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# Standing and Walking Attention Visual Field (SWAVF) task: A new method to assess visuospatial attention during walking

Jing Yuan [a], Xiaolu Bai [a], Brendan Driscoll [b], Ming Liu [b], He Huang [b], Jing Feng [a,*]

[a] Department of Psychology, North Carolina State University, NC, USA
[b] Joint Department of Biomedical Engineering, North Carolina State University, University of North Carolina - Chapel Hill, NC, USA

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ABSTRACT

Visuospatial attention during walking has been associated with pedestrian safety and fall risks. However, visuospatial attention measures during walking remained under-explored. Current studies introduced a newly-developed Standing and Walking Visual Attention Field (SWAVF) task to assess visuospatial attention during walking and examined its reliability, validity, and stability. Thirty young adults completed a traditional computerized Attention Visual Field (AVF) task while sitting, and the SWAVF task under walking and standing settings. Nine participants also performed the SWAVF task under additional distraction conditions. Results showed good split-half reliability during standing ($r = 0.70$) and walking ($r = 0.69$), moderate concurrent validity with the sitting AVF task ($r = 0.42$), moderate convergent validity between the standing and walking settings ($r = 0.69$), good construct validity, and moderate rank-order stability ($r = 0.53$). Overall, the SWAVF task showed good psychometric properties. Potential applications to the evaluation of prosthetic and other exoskeleton devices, smart glasses, and ground-level traffic lights or signs were discussed.

## 1. Introduction

Visuospatial attention is critical for walking performance (Althomali and Leat, 2017). Even for people with normal visual fields, if critical sensory information is not selected by attention, the hazards in the environment could go unnoticed and walking performance may be compromised (Hawkins et al., 1990; Stavrinos et al., 2011). As we only have limited attentional resources to deploy (Dukas, 2004), tasks that consume attention, such as using a cellphone, talking with a friend, or wearing a prosthetic or exoskeleton device, could impair our walking performance (Telonio et al., 2014; Miyasike-daSilva & McIlroy, 2012). As a result, we may miss potential hazards in the environment (e.g., signal lights or vehicles; Stavrinos et al., 2011) and may experience higher fall risks (Lim et al., 2015; Mirelman et al., 2012). Therefore, understanding visuospatial attention performance during walking can be critical for many human factors applications, including a) identifying people with compromised visuospatial attention due to either distraction (e.g., Lim et al., 2015) or visual field impairment (e.g., Freeman et al., 2007) to prevent possible walking incidents, b) acting as an indicator for assessing the attentional demand, a key factor to quantify the effectiveness of rehabilitation training for amputees wearing assistive devices (Brandt et al., 2017) such as prosthesis and exoskeleton, or for patients with Parkinson's disease (White et al., 2009) or dementia (Kemoun et al., 2010) who experience walking difficulties, and c) serving as a threshold to reject designs of traffic lights and signs (e.g., Larue et al., 2020), which demand visuospatial attention during walking.

As the majority of visuospatial attention measures are developed for participants in fixed positions such as sitting in front of a computer or behind the wheel in a car (e.g., Feng et al., 2015; Ball and Owsley, 1993; Shih and Sperling, 2002), measurement of visuospatial attention during walking remained relatively under-explored. One method to measure attention during walking is eye-tracking (e.g., Jiang et al., 2018; Tapiro et al., 2020). Although eye-tracking is known for its ecological validity in assessing goal-directed attention (e.g., Holmqvist et al., 2011), there are limitations of this method. First, even when one looks at a place as shown by the eye-tracker, it does not necessarily mean that the information from the location was processed by attention. This well-known phenomenon called inattentional blindness (i.e., looked but not see; Simons and Chabris, 1999) is a significant cause of overlooked vital

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*Abbreviations:* SWAVF, Standing and Walking Visual Attention Field; AVF, Attention Visual Field.

* Corresponding author. Department of Psychology, Poe Hall 730, North Carolina State University, Raleigh, NC, 27695, USA.

*E-mail addresses:* jyuan7@ncsu.edu (J. Yuan), xbai23@ncsu.edu (X. Bai), bhdrisco@ncsu.edu (B. Driscoll), mliu10@ncsu.edu (M. Liu), hhuang11@ncsu.edu (H. Huang), jing_feng@ncsu.edu (J. Feng).

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visual information in a natural environment especially when the information is unexpected (e.g., Hyman et al., 2010). One study showed that among people who did fixate on an unexpected stimulus as shown by the eye-tracker while engaging with a cognitively demanding task, 35% of them could not report that they had seen the visual stimuli afterward (Richards et al., 2012). Therefore, fixation results do not directly correspond to performance on hazard/target detection. Second, eye movement only measures attention where one gazes at but not attention to peripheral areas. There are two types of visuospatial attention: overt attention - the attention that is allocated to the place where the gaze moves to - and covert attention - the attention that is deployed in the peripheral area without direct gaze (Carrasco, 2011). Although overt attention is more accurate, covert attention is more often used to scan a larger area of the environment and to guide the gaze towards the necessary location or target (Carrasco, 2011; Rai and Le Callet, 2018). Especially when a walker is distracted by a secondary task (e.g., reading text on a smartphone), eye-movement data cannot sufficiently capture whether one pays attention to critical information on the ground that is in the lower visual periphery (Larue et al., 2020). Compromised covert attention performance may lead to missed environmental hazards in tasks such as driving (Crundall et al., 2002) and walking (Vance et al., 2006). Covert attention in the periphery could also change with the task goal and mental workload (Spence et al., 2013). Therefore, an assessment that measures covert attention during walking can not only be used as a critical indicator to predict walking risks but also be used to differentiate cognitive processing performance and mental load level of a walker under various conditions.

A task that requires participants to respond to stimuli presented in various locations in the visual field can be used to measure covert attention during walking. For example, one study investigated covert visuospatial attention during dual-task walking using a task requiring the participants to detect the color or letter change on one center monitor and two side monitors which were at the left upper corner and the right bottom corner of the visual field (Lim et al., 2015). Another study used a ground signal detection task with six ground-level LED signals on the sides of the walkway to investigate the covert visual attention during distracted walking (Larue et al., 2020). However, both studies only measured visual-spatial attention in a limited portion of the periphery. A more recent study did measure covert visuospatial attention in a larger area of visual field with 24 possible locations but only assessed detection of a target without discrimination between a target and distractors (Kim et al., 2021). The attentional ability to differentiate a target with distractors has been shown to be critical for detecting hazards in the driving domain (Feng et al., 2015, 2018). Target-distractor differentiation is also critical for walking performance. With limited attentional resources, selection must be made to emphasize the processing of more critical information in the visual periphery. The ability to differentiate hazardous or vital targets (e.g., holes, bumps, edges of uneven grounds, or ground-level traffic lights or other signals) from less important objects (e.g., leaves, brick patterns) could determine the efficiency of attentional processing and walking safety. Therefore, a covert visuospatial attention measure that assesses differentiation ability during walking across large attentional visual fields could have higher external validity and potentially better represent real-life attentional performance during walking.

