC), Bayesian information criterion (BIC), and maximum likelihood (ML). ANOVA tests checked for significant differences between two consecutive models reported by Chi-squared values (χ^2). To quantify the models' explained variance of the data, we calculated the variance by A) the fixed factors - the marginal R squared (R^2_m) and B) the fixed and random factors - the conditional R squared (R^2_c) [1, 33]. For each model fit, we report the fixed effects coefficients utilizing the white cane as the baseline model, the across participants estimated effects of the IVs (B), and their p-values (based on Satterthwaite's method).

The number of (per walk) alerts and collisions were not normally distributed either but followed a Poisson distribution. Therefore, we relied on generalized linear model (GLM) reporting the coefficients, estimated effect (β), and p-values.

Table 3. Mixed linear models predicting the average blindfolded walking speed (avg. WS) based on the number of unique kinetic alerts, unique vibration alerts, and collisions with random intercepts for each participant. χ^2 values denote report the test between the current and the previous row.

	Predicted	**Random intercepts**	**Fixed effect**	**AIC** †	**BIC** ††	**ML***	χ^2	R^2_m ‡	R^2_c ‡‡
1	avg. WS	participant		-584	-573	295	NA	0	0.62
2	avg. WS	participant	unique kin.	-632	-618	320	<0.001	0.09	0.67
3	avg. WS	participant	unique kin. + unique vib.	-643	-626	327	<0.001	0.10	0.69
4	avg. WS	participant	unique kin. + unique vib. + coll.	-647	-627	330	0.012	0.11	0.70

† *Akaike information criterion* †† *Bayesian information criterion* * *Maximum likelihood*
‡ *marginal* R^2 ‡‡ *conditional* R^2

3.6 Results

On average, the participants completed the walks in 39.1 seconds, with a walking speed of 0.3m/s (*SD*=0.11), 1.4 collisions (*SD*=1.6), and 21.3 alerts (*SD*=18.8). Table 4 lists the averages per aid. Participants walking speeds varied greatly, with the fastest participants (m=0.48m/s) on average walking more than two and a half times faster than the slowest (m=0.19m/s). By the end of the 25 walks, participants on average walked 30% faster than at the beginning. In line with previous work, participants walked significantly slower with the conical view (B=-0.05, $p<0.001$) than with the white cane, but the tunnel view did not slow down participants (p=0.25). To understand why using the conical view yielded slower walking speeds, we investigated each of the four hypotheses.

The more alerts (kinetic and vibrations combined) the participant received per walk the slower they walked (B=-0.001, $p<0.001$), furthermore, the addition of alerts as a fixed effect parameter in the LMM rendered *aid type* (conical, tunnel, white cane) non-significant. Therefore, we excluded aid type from all subsequent analysis. The first hypothesis (H1) suggested that walking speeds get reduced by the additional alerts created by AWCs on top of the kinetic alerts that both they and white canes provide. This was supported by our results as both the number of 1) kinetic (B=-0.002, $p<0.001$), and 2) vibration alerts (B=-0.001, $p<0.001$), predicted walking speeds and reduced them in the LMM with participants as random intercepts (R^2_c=0.66). The speed cost of an alert helped explain why the conical view yielded slower walking, since the conical view (m=21.7, *SD*=15.9) created more than twice as many vibration alerts than the tunnel view (m=9.7, *SD*=7.5). Seen in Figure 4, the conical view yielded marginally more kinetic alerts (β=0.75, p=0.002), while the tunnel view reduced them a little (β=-0.47, p=0.06) compared to the white cane (m=10.2, *SD*=9.2). Adding the number of collisions the LMM almost turned out to be a significant predictor (B=-0.005, p=0.07).

