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At Crossroads in a Virtual City: Effect of Spatial Disorientation on Gait Variability and Psychophysiological Response among Healthy Older Adults

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Keywords
Spatial disorientation · Gait analysis · Older adults · Virtual reality · Wayfinding

Abstract
Introduction: Aging has been associated with a decline in cognitive and motor performance, often expressed in multitasking situations, which could include wayfinding. A major challenge to successful wayfinding is spatial disorientation, occurring mostly at crossings. Although gait changes have been observed in various dual-task conditions, little is known about the effect of disorientation on gait and psychophysiological response among older adults during wayfinding. The study aimed at identifying the effect of spatial disorientation on gait variability and psychophysiological response among healthy older adults during wayfinding in a controlled environment. ***Method:*** We analyzed data of 28 participants (age 70.8 ± 4.6, 18 female), 14 experimental and 14 controls. Participants performed a wayfinding task consisting of 14 major decision points (7 intersections) within a virtual environment (VE) projected on a 180° screen while walking on a self-paced treadmill equipped with a marker-based optical motion-capture system. The VE was held constant for the controls and manipulated for the experimental participants. Disorientation was identified based on a customized annotation scheme. Variability in gait, including the coefficient of variation (CV), was measured as the primary endpoint. Psychophysiological response measures, including heart rate variability (RMSSD) and skin conductance response (SCR), were continuously monitored as secondary endpoints and estimates of cognitive effort. Linear Mixed Effects models were applied to hypothesis-driven outcome measures extracted from decision points. ***Results:*** Walking speed and step length decreased when disoriented ($p < 0.05$), while stride time, stance time, walking speed CV, stance time CV, SCR amplitude, and SCR count increased when disoriented ($p < 0.05$). A higher RMSSD was associated with being disoriented at crossings ($p < 0.05$). SCR count was greater in the older experimental group ($p < 0.001$), including when disoriented ($p < 0.001$). ***Discussion/Conclusion:*** The results provide evidence for the impact of spatial disorientation on changes in gait pattern and psychophysiological response among older adults during wayfinding. Location also had implications for the effect of disorientation on gait and cognitive effort. This gives further insight into the substrates of real-world navigation challenges among older adults, with an emphasis on viable features for designing situation-adaptive interventional devices aiding independent mobility.

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Introduction

Healthy Aging and Spatial Navigation

The World Health Organization (WHO) defines healthy aging as the process of developing and maintaining the functional ability that enables wellbeing in older age. This includes a person's ability to meet their basic needs, learn, grow, and make decisions, be mobile, build and maintain relationships, and contribute to society [1]. As a key aspect of maintaining functional ability, independent mobility is highly dependent on the individual's ability to successfully navigate their spatial environment. Aging is, however, associated with functional decline in selective cognitive domains (e.g., executive and memory function) [2] required for successful navigation. As adults advance in age, they experience serious problems in spatial navigation, often leading to getting lost [3]. As a result, they avoid unfamiliar routes and places, which limits their personal autonomy and in turn diminishes their quality of life [4]. This becomes a cause for concern, given that the ability to ambulate independently has been suggested as a major contributor to wellbeing and autonomy in older individuals [5]. Moreover, declines in spatial navigation can be among the earliest indicators of a progression from healthy aging to Alzheimer's dementia (AD) [6], which further necessitates more exploration into the contributing factors to navigation difficulties among older adults.

The Wayfinding Process

According to Darken and Peterson [7], an important cognitive component of spatial navigation is wayfinding. Wayfinding involves deliberate navigation between two or more points of interest and can take place in both familiar (e.g., near home) and unfamiliar (e.g., on vacation) environments [8]. The wayfinding process is essentially a problem-solving activity [9], and could be influenced by factors such as perception of the environment, availability of wayfinding information (e.g., route descriptions, landmarks), ability to orientate, and cognitive and decision-making processes, which determine the effectiveness of the wayfinding process [10]. Cognitive models that have been put forward to explain the wayfinding process have made reference to the iterative processes of route planning and plan execution [11]. Route planning describes the process of reviewing internal (memory) and/or external (such as maps) information to plan a sequence of navigation actions from an origin to a destination. During route planning, individuals tend to identify potential routes that satisfy their goals and then use several implicit and explicit strategies to quickly reduce options and settle on a route [8]. Following, route planning is the execution of the plan, which manifests in physical actions such as walking in a goal-oriented manner [12]. Walking alone (not only in a goal-oriented manner) is a task requiring cognitive input and this input is even greater in older adults [3]. The wayfinding process can be likened to a dual-task process (i.e., planning and physically moving the body), involving a strong emphasis on two aspects of the environment: landmarks and intersections [8]. Brunyé et al. [8] describe landmarks as environmental features that prompt familiarity, resolve locational ambiguity, and cue sequences of actions. Studies show that wayfinders often focus on landmarks positioned within particular intersections, employing them both for recognition and to cue appropriate actions such as continuing forward or taking a turn [13]. In light of this, intersections have frequently been implicated as critical decision points (DPs), considering that they place a demand on wayfinders to make decisions regarding how to continue their journey (e.g., continue straight, turn right or left) [14]. Support for this argument can be derived from the findings of previous studies which have equally shown that, overall, more errors (indicative of disorientation) were observed at intersections (i.e., crossings) [15, 16]; however, without any further indication of how location influences the effect of spatial disorientation on outcome measures such as gait and psychophysiological response.