In the current studies, we present a new visual attention measure - the Standing and Walking Attention Visual Field (SWAVF) task - by adopting the rigorous settings of the Attention Visual Field (AVF) paradigm. The Attention Visual Field (AVF) task is a computerized task used to map visualspatial attention in the whole visual field (Feng and Spence, 2014). In this task, people need to attend to a large visual field and identify a target among 15 distractors. The target and distractors are located in eight different directions and two eccentricities. This laboratory task uses a rigorous paradigm setting of fixation, interval, target, mask, and response. The measure has been validated to differentiate visual field attention performance in both younger and older adults (Feng et al., 2017). The upper visual field advantage identified using the AVF task has been replicated by other studies (e.g., Erel et al., 2019). When the AVF paradigm was adapted into the driving context, evidence suggests that it can effectively measure hazard detection in driving (Feng et al., 2015), predict driving-related outcomes (Feng et al., 2018), and can also be used as an intervention to improve driver attention (Yuan et al., 2021a).

There are several advantages of adopting the AVF task into the walking setting as compared to eye-tracking and other measures: 1) the need to make reactions to the visuospatial stimuli during walking in the task rules out the possibility of 'looked but not see'; 2) with the rigorous paradigm of the AVF task, attention can be assessed efficiently across a large visual field with repeated measures; 3) by requiring the participant to focus on the fixation in the AVF task, performance at locations with known eccentricities can be measured, thus the spatial distribution of attention can be illustrated; 4) the AVF task covers many locations with various directions and eccentricities across the visual periphery instead of limited locations; 5) the AVF task is a differentiation task which not only requires detection but also discrimination between a target and distractors, which is an important component of visual processing when walking.

To adapt the AVF paradigm into the walking setting, we made the following adjustments. First, to resemble the walking visual setting, instead of fixating on the ground, the participants were asked to fixate at a cross along their natural line of sight during walking. Second, given the importance of the lower peripheral visual field in walking (Graci et al., 2009), especially in the multi-surface terrain (Marigold and Patla, 2008), the SWAVF task focused on the lower peripheral visual field in this study. Third, to resemble the traffic signs or lights that are used in the crosswalks (e.g., Larue et al., 2020), a color differentiation task was chosen.

The purpose of the current studies was to examine the reliability, validity, and stability of the SWAVF task. For reliability, split-half correlations were conducted. For validity, concurrent validity was investigated by comparing the performance on the SWAVF task in standing and walking settings with the original AVF task in a sitting setting. Given attentional performance becomes poorer with increasing eccentricity or in more peripheral visual fields (e.g., Feng and Spence, 2014), construct validity was tested by examining whether the SWAVF task could capture the differences in attentional performance between larger and smaller eccentricities. For stability, rank-order stability was examined with test-retest correlations. The studies followed a within-person design with each participant completing the AVF task in the sitting setting and the SWAVF task in the standing and walking setting (Study 1), and a subset of participants subsequently completing the SWAVF task again in the walking setting with a secondary task (Study 2).

## 2. Study 1

In study 1, the split-half reliability, concurrent validity, and construct validity of the SWAVF task were assessed. Split-half correlation has been used to assess internal consistency reliability for various attention measures (e.g., Luna et al., 2020; Ishigami et al., 2016; Fan et al., 2002). Because the sitting AVF task measured visuospatial attention across both the upper and lower visual field and the SWAVF task measured visuospatial attention only in the lower field, we expected that the sitting AVF task would have a moderate but not high correlation with the SWAVF task. Also, we expected that the performance of the SWAVF tasks in different settings (i.e., standing and walking) would be highly correlated with each other. For the construct validity, we expected that regardless of the task setting, the performance in the visual field with smaller eccentricities (i.e., far rows) would be significantly better than the larger eccentricities (i.e., near rows). A within-subject design was adopted with the same participants taking the AVF task while sitting and the SWAVF task while standing and walking.

## *2.1. Method*

### *2.1.1. Participants*

Thirty participants without disabilities (18 males, 12 females) were recruited from the North Carolina State University community. Every participant reported normal or corrected to normal vision, no color blindness, and no neuropsychological conditions that affect attention, such as attention deficit hyperactivity disorder. Participants' age ranged from 19 to 38 years ($M = 25.0$, $SD = 4.8$). Participants reported their hand dominance given it may be related to visuospatial attention (Colman et al., 2017); one participant was left-handed with the others being right-handed.

### *2.1.2. Measures*

*2.1.2.1. Sitting attention visual field (AVF) task.* The sitting AVF task was programmed using the OpenSesame software (https://osdoc.cogsci.nl/3.3/tutorials/beginner/) and presented on a 20-in × 11.5-in LED monitor. The viewing distance was set to be 19 inches with a chinrest to ensure that the visual angle of the stimuli area was approximately 30° (i.e., 15 degrees of eccentricity from the outer layer of stimuli to the fixation).

The sitting AVF task consisted of a practice session with three blocks of 16 trials (i.e., 48 trials in total) and an experiment session with four blocks of 16 trials (i.e., 64 trials in total). The target occurred at each of the 16 locations with an equal probability. The order of trials was randomized within each block. In each trial, the fixation cross appeared at the center of the display for 500 ms, followed by the stimulus display consisting of 1 target (a circle within a box) and 15 distractors (empty boxes) which stayed on for 40 ms (see Fig. 1). Then, a mask display consisting of grey boxes was shown for 200 ms to disrupt iconic memory thus participants' performance reflects visual processing within the stimulus duration. Afterward, a response display with eight directions appeared and participants indicated the direction of the target by pressing the corresponding number key on a number keypad.