The unnecessary alerts hypothesis (H2) suggested that additional alerts from AWCs do not support avoiding obstacles, i.e. by reducing 1) collisions or 2) slow-downs from physically touching obstacles with the cane. Indeed neither the conical nor the tunnel view reduced collisions while the conical view added on average twice as many vibration alerts as the tunnel to the kinetic alerts of the white cane. Counterproductively, the conical view increased the number of obstacles touched with the cane by 26.2% (β=0.75, p=0.002), while the tunnel view decreased them by 16.4% (β=-0.47, p=0.05) when compared to the white cane (m=2.9, *SD*=1.3). These differences were matched by the trend of the conical view to increase and the tunnel view to reduce collisions (see Table 4), since 70% of collisions happened with obstacles the participant had just touched with the cane (kinetic alert).

The anticipatory slowdown hypothesis (H3) suggested that upon receiving alerts AWC users slow down in anticipation of upcoming obstacles so they can stop in time, i.e. they would proceed

Table 4. Per walk averages for walking speed, collisions, and (kinetic and vibrations) alerts for blindfolded (Study 1) and visually impaired people (Study 2). Alerts are reported by the number of unique obstacles they alerted to and their total number.

	aid type	walking speed	coll.	kin. detected obstacles (out of 6)	kin. alerts total	vib. detected obstacles (out of 6)	vib. alerts total
Study 1	White Cane	0.33m/s	1.4	2.9	10.2	-	-
	Conical View	0.28m/s	1.6	3.6	13.7	4.2	21.7
	Tunnel View	0.31m/s	1.2	2.6	9.7	2.7	9.7
Study 2	White Cane	0.54m/s	1.2	2.5	5.5	-	-
	Conical View	0.50m/s	1.1	2.5	5.1	2.4	7.1
	Tunnel View	0.50m/s	1.2	2.2	4.6	1.2	2.5

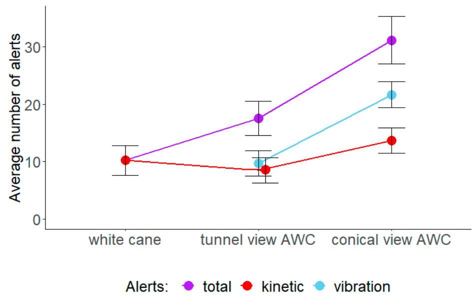

Fig. 4. Mean number of kinetic, vibration and combined alerts for each type of aid collapsed by range, including 0.95 confidence interval error bars.

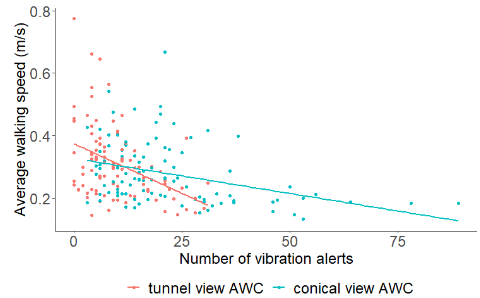

Fig. 5. Average walking speeds (per walk) as a function of vibration alerts with linear trend lines.

more slowly until reaching the respective obstacle. We found no evidence for this as participants slowed down for 1.2-1.5 seconds on average and then accelerated again (see Figure 6). During this time they only travelled 0.25-0.4 meters and did not even come close to the obstacle, which, for vibration alerts, was on average 2.2m away.

The alert complexity hypothesis (H4) blamed the slow down on the higher cognitive demands for decoding different vibration alerts compared to kinetic alerts. However, the LMM (see Table 5 for details) showed that vibrations slowed users down less than kinetic alerts. Furthermore, the four meter preview range, which required users to distinguishing between vibrations at three different locations to determine the distance to the obstacle - should have yielded the highest cognitive cost, compared to the single location from the two meter preview. But range did not predict walking speeds, when controlling for the number of vibration alerts. Instead, the cost of vibration alerts depended on the type of view, with vibrations from the tunnel (*B*=-0.012, p<0.001) slowing down user 50% more than the conical (*B*=-0.008, p<0.001) view (see Figure 5). Only 54% of alerts reduced walking speeds when comparing walking speeds at their reception to their average walking speed the following two seconds after - a consistent finding across participants (*SD*=4.1%), conditions (*SD*=0.9%), and alert types (*SD*=0.7%). When walking faster than 0.2m/s 74% of vibration alerts resulted in slow downs. Participants walked on average at 0.29m/s when receiving alerts that would slow them down, while for the other 46% they were already walking slowly (0.15m/s).