Spatial Disorientation and Wayfinding

A term which has been coined to express the difficulty in wayfinding, experienced mostly by cognitively impaired older adults, and often leading to getting lost is spatial disorientation [17]. Spatial disorientation detection has met considerable attention in the study of Alzheimer's disease (AD) pathology [15, 18]. Considering that instances of spatial disorientation are ubiquitous, detecting these instances in real time becomes a priority. However, for real-time detection to be achievable, patterns of change in behavior (e.g., gait, psychophysiological response, interacting with the environment), which co-occur with spatial disorientation, need to be recognized. Following the outcome of a previous field study [19], a clear set of behaviors considered to be indicative of disorientation was identified. An example of such behaviors is "surveying the surrounding," which, according to Yordanova et al. [19], is indicative of the process of trying to reorient oneself during moments of disorientation (e.g., taking the wrong turn). In this field study concerned with wayfinding behavior in persons with mild cognitive

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impairment and dementia [15], real-time instances of spatial disorientation were identified by means of the indicators developed in Yordanova et al. [19]. Further evaluation of these disorientation instances, based solely on properties of the composite acceleration amplitude of accelerometers placed on the chest and ankle, showed an above-chance level of accuracy (area under the receiver operating characteristics curve = 0.75), which was, however, not high enough for individual prediction of instances of disorientation. The outcome of this study suggested that instantaneous detection of disorientation is feasible; however, the accuracy was not sufficient to serve as a basis for individual support due to the major study limitations – limited number of training features based only on properties of the accelerometric signal, ignoring other possible data sources such as psychophysiological data or precise gait features, a limited number of instances of disorientation, and an uncontrolled environment. An alternative to real-world navigation studies, which has gained popularity in recent times, is laboratory-based virtual reality (VR) studies [6]. In summary, navigation tasks posed in a virtual environment (VE) enjoy the advantage of having naturalistic interactive settings while ensuring a high degree of control and standardization [20]. This creates the enabling environment for accurately singling out the effect spatial disorientation might have on motion and psychophysiological behavior.

The Current Study

Extending the study by Schaat et al. [15], the current study sought to investigate the possible effect of spatial disorientation on gait and psychophysiological response among healthy older adults in a more controlled setting involving the Gait Real-Time Analysis Interactive Lab (GRAIL). The GRAIL has been reliably used by a number of previous studies in measuring gait performance [16, 21]. We expected that undertaking a wayfinding task would place similar cognitive demands on the participants as a dual-task condition (e.g., mental fatigue task), and that moments of disorientation would lead to heightened cognitive workload, as participants try to reorient themselves. To ensure that adequate instances of disorientation were observed among the healthy older adults who were the focus of the current study, and thereby overcoming the limitation of an earlier field study [15], disorientation was systematically induced for half of the older participants. Hence, this study was motivated by two major questions: (1) does spatial disorientation have an effect on gait parameters, and (2) does spatial disorientation have an effect on psychophysiological parameters? The focus on healthy older participants was motivated by the importance of detecting correlates of spatial disorientation earlier on in older participants before any neurodegeneration occurs. This will enable the prospect of early detection and intervention using assistive technology devices (ATDs). Furthermore, the gait and psychophysiological parameters were chosen as primary and secondary outcomes, respectively, considering that they have been well explored in different dual-task [22, 23] walking conditions and have appeared to produce significant age effects [22]. Gait and psychophysiological parameters have also previously provided indications of cognitive effort [22] and cognitive deficit [24]. Additionally, psychophysiological parameters are reliable measures of associated stress response even in nonambulatory conditions [25, 26]. An additional rationale for focusing on gait and psychophysiological measures lies in the high potential for evaluating real-time changes in these parameters by a wearable assistive navigation device. We therefore hypothesized that (1) changes in gait pattern will be associated with spatial disorientation and (2) changes in psychophysiological response will be associated with spatial disorientation. Lastly, the consideration of location (i.e., non-crossing vs. crossing) as an additional predictor is motivated by the proven influence of intersections on wayfinding behavior [8, 15, 16].

Table 1. Demographic characteristics of the control and experimental participants

	Older control (n = 14)	Older experimental (n = 14)
Females, n (%)	9 (64.3)	9 (64.3)
Age, years	69.5±3.9	72.0±5.3
Education, years	13.9±2.9	14.9±2.5
MMSE	28.9±0.9	29.4±0.6

Data are presented as mean ± standard deviation. MMSE, mini-mental state examination.