*2.1.2.2. Standing and Walking Attention Visual Field (SWAVF) tasks.* The SWAVF tasks were operated from a LED platform which consisted of 8 rows of LED lights. An Arduino Mega 2560 board was adopted as the control interface for all the individually programmable LEDs (WS2812B; 60 LEDs per meter). The Arduino board received commands from a desktop app, which decided the pattern of the LED array. The Arduino converted the patterns into color and brightness commands for each individual LED and sent the commands using pulse-width modulation using the fastLED Arduino library (Garcia, 2020). The targets and distraction lights were made up of 2x2 segments of LEDs (size of one target or distractor: 2 cm in width and 3 cm in length) with green (RGB: 0, 255, 0) and yellow (RGB: 255, 165, 0) lights respectively as shown in Fig. 2. A separate 5x5 LED array, also controlled by the Arduino board, was placed in the center of the LED platform to act as the fixation display. The power supply for the strips was 5V. The typical RGB (red, green, and blue) luminous intensity of LED light model WS2812B is respectively 390–420 mcd (voltage of 2.0–2.2), 660–720 mcd (voltage of 3.0–3.4), and 180–200 mcd (voltage of 3.0–3.4; Worldsemi, 2013).

During the SWAVF tasks, participants were directed to face towards the LED platform while standing or walking on the middle of the treadmill, fixate their eyesight on the fixation point on a screen behind the task platform, and use their peripheral vision to look at the task platform (see Fig. 3A). The position of the fixation point ensured that the participant's line of sight would be about 10° from the horizontal line which is the normal line of sight during walking (Proctor and Zandt, 2008). Participants held two clickers with one in each hand for task response.

The SWAVF task consisted of a practice session with 6 trials and an experiment session with two blocks of 24 trials (i.e., 48 trials in total). In each trial, a fixation square in white light (RGB: 255, 255, 255) was first presented at the center of the platform on the task platform for 300 ms (see Fig. 2). After a random interval between 1 and 3 s, all the five distractors in green light and one target in yellow light would be on at the same time for 60 ms (see Fig. 3B). Then a mask with all lights on in blue color (RGB: 0, 0, 255) was displayed for 2 s to disrupt iconic memory and followed by a 3-s response window. Participants were asked to respond whether the yellow light was on the left side (column A, B, C in Fig. 3B) or the right side (column D, E, F in Fig. 3B) of the platform by clicking the left or right clicker. The distance between adjacent rows was approximately 25 cm and the distance between adjacent columns was approximately 27 cm.

The target and distractor locations in the 48 trials were generated with randomization and manual adjustment based on the following principles: a) Each of the 24 possible target locations (see Fig. 3B) was displayed twice in the experiment session; b) There were one target and five distractors in each trial; c) Each location was chosen as the target twice and as the distractor ten times throughout the 48 trials; d) Each row had at least one light but no more than two lights; e) Each column had one light. After a fixed list of 48 trials was generated, the order of 48 trials was randomized for each participant.

As shown in Fig. 3C, a white shield was used to block most of the visual distractions on the back. Black boxes were also used to hide the equipment and lines on the platform during the experiment. The lux level of the room was approximately 200 with distributed lights in the lab.

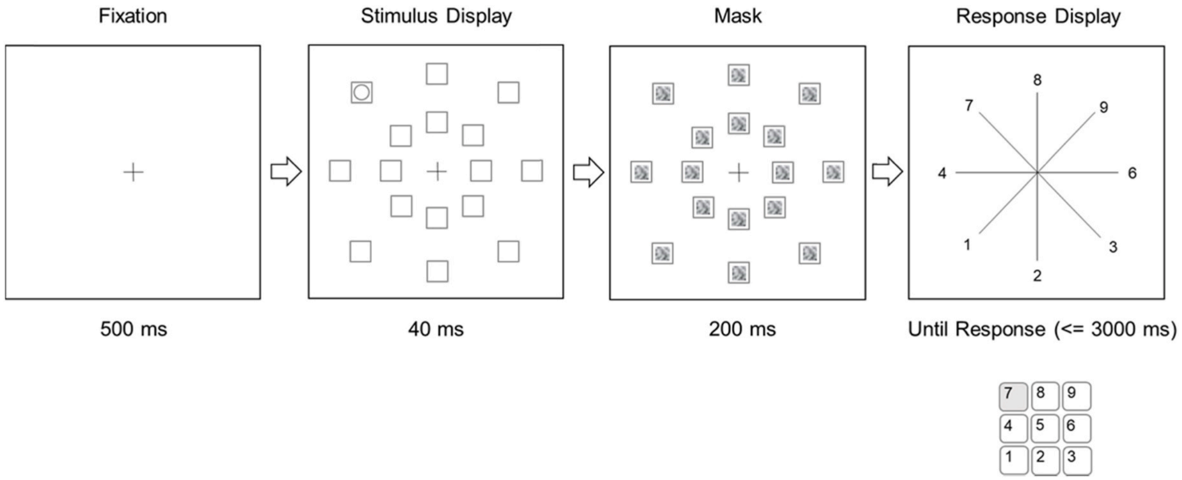


**Fig. 1.** An illustration of the displays in one example trial of the sitting Attention Visual Field (AVF) Task.

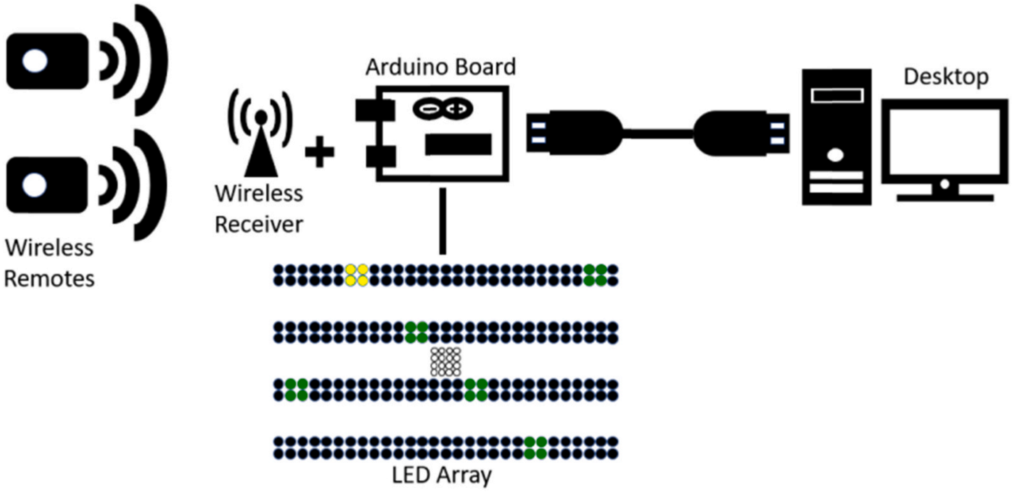


**Fig. 2.** Led Platform Diagram. Subject input from wireless remotes travels to the Arduino board and then to the desktop. Commands from the desktop travel to the Arduino board which controls the led array.