Given that people could receive multiple alerts per obstacle and not all resulted in slowdowns we tested whether the number of unique objects to which people were alerted through either vibrations or kinetically were better predictors than the total number of alerts in each modality. These two predictors (see columns four and six in Table 4) were both significant and yielded a better fit (R_c^2=0.7) than the previous models. Moreover, when added to this model obstacle collisions became

Table 5. Walking speed model with intercept (walking speed) and estimated (*B*) influence of the fixed effects on walking speed in m/s - all significant. Included participants as random intercept.

study	users	walking speed	collisions	unique kin. alerted obstacles	unique vib. alerted obstacles
1	blindfolded	0.37m/s	-0.006	-0.015	-0.009
2	visually impaired	0.59m/s	-0.001	-0.025	-0.012

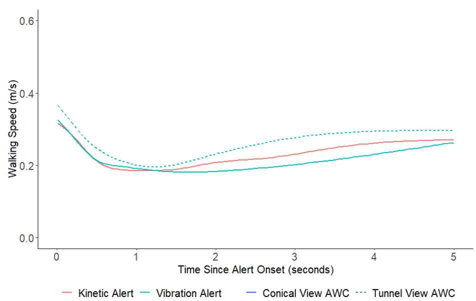

Fig. 6. Study 1: Blindfolded participants change in walking speed over time of alerts resulting in slowdowns by alert type and AWC type

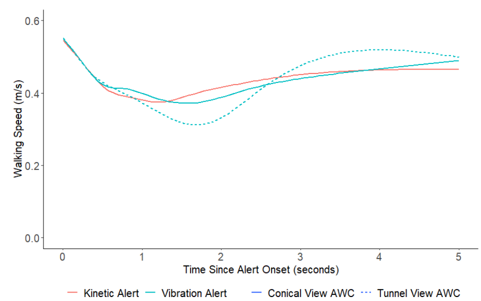

Fig. 7. Study 2: Visually impaired participants change in walking speed over time of alerts resulting in slowdowns by alert type and AWC type

a significant predictor of walking speed (see the final model in Table 5). As could be expected, the conical view detected and alerted on average to significantly more (m=4.6, *SD*=1.0) obstacles (β=1.8, p<0.001), than the white cane baseline (m=2.9, *SD*=1.5), while the tunnel view did not (β=0.4, p=0.07).

In summary, we found evidence that additional alerts (H1) and unnecessary alerts (H2), which did not help avoid obstacles/collisions, were responsible for slow AWC walking speeds but no evidence that people slowed down in anticipation of upcoming obstacles (H3). The results neither confirmed nor rejected the alert complexity assumption (H4) as kinetic alerts slowed down more than vibration alerts and more complex mappings yielded the same cost as simpler ones. However, tunnel vibration alerts incurred a higher cost than their conical counterparts pointing to complexity as a potential source. Study 2 aimed at establishing whether these results hold for blind- or visually impaired users.

4 STUDY 2

A study with six visually impaired participants aimed at validating the results from Study 1 and employed the same experimental design, apparatus, procedure, and measurements except for two changes. It included five additional obstacle scenarios (10 total) to increase statistical power and a 10 minute debrief interview with the participant about their thoughts regarding the AWCs.

4.1 Participants

One female and five male visually impaired participants (mean age = 56) volunteered their time. Five of the participants were completely blind (or had low light sensitivity), while one had central blindness with 3% peripheral vision. All participants used the white cane as their main mobility aid.