Materials and Methods

Participants

The 28 participants were community-dwelling older adult volunteers between the ages 60 and 85. Participants were randomly assigned to either the control (n = 14) or experimental (n = 14) group. Prescreening of participants comprised the Consortium to Establish a Registry for Alzheimer's disease (CERAD) cognitive battery, which included the mini-mental state examination (MMSE) test [27]. Exclusion criteria for all participants were past

Fig. 1. Depiction of the experimental setup (top left and right). Image is used with permission of the participant. Wayfinding route (bottom left). Red crosses denote locations where the VE was manipulated in the experimental group. DP1 to DP14 indicate the DPs from start to finish. The changes as described earlier were always the same for all older participants in the experimental group.

or present unstable medical conditions, major psychiatric disorders or neurological diseases, and musculoskeletal injuries. All participants had either normal or corrected-to-normal vision. Table 1 shows the demographic characteristics of the participants. All volunteers were informed about the experimental procedures and possible risks associated with the experiment before giving their written consent. The study followed the guideline of the Declaration of Helsinki [28], and was approved by the Ethics Committee of the University Medicine Rostock (Approval number: A 2019-0062).

Materials

The experiments were carried out in the GRAIL (Motek Medical B.V). The GRAIL system consisted of a treadmill, a large 180° projection screen, and an optical motion-capturing system. Twenty-six passive markers were placed on the participant's anatomical landmarks based on the Plug-in-Gait model of VICON (C7, T10, sternum, clavicle, 4 on the pelvis; anterior and posterior superior iliac spine, 2 on the thighs, 4 on the knees, 2 on the tibias, and 5 on each foot; toe, 5th metatarsus, inner ankle, outer ankle, and heel) and detected by 12 VICON infra-red cameras (www.vicon.com). A low-detail 3D virtual model of the Rostock city center was projected onscreen. The VE was generated from OpenStreetMap data of the city using the OSM2World tool (osm2world.org). This data includes building heights and rudimentary 3D models of landmark buildings. The resulting VR environment is a low-detail replication of the real city but does not contain moving objects like cars or pedestrians (see online suppl. material A; for all online suppl. material, see www.karger.com/doi/10.1159/000527503). Participants navigated through the VE by walking on a self-paced treadmill. Additionally, participants were equipped with three wearable sensors (Movisens GmbH) on the left wrist, right ankle, and chest that each contains a three-axis accelerometer with a sampling rate of 64 Hz. In addition to accelerometry, the chest sensor also recorded electrocardiographic activity (ECG, 1024 Hz), while the wrist sensor recorded electrodermal activity (EDA, 32 Hz). Participants' orientation behavior was further unobtrusively recorded using a GoPro Hero 7 action camera (www.gopro.com). The camera was placed facing the treadmill and projection screen at a distance of about 2 meters to the left side of the treadmill, and at a height of about 0.5 m. Figure 1 shows a depiction of the experimental setup. The ECG and EDA data were preprocessed using Kubios HRV Premium (University of Kuopio, Finland) and LEDALAB (www.ledalab.de), respectively. As for the video data, annotation by 2 trained annotators was carried out using the ELAN software (ELAN Linguistic Annotator 5.6.0.; Max Planck

Institute for Psycholinguistics, Nijmegen, The Netherlands). Further specific details about the study setup can be found in Amaefule et al. [16].

Study Design and Procedure

The current study employed a 2 (*orientation:* oriented vs. disoriented) × 2 (*location:* crossing vs. non-crossing) × 2 (*group*: older controls vs. older experimental) mixed-factorial design. Orientation and location were manipulated among participants. Participants performed a wayfinding task consisting of 14 major DPs (7 crossings) within the VE. A crossing was defined as a point where movement in 4 directions was possible, while a non-crossing was defined as a point where movement was only possible in less than 4 directions for the DPs. Movement through the VE was achieved by walking on the treadmill. Participants chose their walking direction by walking in the center or on either side of the treadmill. Walking on the left side of the treadmill resulted in a left turn in the VE and vice versa. Walking in the center resulted in a linear forward progression. Prior to the wayfinding task, participants underwent a training session in which they were properly familiarized with navigating using the setup. The study only proceeded upon oral confirmation from the participants that they were comfortable with using the setup. Additionally, the comfortability of the setup has previously been explored in an earlier feasibility study [16]. The wayfinding task consisted of two trials. For the first trial, participants were *guided* along a path (start to goal position) in the VE (shown in Fig. 1). The participants were instructed to learn the path during the guided walk, and were familiarized with the wayfinding route by briefly showing them a map (Fig. 1). The map (excluding details about the DPs) was shown to participants on a printed out A4-size paper for approximately 1 min. In comparison to some previous navigation studies [29, 30] in which route maps were shown for 5 min, we deemed 1 min sufficient for 2 reasons. (1) Participants were additionally led along the route in the first (learning) trial, in addition to being shown a map. Hence, in contrast to Meneghetti et al. [29] and De Beni et al. [30], the map served as an additional reference in explaining the task, but was not the primary means of route learning. (2) The focus of the current study was on establishing motion and psychophysiological correlates of navigation errors and not on the dynamics of route learning or visuospatial and other cognitive factors affecting navigation ability. The study instructions can be found in online supplementary material B. This ensured that errors during the wayfinding task were mainly due to disorientation, instead of exploration in an unfamiliar environment [15]. In the second trial, participants were set back to the starting position and asked to walk the same path again, this time *unguided*. For half of the healthy older subjects (the experimental group), phases of disorientation were induced by changing landmarks or DPs in the VE during the unguided walk. The changes included moving a landmark from one intersection to the next intersection, adding a DP, blocking a road, or moving the goal indicator to a different location. Overall, five locations were manipulated (shown in Fig. 1). More specifically, the DPs were altered as follows: DP4 – a red pillar was moved to DP4 from DP7; DP9 – the road was blocked; DP11 – a new path was introduced; DP13 – the color of the pillar was changed to red; DP14 – the goal location was moved a little further away. The reason for inducing disorientation among the experimental group was to allow enough instances of navigation errors, enabling the sufficient observation of the effect of disorientation on gait and psychophysiological response. Additional depiction of the changes can be found in online supplementary material A. The changes were always the same for all older participants in the experimental group. The experiment lasted an average duration of 40 min. The older participants' information sheet can be found in online supplementary material C.