### 2.1.3. Procedures

The study was approved by the Institutional Review Board of the University of North Carolina at Chapel Hill Human Research Ethics. Prior to the study, each participant first consented to voluntary participation and completed a pre-test survey, followed by a 10-m walk test (Shirley Ryan AbilityLab, 2014) to determine the preferred walking speed. The 10-m test was performed three times per participant and only the speeds in the middle 6 m were averaged. Participants had an average preferred walking speed of 1.28 m/s (*SD* = 0.15). The pre-test survey asked for demographic information, vision and neuropsychological conditions, and current mood and anxiety level. After determining the preferred walking speed, participants went through the sitting AVF task. The chair height and chinrest height were adjusted so that the participants' eye height was around the middle of the monitor. Then they performed the SWAVF tasks in standing and walking settings. Before standing or walking on the treadmill, an additional harness was provided to ensure the safety of the participants. Participants were instructed to hold one clicker on each hand and make a response to each target using the corresponding clicker. To account for the potential reaction time differences between the two hands, baseline reaction time for each hand was measured at the beginning by asking the participants to react to a flashing light 10 times, respectively, with their left and right hands. The order of standing and walking tasks was counterbalanced. During the instruction delivery, the color and shape of the target and distractor lights were shown to the participants to avoid confusion. Each participant was instructed to fixate the eyesight on the fixation point on a screen behind the task platform and use peripheral vision to process information from the task platform. Participants were told to perform the SWAVF task as quickly and as accurately as possible. No specific prioritization instruction was given regarding the walking task but participants had to keep up with the constant speed of the treadmill. In each setting, the practice session was performed first and followed by the experiment session. Afterward, participants reported mood again.

## 2.2. Results

The analyses in the following sections were performed for both accuracy and response time. There was no speed-accuracy trade-off during both standing, $r(28) = -0.29$, $p = .12$, and walking settings, $r(28) = -0.04$, $p = .86$. Results of response time were similar to those of accuracy and were briefly presented in the following table. Table 1 presents the descriptive statistics of both accuracy and response time in the SWAVF task in Study 1.

### 2.2.1. Split-half reliability

Usually, the split-half correlation was calculated by randomly splitting the trials into half and then averaging the scores (e.g., Luna et al., 2020; Ishigami et al., 2016). However, as attentional performance may intrinsically differ depending on the target location (e.g., better processing in the upper visual field), we adopted the method used in Fan et al. (2002) to calculate the correlation between two sets of 24 trials with equal coverage of each possible target location.

The sets were predetermined with one of the two trials of every target location being randomly allocated to one set and another trial allocated to the other set. The set compositions were consistent across participants. This randomized allocation of trials with the constraint of each set including all target locations eliminates confounds due to order or spatial location. The mean accuracy of each set was calculated for every participant and the split-half correlation was calculated by correlating the first set and the second set. The two sets had similar mean and standard deviation scores for both standing (First set: $M = 0.69$, $SD = 0.18$; Second set: $M = 0.70$, $SD = 0.15$) and walking settings (First set: $M = 0.69$, $SD = 0.17$; Second set: $M = 0.71$, $SD = 0.16$), which met the criteria for parallel halves and maximum reliability (Chakrabartty, 2013). Correlations between the two halves during the standing ($r = 0.70$) and walking setting ($r = 0.69$) suggests that the reliability of the SWAVF task was acceptable (0.6–0.7; Ursachi et al., 2015) or high (0.6–0.8; Putri et al., 2020).

### 2.2.2. Concurrent validity

When including all the participants, results showed that there were significant and moderate correlations between the sitting AVF ($M = 0.80$, $SD = 0.25$) and SWAVF in the standing setting, $r(28) = 0.49$, $p = .003$ (one-tailed), and in the walking setting, $r(28) = 0.42$, $p = .010$ (one-tailed). After excluding the six participants who had performance lower than or at the guessing rate (i.e., SWAVF task: 50%, sitting AVF: 12.5%), the results remained significant in the standing setting, $r(22) = 0.48$, $p = .009$ (one-tailed), and in the walking setting, $r(22) = 0.40$, $p = .025$ (one-tailed). This suggests that the SWAVF task showed intermediate (0.4–0.7; Putri et al., 2020) concurrent validity with the sitting AVF task.

The accuracy of the SWAVF task in the standing and walking settings showed significant and higher correlations with each other, $r(28) = 0.69$, $p < .001$ (one-tailed). After excluding the six participants who had performance lower than or at the guessing rate, the correlation remained significant, $r(22) = 0.51$, $p = .005$ (one-tailed). This suggests that the SWAVF task showed intermediate (0.4–0.7; Putri et al., 2020) concurrent validity in different settings.