4.2 Results

If not explicitly mentioned otherwise the results from the visually impaired participants mimicked those from the blindfolded in Study 1. As expected, across conditions visually impaired participants (VIPs) walked 70% faster (m=0.51,*SD*=0.14) and thereby experienced 68% fewer total alerts (7.71, *SD*=5.69) and 21% fewer collisions (m=1.15, *SD*=1.16) per walk than the blindfolded participants. VIPs walked fastest with the white cane (m=0.54m/s,*SD*=0.14) compared to the conical and tunnel view (both m=0.5m/s, *SD*=0.14) contradicting the blindfolded participants whom the tunnel view did not slow down. Neither AWC reduced collisions. But collisions with our cardboard boxes did not slow down the VIPs in contrast to the blindfolded (see Table 4). We excluded collisions as a factor from all subsequent analysis as they did not improve the fit of the LMM models.

Their results supported the additional alerts hypothesis (H1), since both kinetic (B=-0.01, $p<0.001$) and vibration alerts (B=-0.003, $p<0.001$), albeit less so, slowed VIPs down. As expected the conical view (β=4.39, $p<0.001$) added vibration alerts resulted in a higher total number of alerts than the white cane (m=5.45,SD=3.6). While the tunnel view added vibration alerts it reduced kinetic alerts leading to no significant increase in overall alerts (p=0.18).

Neither AWCs helped reduced collisions compared to the white cane supporting the unnecessary alerts hypothesis (H2). However, the tunnel view did helped avoid 12% of unique kinetic obstacles alerts in the path. VIPs did not slow down in anticipation (H3) but experienced a dip followed by a quick recovery to their previous walking speeds (see Figure 7 and c.f. Figure 6).

Regarding the feedback complexity hypothesis (H4) the added complexity from receiving vibrations at different locations in the white cane handle did not affect walking speeds, after controlling for the number of received alerts. When walking at 0.52m/s or faster 75% of received vibration alerts slowed VIPs down. Of the vibration alerts, which slowed VIPs down, the tunnel were 37% more costly (B=-0.041, $p<0.001$) than the conical alerts (B=-0.030, $p<0.001$) drawn from separate LMMs for each AWC type including random intercepts for participants. The costs of kinetic alerts were identical in both views. Alerting to unique obstacles slowed down users more than repeated alerts to the same obstacle, and provided a better fit for the LMM (see Table 5).

The VIPs deemed four meter previews excessive to stop or take action and that this provided too many alerts, mentioning problems with sorting or filtering them. "*It is like the boy who cried wolf, I don't know which of the vibrations are relevant*" (VIP1). Some suggested different types of feedback for obstacles in-front or to the side (VIP5,6). Preferences for the conical or tunnel view depended on context: "*It depends on the situation* [...] *when walking along the sidewalk I don't need information to my sides, but if I have to search for something it would be very nice to have*" (VIP 3). All the VIPs wanted to be able to turn the vibrations off e.g. when standing still and most preferred the tunnel as default with optional switching to the conical view and While one VIP outright disliked it for being too limiting and not intuitive compared to the conical view (VIP4), most VIPS liked the tunnel but found it abstract or complicated (VIP2,3,6). They linked its complexity to having to consider the direction the torso pointed to instead of the head which VIP2 suggested.

5 DISCUSSION

Matching the literature [10, 28, 41], the conical and the tunnel view slowed down VIP white cane walking speeds. Vibration alerts resulted in temporary slowdowns in line with the additional alerts hypothesis (H1). Alerts to stationary obstacles outside the path were indeed unnecessary in both studies as suggested per H2 [8], since they neither reduced collisions nor kinetic alerts in the path. Vibration alerts limited to the tunnel view were relevant and led to a small reduction in touching obstacles with the cane. But as walking speeds declined for VIPs the provided benefit did not outweigh the cognitive cost of processing the alerts. In our high density obstacle setting, we could discard the anticipatory slow down hypothesis (H3) as both VIPs and blindfolded sped up before reaching the obstacles they had been alerted to.