Outcome Measures

Primary outcome measures included spatiotemporal gait parameters. The gait parameters of walking speed, step length, stride time, and stance time were continuously computed during the experiment by the D-Flow software (Motek Medical) controlling the GRAIL system as follows: during initialization, parameters of a skeleton model were estimated from the 3D coordinates of the 26 optical markers (see above), while the subject was at an initialization pose. During the experiment, the body pose was estimated from the 3D marker positions by solving an inverse kinematics problem [31]. Next, heel strike and toe off events, required for the definition of gait cycles, were obtained from the optical foot markers, as described in Zeni et al. [32]. Stance time was calculated as the time between heel strike and toe off. The walking speed was calculated based on the average horizontal displacement of the pelvis markers plus the current treadmill speed. Step length was calculated as the difference in anterior/posterior position in the global reference frame of the heel markers during subsequent heel strikes plus the traversed distance of the treadmill between the heel strikes, where the traversed distance was calculated by taking the integral of belt speed over time. Stride time was calculated as the time span between two consecutive ipsilateral heel strikes. Furthermore, the coefficient of variation (CV) of all gait parameters, an index of gait variability, which has been shown to be affected by cognitive effort in dual-task walking conditions [22] among healthy older adults, was derived. The CV was calculated for each gait parameter as the ratio of the standard deviation to the mean multiplied by 100 (CV = standard deviation × mean^{-1} × 100).

Secondary outcome measures included psychophysiological parameters – root mean square of the successive heartbeat interval differences (RMSSD), which is a measure of heart rate variability (HRV), and skin conductance response (SCR, amplitude and count; both representing the magnitude and frequency of changes in electrodermal conductivity, respectively) that were continuously monitored using the sensors on the chest and wrist, respectively. Changes in both psychophysiological measures (i.e., reduction in RMSSD and increase in SCR) have also been associated with cognitive effort [22, 33]. The gait parameters listed above were specifically investigated following the outcomes presented in Smith et al. [34]. The psychophysiological parameters were equally selected on a similar basis [22, 33]. All resulting data were synchronized by an event-based mechanism (participants performed a distinctive movement at the beginning of the recording, which can be easily located in all sensors) and resampled to 100 Hz.

Additional outcome measures included if participants were oriented or disoriented (orientation), and if the DP which they were at was a crossing or non-crossing (location). In order to identify instantaneous disorientation, the video data from the unguided walk was annotated using a customized scheme, which was an adequate adaptation of the scheme earlier employed in [15]. More specifically, we annotated when participants showed wandering behavior (i.e., non-goal-directed walk), communication behavior (i.e., asking for help when disoriented), topological orientation (i.e., trying to orient themselves based on the surrounding environment), or spatial orientation (i.e., trying to orient themselves based on landmarks). In addition, four different types of errors that are associated with disoriented behavior were annotated [16]. These included initiation (i.e., failure to commence the task), realization (i.e., failure to make a correct turn leading to the goal location at DPs), sequence (i.e., failure to proceed continuously with the task), and completion (i.e., failure to locate the goal point) errors. Following the annotation, observed features of orientation behavior were then categorized as "oriented" in the absence of disoriented behavior and "disoriented" when any disoriented behaviors or errors occurred. Following, all outcome measures for each participant were segmented according to the DPs along the wayfinding route, and each outcome measure was computed for each segment.