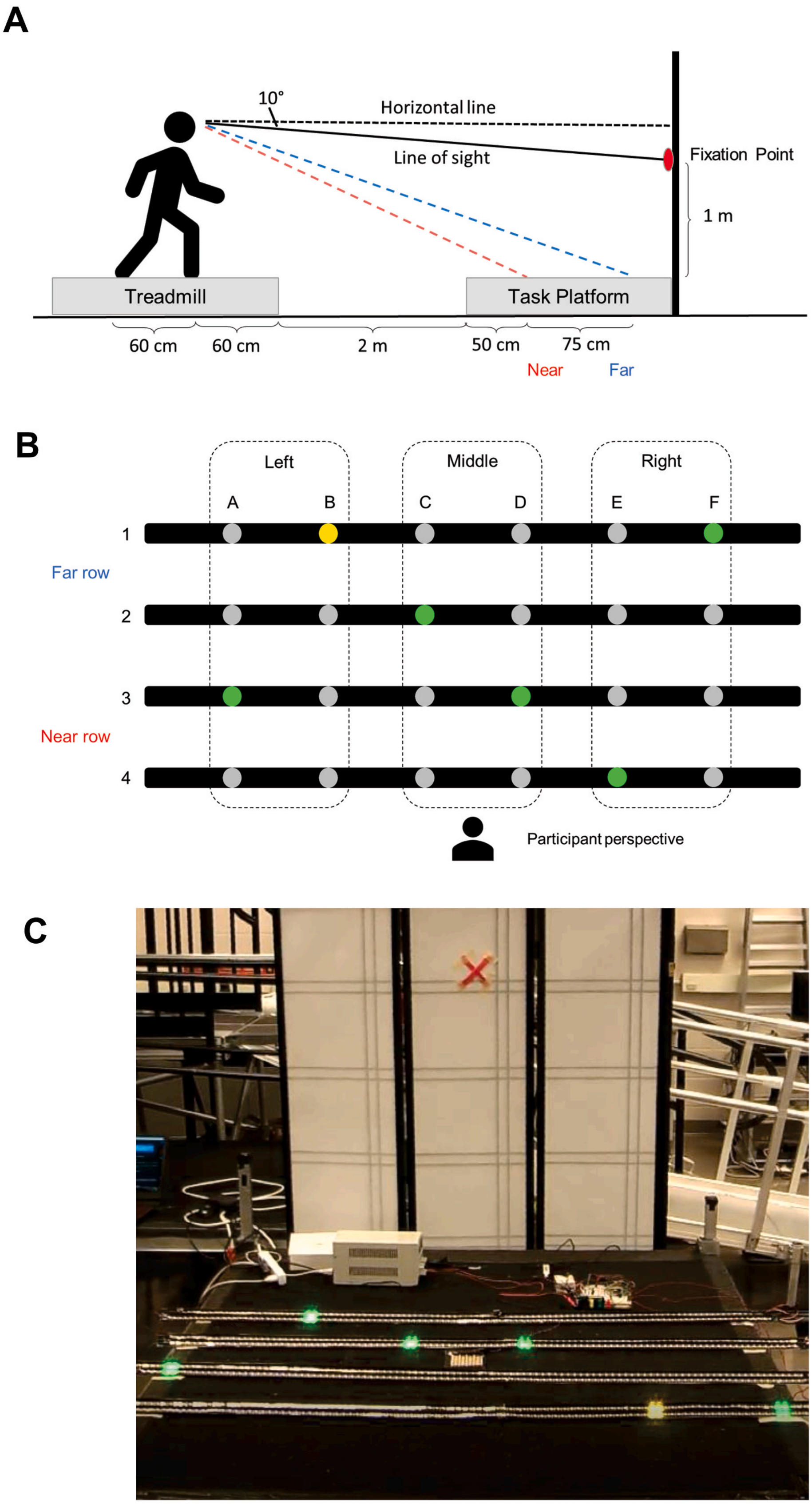


**Fig. 3.** (A) An illustration of the Standing and Walking Attention Visual Field (SWAVF) task Setup. (B) An illustration of the SWAVF task display. (C) An illustration of the SWAVF task setting in the lab. The green lights were distractors. The yellow light was the target. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

**Table 1**
Means and standard deviations of accuracy and reaction time of the SWAVF tasks in study 1.

| | Standing SWAVF | | Walking SWAVF | |
|---|---|---|---|---|
| | Accuracy *M (SD)* | Reaction Time *M (SD)* | Accuracy *M (SD)* | Reaction Time *M (SD)* |
| Overall Score | 0.69 (0.15) | 853 (229) | 0.70 (0.15) | 867 (362) |
| Columns | | | | |
| Left | 0.68 (0.23) | 867 (253) | 0.67 (0.27) | 877 (366) |
| Middle | 0.67 (0.16) | 865 (235) | 0.65 (0.17) | 851 (338) |
| Right | 0.74 (0.21) | 826 (227) | 0.79 (0.19) | 872 (393) |
| Rows | | | | |
| Near | 0.65 (0.17) | 883 (237) | 0.66 (0.15) | 893 (385) |
| Far | 0.74 (0.15) | 822 (224) | 0.75 (0.16) | 840 (341) |

*Note.* n = 30. Reaction times were in milliseconds. In the SWAVF task, Left (columns) refers to columns A, B; Middle (columns) refers to columns C, D; Right (columns) refers to columns E, F; Near (rows) refers to rows 3 and 4; Far (rows) refers to rows 1 and 2.

### 2.2.3. *Construct validity*

A 2x2 repeated-measure ANOVA was conducted with task condition (walking, standing) and target area (near, far) as within-subject factors (n = 30). The near target locations included the near two rows (row 3 and 4 as shown in Fig. 3B) and the far locations included the far two rows (row 1 and 2 as shown in Fig. 3B). Table 1 presents the descriptive statistics. No main effect of task condition was found, $F(1, 29) = 0.14$, $p = .71$, $\eta_p^2 = 0.01$. Participants had comparably accurate rates on the SWAVF tasks during the standing setting ($M = 69.4\%$) and the walking setting ($M = 70.2\%$). There was a significant main effect of target location, $F(1, 29) = 40.13$, $p < .001$, $\eta_p^2 = 0.58$. As expected, participants had much poorer accuracies when the target was in the near rows (i.e., larger eccentricity; $M = 65.1\%$) than in the far row (i.e., smaller eccentricity; $M = 74.5\%$). There was no significant interaction between the two factors, $F(1, 29) = 0.0004$, $p = .98$, $\eta_p^2 < 0.001$.

When we excluded the six participants whose performance on the SWAVF tasks was below the guessing rate (thus n = 24), the significance patterns remained the same. There was a significant main effect of target location, $F(1, 23) = 28.28$, $p < .001$, $\eta_p^2 = 0.55$ (near: $M = 70.1\%$; far: $M = 79.3\%$), but neither main effect of task condition, $F(1, 23) = 0.01$, $p = .93$, $\eta_p^2 < 0.001$ (standing: $M = 74.6\%$; walking: $M = 74.8\%$), nor interaction between the two factors, $F(1, 23) = 0.55$, $p = .47$, $\eta_p^2 = 0.02$, was significant.