The complexity hypothesis (H4) posited that vibrations incurred a higher cognitive cost than the kinetic alerts. But vibrations – including the most complex in our study – reduced speed much less than kinetic white cane alerts. Whether this was due to vibration alerts being less cognitively demanding than kinetic alerts, or kinetic alerts physically stopping users when making direct contact with the obstacle remained unclear. Our findings suggested that the cost of alerts depended on: 1) their informational novelty, 2) relevance, 3) complexity, and 4) the users walking speed when receiving the alert. Pre-existing knowledge about obstacles reduced the cost of subsequent alerts in line with Friston's free energy principle [13]. It envisions the brain as a predictive machine continuously trying to optimize its predictions of the perceived world. Gained information about an obstacle will cause users to predict a higher chance of additional alerts requiring fewer cognitive resources. Potentially due to their higher relevance, tunnel view alerts slowed down more than vibrations from the conical view. One explanation could be that on reception of a tunnel alert users know the obstacle is directly in-front of them requiring slowing down more to change course to circumvent the obstacle. The tunnel view indeed reduced kinetic alerts. Qualitative feedback from the VIPs pointed at tunnel alerts requiring more attention to integrate their body posture and cane direction. Walking fast during alerts usually resulted in slow downs, while slower paces did not. This matched that visually impaired people walk slowly during attention-demanding tasks [39].

Given AWCs' raison d'être of reducing collisions with obstacles missed by cane sweeping, it is startling that the the surveyed AWC literature did not discuss reasons for this failure for non-elevated obstacles [10, 36]. Our users had been alerted to most obstacles with which they eventually collided. Apparently, they could not circumvent obstacles based on vibrations and collided with them because they either A) missed them with the cane due to its sweeping rate, B) misjudged the end of obstacles when trying to walk around them too closely or C) could simply not terminate their gait in time after the kinetic alert. Unlike for blindfolded, obstacle collisions did not slow down the VIPs. Likely, because they are more used to bumping into obstacles and collisions with our cardbodard were inconsequential. Had we or any of the studies replaced the harmless cardboard boxes with steady realistic obstacles such as lampposts, road signs, etc. collisions with them would likely slow down more. This offers an explanation why reduced collisions with elevated obstacles did not increase but decrease walking speeds in previous studies [25, 28, 41, 44]. The cognitive cost of the alerts was most likely higher than the time gained from avoided collisions.

Both the design and research into AWCs has been technology driven, focusing on building ever more advanced systems with better sensors capable of alerting to more obstacles [14, 26, 34, 35]. However, the interactive strategies for using AWCs - alerting to any obstacle within the preview range - have remained unchanged since the Laser Cane's commercial availability in 1965 [3]. The adoption of AWCs from the blind community has been a universal failure, with many contributing factors such as technical limitations, price, reliability, weight, robustness, portability, etc. [40]. However, given our study some of AWCs fundamental design assumptions have been irking us.

Why are all AWCs designed with a conical view alerting to every obstacle they detect? Presumably, their designers deem all obstacles relevant. However, in the ethnographic account of a former AWC user its abandonment was due to detecting too many obstacles such as walls that could be sensed without it [49]. Our study quantified the cost of such unnecessary alerts rendering travel inefficient with no gain from avoiding collisions. For the same reason, O&M techniques limit sweeping to the width of a person's shoulder. Wider sweeps result in more slowdowns from alerts [48]. Designing AWCs should not focus on how much can be detected, but on filtering out and alerting to only what is relevant. What is relevant according to our participant depends on the situation. For example, when walking along a sidewalk in urban environments alerts to obstacles to the side are not relevant unless they are moving and soon to enter the path of the user. For example, the Sonic Pathfinder (a secondary electronic mobility aid) only alerted to obstacles getting closer to the user [15].