Statistical Analysis

The resulting data were assessed for normality by inspection of histograms and the Shapiro-Wilk test. This initial inspection revealed starting-point artefacts for the gait parameters. Hence, a filter function was applied to exclude these artefacts (17 starting data points). Subsequently, Pearson's χ^2 Test [35] was used to evaluate if the observed frequency of disorientation instances differed between locations (i.e., non-crossing, crossing), and between groups (i.e., older control, older experimental). To determine if there were differences between groups for the distribution of gender, the Pearson's χ^2 test was equally applied. Differences in age, education years, MMSE score, and all outcome variables between participant groups were evaluated using independent sample t tests. Using the R package VCD, the reliability of the video annotations between the 2 annotators (i.e., inter-rater reliability) was assessed based on the Cohen's kappa, which in comparison to percent agreement, is especially robust against agreement by chance [36]. We used R (R Core Team, 2018) and the package lme4 [37] to perform linear mixed effects analysis of the relationship between all gait and psychophysiological parameters (as outcome variables), orientation, location, and group, with age and sex included as covariates. The interaction between orientation and location, as well as orientation and group, were fitted as fixed effects and the intercepts for subjects as random effects. The models were fitted in a step-wise manner, first, with orientation and the covariates included in the *baseline model*, and subsequently, with orientation, location, group, and the covariates included in the *final model*. Considering that the model residuals were slightly skewed, we followed up with 100 bootstrap replications using the LMERESAMPLER package [38] to ascertain the robustness of the findings. Subsequently, we performed sensitivity analyses whereby the mixed effects models and bootstrap simulations mentioned previously were refitted, with the exception that 3 remnant outlier data points (assessed based on QQ plots of residuals) were excluded to ascertain if they had a considerable effect on the model outcomes. The sensitivity analyses were only performed in the case whereby the final models showed significant effects. In total, 96.2% of the data was retained after excluding outliers. In the following sections, we report and evaluate both the results of the original analyses and sensitivity analyses based on their confidence intervals (CI). In cases where the confidence intervals differ considerably, we report these results as inconclusive. The level of statistical significance was set at $p < 0.05$ for all analyses.

Results

Descriptive Analyses

Evaluation of the participants' orientation behavior showed that a significantly higher number of disorientation instances occurred mainly at crossings (χ^2 (1, N = 28) = 35.76, $p < 0.001$). Additionally, participants in the experimental group showed, overall, more instances of disorientation (χ^2 (1, N = 28) = 35.46, $p < 0.001$). Figure 2 shows an overview of the disoriented behavior instances by location and participant group. Furthermore, there were no significant differences in all other demographic variables (shown in Table 1). As for the outcome variables, walking speed ($p < 0.001$), step length ($p < 0.05$), stride time ($p < 0.001$), stance time ($p < 0.001$), walking speed CV ($p < 0.001$), and SCR count ($p < 0.001$) significantly differed between groups (Table 2). As regards the reliability of the video annotations, we found a substantial level of agreement, Cohen's $\kappa = 0.61$ (95% CI, 0.37 to 0.85, $p < 0.001$).

Spatial Disorientation and Gait Variability

To assess the effects of orientation, location and group on walking speed, step length, stride time, stance time, walking speed CV, step length CV, stride time CV, and stance time CV (gait parameters), we fitted separate mixed effect models using the gait values as outcome and the interaction terms between orientation and location, as well as, orientation and group as fixed effects with age and sex as covariates.

Walking Speed

Our baseline model revealed that being disoriented was associated with a lower walking speed (B = 0.21, t (473.77) = 7.15, 95% CI, 0.15 to 0.27, $p < 0.05$). An increase in age was also associated with a decrease in walking speed (B = −0.01, t (24.55) = −2.14, 95% CI, −0.02 to −0.0001, $p < 0.05$). For the final model, our results did not reveal any significant main or interaction effects for walking speed (Table 3), indicating that there was no effect of orientation across locations and groups.

Step Length

Our baseline model revealed that being disoriented was associated with a lower step length (B = 0.07, t (472.88) = 5.86, 95% CI, 0.05 to 0.10, $p < 0.05$). An increase in age was also associated with a decrease in step length (B = −0.005, t (24.64) = −2.16, 95% CI, −0.01 to −0.0002, $p < 0.05$). For the final model, our results only revealed a main effect of location (Table 3), whereby being at cross-