### 2.2.4. *Attention distribution*

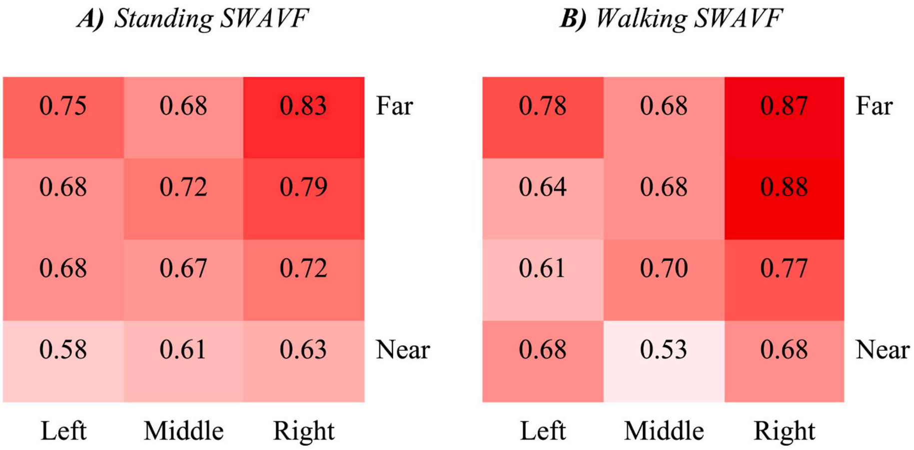
In order to better visualize the attention distribution using the SWAVF task, we averaged the results from two columns on the left, middle, and right sides respectively into one score (as illustrated in Fig. 3B, which resulted in 12 areas. The accuracy in each area, as illustrated in Fig. 4, was averaged between participants. The attention distribution confirmed the ANOVA results that the performance in the far rows was better than that in the near rows.

The visualization seems to imply overall better performance in the right visual field. As an exploratory follow-up to test whether there is a right bias, a 2x3 repeated-measure ANOVA was conducted with task condition (walking, standing) and target location (left, middle, right) as within-subject factors (n = 30). No main effect of task condition was found, $F(1, 29) = 0.20$, $p = .65$, $\eta_p^2 = 0.01$. Participants had comparably accurate scores on the SWAVF tasks during the standing setting ($M = 69.3\%$) and the walking setting ($M = 70.3\%$). There was a significant main effect of target location, $F(2, 58) = 4.36$, $p = .02$, $\eta_p^2 = 0.13$. Pairwise comparisons showed that participants had better accuracy when the target was on the right side ($M = 76.3\%$) than the middle side ($M = 65.9\%$) but no differences with the left side ($M = 67.2\%$). There was no significant interaction between the two factors, $F(2, 58) = 1.18$, $p = .32$, $\eta_p^2 = 0.04$.

When we excluded the six participants whose performance on the SWAVF tasks was below the guessing rate (thus n = 24), the significance patterns remained the same. There were no main effect of task condition, $F(1, 23) = 0.04$, $p = .84$, $\eta_p^2 = 0.002$ (standing: $M = 74.4\%$; walking: $M = 75.0\%$), a significant main effect of target location, $F(2, 46) = 4.20$, $p = .02$, $\eta_p^2 = 0.15$ (left: $M = 74.6\%$; middle: $M = 70.2\%$; right, $M = 79.2\%$), and no significant interaction between the two factors, $F(2, 46) = 1.50$, $p = .23$, $\eta_p^2 = 0.06$.

## 3. Study 2

In addition to split-half reliability, and concurrent and construct validity, we examined another psychometric property of the SWAVF task, the rank-order stability. This stability measure requires the test and retest of the same participants. Therefore, in study 2, we recruited part of the sample in Study 1 to take the SWAVF task again while walking with distractions during the task from the left or right sides to mimic the varying road distraction to assess task stability (e.g., Ishigami and Klein, 2010) under different conditions with higher external validity. The rank-order stability was assessed with the intra-class correlation between the SWAVF task under no distraction, left distraction, and right distraction. We expected that the SWAVF task would achieve fair to good rank-order stability (0.4–0.75; Fleiss, 1986) which means that people who score higher under no distraction would also score higher when there is a distraction (i.e., participants' rank order of performance remains stable across different task conditions).



*A) Standing SWAVF*

| | Left | Middle | Right | |
|---|---|---|---|---|
| | 0.75 | 0.68 | 0.83 | Far |
| | 0.68 | 0.72 | 0.79 | |
| | 0.68 | 0.67 | 0.72 | |
| | 0.58 | 0.61 | 0.63 | Near |

*B) Walking SWAVF*

| | Left | Middle | Right | |
|---|---|---|---|---|
| | 0.78 | 0.68 | 0.87 | Far |
| | 0.64 | 0.68 | 0.88 | |
| | 0.61 | 0.70 | 0.77 | |
| | 0.68 | 0.53 | 0.68 | Near |

**Fig. 4.** Attention distribution heatmap of the SWAVF tasks under the (A) standing setting and (B) walking setting. Lighter color means lower accuracy. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

## 3.1. Method

### 3.1.1. Participants

Nine able-bodied participants (8 males, 1 female) who have completed Study 1 were invited to participate in the study again. These participants met the following criteria: a) overall performance in Study 1 was not below guessing rate (50%); b) to observe potential changes in the performances, left and right side performances (i.e., performances in the left two columns and right two columns) did not show floor effects (i.e., below the guessing rate of 50%), and given the right-side bias as shown in Study 1, the right-side performance did not show ceiling effects (i.e., 100%); c) participants were still available during the time of this second experiment. Participants' age ranged from 19 to 38 years ($M = 27.3$, $SD = 5.5$). All participants were right-handed. Participants had an average preferred walking speed of 1.29 m/s (SD = 0.16). The time between the Study 1 and Study 2 tests ranged from three weeks to six months.

### 3.1.2. Measures

The same SWAVF task was used for the walking setting. In order to test the stability of the SWAVF task and also mimic the road distraction situations to increase the external validity, a secondary hand-raise task was added in addition to the regular SWAVF task. Participants were told that there would be random hand raises throughout the process and they needed to verbally report "hand" immediately after they saw a hand raise from the experimenter who was sitting next to the experiment platform with the back toward the participants. Each participant performed two walking sessions. The experimenter sat on the left side of the task platform in one session and the right side in another session. The order was counterbalanced.

The experimenter sat next to the middle of the task platform with a distance of 40 cm. In total, there were 5 times of hand raises, the order of which was randomly chosen and predetermined for each participant. The experimenter was trained to raise the hand close to the platform for around 1 s at a steady pace but not make other movements. The timing of the hand raise was in the between-trial interval (after the blue mask) to minimize the interruption on the trial response or trial display.

### 3.1.3. Procedures

The participants reviewed the informed consent again. They were then reminded of the SWAVF task rules and were told that in addition to the SWAVF task, one experimenter would raise his left (or right) hand randomly throughout the experiment and they needed to say "hand" immediately after you see the hand raise (within 2s). Participants were told to prioritize the hand-raise task, make sure that they spotted every hand, and report as quickly as possible. Meanwhile, they were told to perform the light differentiation task as accurately and quickly as they can.