Why do almost all AWCs provide information about obstacle distances? To the best of our knowledge, no study has provided evidence about whether blind users actually want, need, or use this information [45]. Our VIPs all stated the 4m preview was too long and their results suggested they discarded the distance information to obstacles and only retained their presence. Our AWC users might have ignored the more complex parts of the feedback because they: 1) did not understand the distance mapping, 2) could not discriminate between the three different vibrators e.g. due to insufficient short duration of the vibration. 3) did not have enough time to learn and incorporate the distance mapping into their behavior. Based on our data we cannot say with certainty which of these explanations are correct - if any. Future works have to address this core design decision.

These questions about only alerting to relevant obstacles and whether or not to give distance information is not limited to AWCs, but electronic mobility aids (EMA) in general. While the cost of an individual alert may vary, it is clear that increasing the amount of information provided to the user will result in an inefficient travel. However, two secondary EMA with tunnel view have managed to make VIPs walk faster than they did with only the white cane [7, 30]. These EMAs separated the distance sensors from the cane to the users torso/head and relied on auditory feedback, which, risks blocking out important environmental sounds [31].

As expected based on Santos' findings [10], the absolute values from our proxy groups could not be transferred directly to the VIPs. However, their results mimicked each other in almost every way with only one major difference: the tunnel view slowed down the VIPs but not the proxy. Likely due to VIPs being expert white cane users, thus they only had to learn the added complexity of accounting for body posture when using the tunnel. Therefore, with extended training or a redesign of the tunnel VIPs might be able to account for this complexity subconsciously.

We introduced a novel approach to use a Virtual Reality sensors for tracking as a cheap, fast, and accurate prototyping system to evaluate the effects of new AWC designs without the need for physically building one. We believe this approach provides a versatile and highly agile substitute to prototyping physical systems during the design process of AWCs and other EMAs. While collecting more in-depth results than the commonly and ensuring the AWC did not alert to unintended obstacles in the environment such as walls.

Our results are subject to a few limitations. In terms of ecological validity the lab conditions were easier than real life conditions by omitting 1) elevated or moving obstacles and 2) ambient sounds common when walking in urban settings, which should lead to faster walking and fewer collisions. On the other hand, the high obstacle density resulting in participants accelerating and slowing down often. According to one of our VIPs this hindered getting into a more coherent walking flow. Our study only included ten minutes to familiarize with the vibration patterns. Their cognitive cost is likely higher due to the conscious effort required for interpretation and thereby lowering walking speeds. Studies having shown higher walking speeds typically included training of a few days [37, 41]. In terms of external validity, we only tested obstacle distances mapped spatially to vibration feedback and other mappings e.g. to vibration intensity, frequency, or audio alerts might be easier to learn. Common to AWC designs, receiving the vibrations alerts in the same hand as the kinetic feedback from the cane might have reduced performance due to sensory limitation.

6 CONCLUSION

Despite being on the market for decades, AWC adoption by the blind community has been low and often faulted high prices, reliability, or technical limitations [40]. Based on our study we argue that AWCs have a much more fundamental design flaw, in detecting and alerting to as many obstacles as possible with a high level of distance information. Our result showed users are temporary slowed down when touching obstacles with the cane and receiving vibration alerts, while not using the distance information. Furthermore, many of the vibration alerts are unnecessary as they hardly help circumvented obstacles and avoid collisions. Given the small benefit of vibration alerts to avoid non-elevated obstacles and the reduction in speed they entail, the only justification for using AWCs with their current design is to avoid elevated obstacles. AWC solutions have to become much more sophisticated in filtering out information and only alert to the obstacles users need to know about in the given situation. As a starting point, AWC designers should minimize the number of alerts by not reporting on stationary objects 1) outside the path straight ahead and 2) further than 2m away, while giving users the possibility to obtain larger alert coverage on-demand.

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