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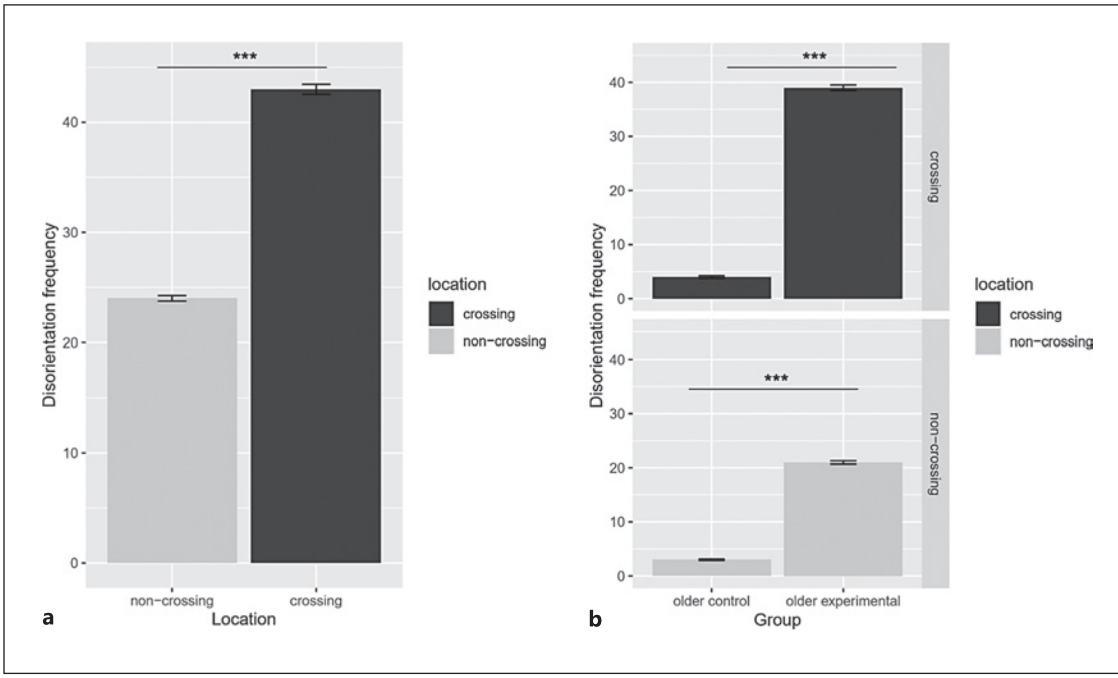

Fig. 2. Bar plots showing frequency of disoriented behavior instances: **a** all groups at non-crossings and crossings and **b** different groups at non-crossings and crossings, ***$p < 0.001$.

Table 2. Descriptive overview of all parameters for the control and experimental participants

	Older control	Older experimental
Walking speed, m/s	1.09±0.25	0.99±0.27***
Step length, m	0.58±0.11	0.56±0.12*
Stride time, s	1.10±0.11	1.17±0.20***
Stance time, s	0.73±0.10	0.78±0.18***
Walking speed CV (unitless)	2.15±5.27	5.29±10.80***
Step length CV (unitless)	2.80±27.30	2.55±7.35
Stride time CV (unitless)	10.30±131.0	10.50±57.80
Stance time CV (unitless)	1.93±13.60	3.44±12.5
HRV RMSSD, ms	127.0±120.0	141.0±96.80
SCR amplitude, μS	12.30±26.70	9.01±20.50
SCR count (unitless)	9.98±9.98	16.2±22.40***

Data are presented as mean±standard deviation of the parameter for the respective group. CV, coefficient of variation; HRV, heart rate variability; RMSSD, root mean square of the successive differences of adjacent inter-heartbeat intervals; SCR, skin conductance response; m/s, meters per second; m, meters; s, seconds; ms, milliseconds; μS, microSiemens. * Denotes a significant difference between groups (* $p < 0.05$, *** $p < 0.001$).

ings was associated with a higher step length regardless of orientation. A follow-up sensitivity analysis (Table 4) replicated the outcome as reported previously in the final model, whereby a significant main effect of location for step length was observed.

Stride Time

Our baseline model revealed that being disoriented was associated with a higher stride time (B = −0.13, t (475.55) = −6.72, 95% CI, −0.168 to −0.09, $p < 0.05$). For the final model, our results did not reveal any significant main or interaction effects for stride time (Table 3), indi-

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cating that there was no effect of orientation across locations and groups.

Stance Time

Our baseline model revealed that being disoriented was associated with a higher stance time (B = −0.09, *t* (478.54) = −5.44, 95% CI, 0.13 to −0.06, $p < 0.05$). For the final model, our results did not reveal any significant main or interaction effects for stance time (Table 3), indicating that there was no effect of orientation across locations and groups.

Walking Speed CV

Our baseline model revealed that being disoriented was associated with a higher walking speed CV (B = −8.45, *t* (483) = −7.58, 95% CI, −10.5 to −6.23, $p < 0.05$). For the final model, our results did not reveal any significant main or interaction effects for walking speed CV (Table 3), indicating that there was no effect of orientation across locations and groups.

Stance Time CV

Our baseline model revealed that being disoriented was associated with a higher stance time CV (B = −4.26, *t* (455.46) = −2.46, 95% CI, −7.83 to −0.97, $p < 0.05$). For the final model, our results did not reveal any significant main or interaction effects for stance time CV (Table 3), indicating that there was no effect of orientation across locations and groups. There were no significant effects found in either of the models for step length CV and stride time CV (Table 3).

Spatial Disorientation and Psychophysiological Response

To assess the effects of orientation, location and group on RMSSD, SCR amplitude, and SCR count (psychophysiological parameters), we fitted separate mixed effect models using the psychophysiological values as outcome and the interaction terms between orientation and location, as well as orientation and group as fixed effect with age and sex as covariates.