## 3.2. Results

The intra-class correlation was calculated with the accuracy of the SWAVF task in the walking setting under no distraction, left distraction, and right distraction. Given that the sample size in the follow-up study was small (n = 9), performances in the near rows and the far rows were analyzed separately (n = 18). Table 2 presents the descriptive statistics. The absolute agreement between the three scores using the model of two-way mixed effects and single rater type showed that the SWAVF task had moderate (Koo and Li, 2016) or good (Fleiss, 1986) rank-order stability under different conditions, ICC (3,1) = 0.53, CI = [0.25, 0.77], $p < .001$.

## 4. Discussion

The current studies examined the reliability, validity, and stability of the newly developed SWAVF task for visuospatial attention in the lower peripheral visual field during walking. Different from existing visuospatial attention measures (e.g., eye-tracking) that assessed either only overt attention or partially covert attention, the SWAVF task assessed covert attention during walking in a larger visual field using a task with higher ecological validity (i.e., discrimination task from distractors) and a rigorous paradigm. Overall, the SWAVF task showed fair to good split-half reliability, concurrent validity with another well-established visuospatial attention measure (i.e., sitting AVF task), convergent validity under different settings (i.e., standing and walking), construct validity regarding eccentricities differences, and rank-order stability under different conditions.

As expected, the performance in the sitting AVF task was correlated with the SWAVF task under walking and standing settings. This suggests that the SWAVF task was valid in measuring visuospatial attention with the current version focusing on assessing attention in the lower visual field in a young sample. An interesting finding was that walking did not compromise the visuospatial attention performance but instead led to slightly better performance compared to performance during standing. It is possible that walking may not be a cognitively intensive dual-task at least for this young healthy sample. In addition, walking may improve vascular circulation that may lead to cognitive benefits (Hsu et al., 2018). Specifically, walking has been found to enhance working memory (Dodwell et al., 2019) and peripheral vision (Cao and Händel, 2019). Depending on how proficient a person is in walking (e.g., older adults, amputees wearing a new prosthesis or other exoskeleton device, stroke patients), the effects of walking may differ. For example, age-related declines in spatial attention may relate to heightened fall risks (Mirelman et al., 2012). Future studies could further validate the SWAVF task beyond healthy young individuals by including older adults, the amputee population, or patients with stroke, Parkinson's disease, or dementia.

We also found that participants performed poorer in the middle columns than in the left or right columns. This may be due to the response setting that participants were required to determine whether the target was on the left and right half of the display area, making the judgment for targets near the center more difficult. Another possible reason is that the current display area is relatively small (approximately 15–24 degrees of horizontal visual angle) as compared to more traditional AVF tasks on a computer (e.g., 50–60 degrees of visual angle, Feng and Spence, 2014; Feng et al., 2017). Within this smaller area, attentional performance may not be declining rapidly with increasing eccentricity along the horizontal axis.

Although the studies already suggest good psychometrics of this novel visuospatial attention measure during walking with a small

**Table 2**
Mean and standard deviation of accuracy and reaction time of the SWAVF tasks under different conditions in study 2.

| | Walking SWAVF with no distraction | | Walking SWAVF with left distraction | | Walking SWAVF With right distraction | |
|---|---|---|---|---|---|---|
| | Accuracy | Reaction Time | Accuracy | Reaction Time | Accuracy | Reaction Time |
| Overall Score | 0.81 (0.07) | 712 (164) | 0.81 (0.09) | 740 (155) | 0.81 (0.05) | 705 (125) |
| Rows | | | | | | |
| Near | 0.76 (0.09) | 735 (181) | 0.73 (0.11) | 774 (158) | 0.73 (0.09) | 716 (105) |
| Far | 0.86 (0.08) | 688 (148) | 0.88 (0.09) | 706 (154) | 0.89 (0.06) | 694 (148) |

*Note*. n = 9. Reaction times were in milliseconds. In the SWAVF task, Near Rows refers to row 3 and 4; Far Rows refers to row 1 and 2.

sample, it has several limitations. First, our participants were healthy individuals at a young age (i.e., college students), future studies can validate the task among other populations such as older adults or amputees wearing new prostheses. Second, with various criteria for participant inclusion, our sample size in Study 2 was relatively small with an unbalanced gender composition. Future studies could aim to reexamine rank-order stability with a larger and more balanced sample. Third, we only assessed the concurrent validity with one visualspatial attention task. Future studies could examine the concurrent validity with other visuospatial attention tasks and the predictive validity of the SWAVF task on real-life outcomes such as participants' obstacle crossing performance or walking performance on roads or under virtual reality settings. Next, the current SWAVF task only measured attention in the lower visual field. However, in real life, although the lower visual field is critical during walking, other important objects such as pedestrians or bicycles appear in the upper visual field. Therefore, future studies could expand the testing field of the SWAVF to the entire visual field. Last, one inherent limitation of using a treadmill in a lab setting is the lack of optic flow. Future studies could consider adding optic flows into walking with a treadmill using virtual reality (e.g., De Keersmaecker et al., 2019).

With the satisfactory psychometric properties, the SWAVF task can potentially be applied to assess human factors considerations in other domains, such as evaluations of assistive technologies, training programs for locomotion, and ground-level traffic lights or signs design. In the domain of assistive devices, such as prosthesis and exoskeleton, attention has been called upon not only physical performance of walking but also cognitive fitness during walking (Stirling et al., 2020; Yuan et al., 2021b). In addition to the biomechanical and gait assessment, the SWAVF task can provide additional information regarding the attentional load of people wearing assistive devices under different device settings, cognitive loads, training program stages, and environmental conditions. Fig. 5A illustrates the setup of an ongoing study in our lab that examined spatial attention during walking with a prosthesis together with biomechanical metrics.

Assessments of walking performance from both biomechanical and cognitive aspects can provide a comprehensive understanding of walking safety and experience. For example, an amputee's biomechanical data might suggest that the gait performance does not differ between two different prosthesis designs, but one design comes with a higher accuracy in the SWAVF task, suggesting the more favorable design with a lower risk of falling. The pattern of attentional distribution may also provide useful information in terms of which device design leads to a more natural distribution of attention and how the distribution is improved over time as an amputee gets more used to the prosthesis. It is also possible that the amputee's cognitive performance does not differ between prostheses, but the biomechanical data showed better gait performance with one design than the other. In this case, the SWAVF task serves as an additional visuospatial loading task.

In addition, the task can be used to evaluate the covert visuospatial attention performance during distracted walking. Distracted walking could lead to a lack of attentional processing of traffic information. For example, Stavrinos and colleagues (2011) found that pedestrians walking in a virtual environment were more likely to be hit by a vehicle when talking on a phone than without the distraction, even though they still checked the traffic by moving their heads left and right when crossing the street. To evaluate the visuospatial attention during distracted walking, the SWAVF task can be used in combination with a talking or texting task.