HRV (RMSSD)

Our baseline model showed no significant effects. For the final model, our results revealed a main effect of location (Table 3), whereby being at crossings was associated with a higher RMSSD regardless of orientation. Additionally, there was an orientation by location interaction for RMSSD (Table 3), indicating that a higher RMSSD was associated with being disoriented at crossings

Table 3. Linear mixed effects analysis

	Orientation			Location			Group			Orientation × location			Orientation × group		
	estimate	t	95% CI	estimate	t	95% CI	estimate	t	95% CI	estimate	t	95% CI	estimate	t	95% CI
Gait parameters															
Walking speed, m/s	0.10	1.14	−0.07 to 0.28	−0.09	−1.77	−0.21 to 0.003	−0.12	−1.19	−0.30 to 0.06	0.08	1.39	−0.02 to 0.21	0.09	1.07	−0.08 to 0.26
Step length, m	0.04	1.16	−0.02 to 0.12	−0.06	−2.44	−0.10 to −0.01*	−0.01	−0.24	−0.10 to 0.08	0.05	1.92	0.004–0.10	0.02	0.49	−0.06 to 0.09
Stride time, s	−0.05	−1.01	−0.17 to 0.06	−0.01	−0.52	−0.08 to 0.05	0.11	1.78	−0.003 to 0.26	0.01	0.45	−0.06 to 0.09	−0.08	−1.42	−0.20 to 0.02
Stance time, s	−0.06	−1.15	−0.16 to 0.03	−0.009	−0.28	−0.07 to 0.05	0.07	1.27	−0.04 to 0.18	0.01	0.48	−0.04 to 0.08	−0.04	−0.88	−0.14 to 0.05
Walking speed CV (unitless)	−5.85	−1.71	−12.3 to 0.23	−0.42	−0.19	−5.27 to 4.07	4.44	1.32	−1.94 to 10.3	1.05	0.45	−3.99 to 6.46	−3.03	−0.87	−8.81 to 3.26
Step length CV (unitless)	−2.15	−0.27	−17.6 to 12.9	−1.18	−0.24	−10.2 to 6.99	2.58	0.33	−13.6 to 17.9	2.99	0.55	−6.39 to 12.8	−4.30	−0.54	−20.1 to 12.5
Stride time CV (unitless)	−5.79	−0.14	−81.2 to 64.5	−13.19	−0.52	−63.3 to 38.1	17.02	0.43	−60.4 to 85.5	24.66	0.89	−34.7 to 79.7	−24.81	−0.61	−92.3 to 54.8
Stance time CV (unitless)	−2.45	−0.46	−14.8 to 8.66	−0.14	−0.04	−6.79 to 6.32	3.75	0.71	−8.00 to 14.1	2.26	0.62	−4.65 to 9.22	−3.98	−0.74	−14.4 to 8.32
Psychophysiological parameters															
HRV RMSSD, ms	−18.02	−0.59	−77.2 to 34.7	−52.59	−2.83	−89.2 to −14.4*	10.42	0.23	−91.1 to 92.5	53.25	2.62	11.0–95.4*	12.40	0.40	−44.3 to 72.2
SCR amplitude, μS	−15.08	−1.86	−30.9 to −0.25	−3.23	−0.65	−13.7 to 7.50	−13.21	−1.38	−36.6 to 6.85	−6.52	−1.21	−18.0 to 4.60	10.52	1.28	−6.28 to 29.3
SCR count (unitless)	−0.76	−0.12	−13.6 to 10.3	−3.45	−0.89	−10.6 to 3.38	23.50	3.63	9.57–35.6***	−2.43	−0.57	−10.3 to 5.81	−22.52	−3.52	−33.8 to −8.96***

Results of the final models are reported. CV, coefficient of variation; HRV, heart rate variability; RMSSD, root mean square of the successive differences of adjacent inter-heartbeat intervals; SCR, skin conductance response; CI, confidence interval (estimated from bootstrap simulations with 100 replications); m/s, meters per second; m, meters; s, seconds; ms, milliseconds; μS, microSiemens. *Denotes a significant effect (* $p < 0.05$, *** $p < 0.001$).