The SWAVF task can also be used to guide the development of augmented road signs or signals displayed on the ground (Fig. 5B). Ground-level traffic signs have become increasingly popular in recent years, with the potential benefit to reduce the safety risks of distracted pedestrians (Kim et al., 2021; Larue et al., 2020). As the technology advances, more information (i.e., distractors) may be displayed while

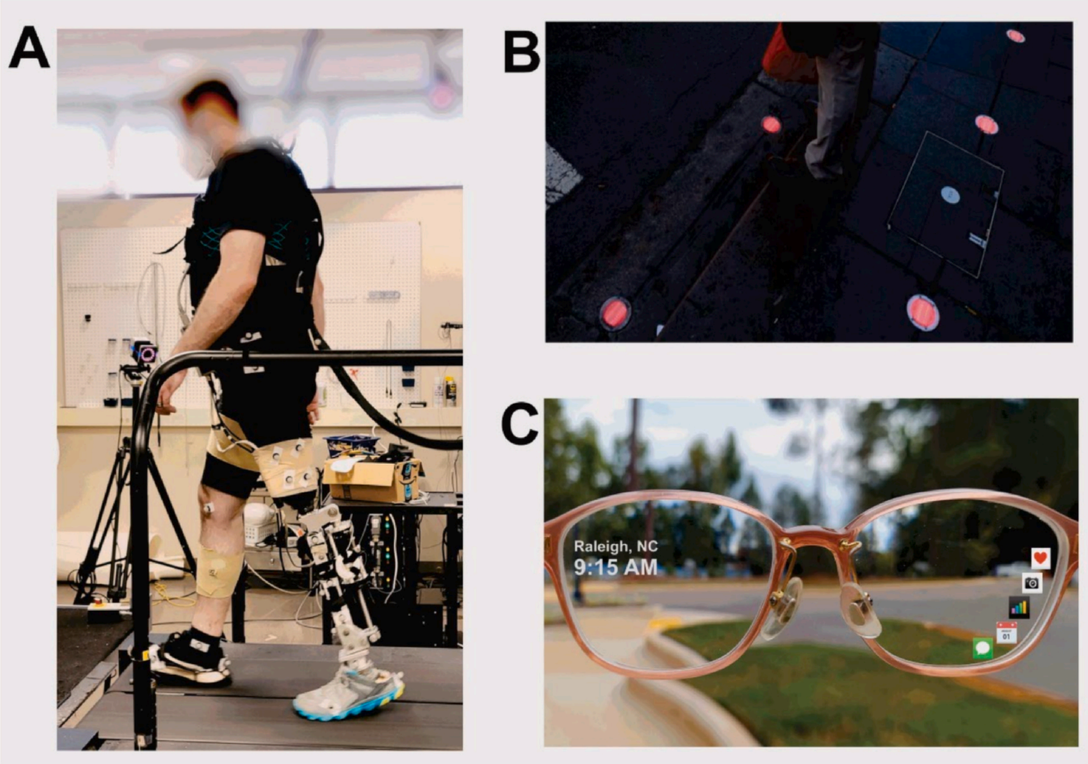


**Fig. 5.** Potential applications of the SWAVF task. (A) Examining spatial attention of a prosthesis wearer while walking in the Neuromuscular Rehabilitation Engineering Laboratory in Raleigh, USA. (B) In-ground traffic signals at an intersection in Sydney, Australia. Adapted from "In-ground pedestrian lights switch on", by Fairfax Media (2017, March 30). Retrieved from https://www.smh.com.au/national/nsw/sydneys-inground-street-signals-to-combat-wayward-pedestrians-on-mobile-phones-20170330-gv9ii5.html. (C) A visual prototype of smart glasses with augmented information displayed on the device.

walking and both detection and differentiation will be required. Compared to other existing visuospatial attention measures, one of the advantages of the SWAVF task is that it measures not only the detection but also the differentiation ability of the target from the distractors during walking. Prior research has shown that complexity on the road surface may increase fall risks (Talbot et al., 2005; Thomas et al., 2020). To evaluate the effectiveness of various ground-level signal designs (e.g., color and brightness of the lights, spacing, or blinking pattern and frequency) when a pedestrian is distracted, the target and distractor setup in the SWAVF task can be manipulated accordingly. For example, if we would like to investigate which level of brightness should be used for the signal light during the day- or nighttime, the SWAVF task can be repeated with different brightness levels in day and night illumination conditions.

Furthermore, the design of wearable devices with head-mounted displays, such as smart glasses (Fig. 5C), can also benefit from the understanding of attentional processing of information across locations in the visual field. Gait performance such as walking speed has been used as an indicator to evaluate the design considerations such as the text location on the smart glasses (e.g., Rzayev et al., 2018). However, a slower walking speed itself could just be a compensatory behavior and cannot directly suggest how the attentional processing of the visual environment has been compromised. Measuring covert visuospatial attention while walking using the SWAVF task can directly inform the attention processing performance while wearing the head-mounted devices and can be more sensitive to differential display designs than measures such as walking speed. The SWAVF task can be used to answer research questions, such as whether certain design features (e.g., text and notification icons in the lower area of glasses) are more likely to compromise a wearer's ability to detect and differentiate road hazards, by mapping out a wearer's attentional distribution across visual fields when wearing such a device. For example, the SWAVF task can be used to compare conditions (e.g., no text message, message on the left side, and message on the right side) by examining the attentional performance.

## 5. Conclusion

Although there has been a lot of effort examining visual processing during walking, few measures could assess visuospatial attention across a large visual field. This paper presents the first effort of developing a visuospatial covert attention measure that assesses discrimination ability in the lower visual field during walking. The results showed that the SWAVF task had fair to good reliability, validity, and stability in a young-adult sample. In the future, this task has the potential to be used a) to differentiate people with higher and lower visuospatial attention performance during walking, b) to identify people with impaired visuospatial attention in various visual fields, c) to assess the visuospatial attention demand of walking assistive technology, such as prosthetic or exoskeleton devices, as well as augmentation technology, such as smart glasses, d) to evaluate the training effects of walking training programs, and e) to evaluate the design of novel traffic lights or signs. Future studies should further test the criteria validity with these real-world outcomes in more diverse and larger samples with a wider variety of task settings.

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## Declaration of competing interest

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

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