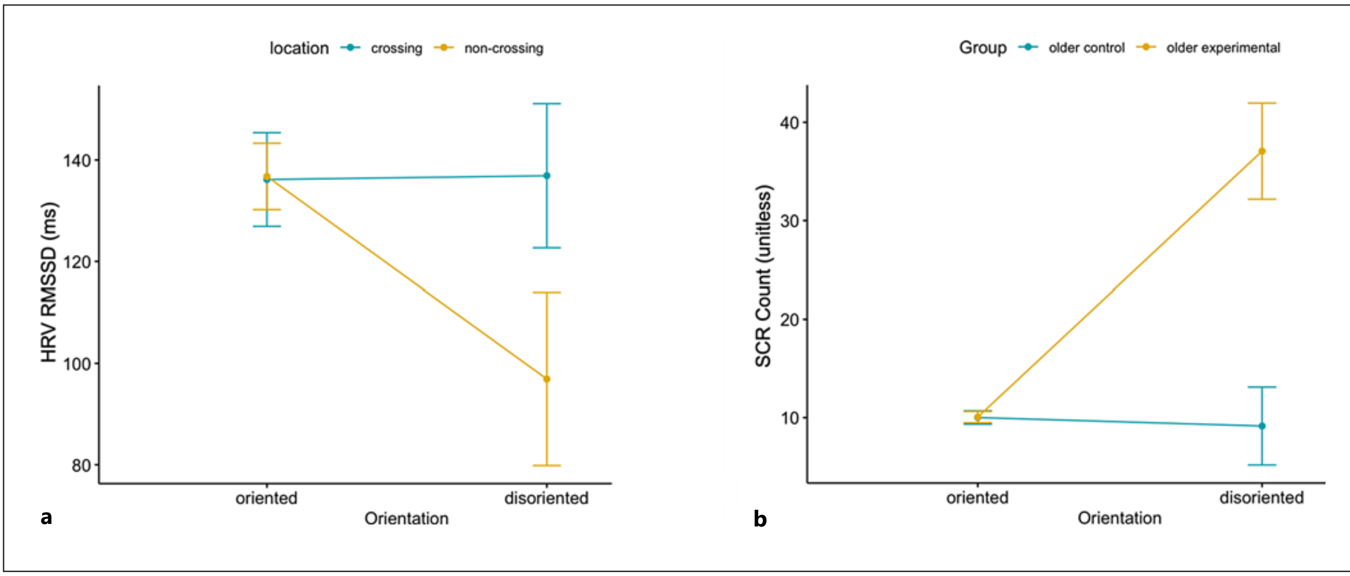

Fig. 3. Line plots showing interaction effects: **a** HRV RMSSD and **b** SCR count. HRV, heart rate variability; CV, coefficient of variation; RMSSD, root mean square of the successive differences of adjacent inter-heartbeat intervals; SCR, skin conductance response; ms, milliseconds. Error bars represent the standard error of the mean.

(Fig. 3a). There was no orientation by group interaction (Table 3), indicating that there was no effect of orientation across groups. A follow-up sensitivity analysis (Table 4) replicated the outcomes as reported previously in the final model, whereby a significant main effect of location and an orientation by location interaction effect were observed for RMSSD.

SCR Amplitude

Our baseline model revealed that being disoriented was associated with a higher SCR amplitude (B = −12.61, t (470.01) = −4.60, 95% CI, −24.9 to 132, $p < 0.05$). For the final model, our results did not reveal any significant main or interaction effects for SCR amplitude (Table 3), indicating that there was no effect of orientation across locations and groups.

SCR Count

Our baseline model revealed that being disoriented was associated with a higher SCR count (B = −24.31, t (482.83) = −11.41, 95% CI, −28.8 to −20.4, $p < 0.05$). For the final model, our results revealed a main effect of group (Table 3), indicating that a higher SCR count was associated with being in the experimental group. Additionally, we observed an orientation by group interaction (Table 3), indicating that a higher SCR count was associated with being disoriented in the experimental group (Fig. 3b). There was no significant orientation by location interaction (Table 3), indicating that there was no effect of orientation across locations. A follow-up sensitivity analysis (Table 4) replicated the outcomes as reported previously in the final model, whereby a significant main effect of group and an orientation by group interaction were observed for SCR count.

Discussion

The present study investigated the effect of spatial disorientation on gait variability and psychophysiological response among healthy older adults during wayfinding in a VE. Firstly, results from this study provide a new insight in aging navigation research [3, 4, 21], by indicating that spatial disorientation can be successfully induced and evaluated among healthy older adults in an ambulatory VR setting, judging by the significantly higher instances observed among the experimental participants. Previous spatial disorientation studies involving healthy older adults and/or patients have mainly employed either computer-based VR tasks [39] or real-world wayfinding tasks [15, 39]. Secondly, results showed a significant effect of spatial disorientation, most of which were observed at crossings, on gait variability and psychophysiological response. This also adds new insights to the existing litera-

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ture on the detection of spatial disorientation [15, 18] and to the associated changes in gait [22, 40] and psychophysiological response [22], resulting from the cognitive demands posed by spatial disorientation during wayfinding. As regards the VE used in the current study, considering that it was a low-detail replication of the Rostock city center (with landmarks from the real-world presented in a highly degraded form), we did not expect extent of familiarity outside the context of the study to play any considerable role in performance outcomes; nonetheless, the potential effect of prior familiarity has been acknowledged further down as a possible limitation.

Impact of Spatial Disorientation on Gait Variability

Spatial disorientation had an effect on gait variability among the healthy older adults. This was evident in the main effects observed for walking speed, step length, stride time, stance time, walking speed CV, and stance time CV in our baseline model, thereby confirming Hypothesis 1. These effects were, however, not replicated in the final models with location and group as additional predictors. Gait measures such as speed, stride length, and stance time have been investigated previously in dual-task conditions involving older adults [22, 40]. Behrens et al. [22], for instance, investigated the effect of a state of heightened cognitive demand (mental fatigue) on gait variability. Results from the study by Behrens et al. [22] showed significantly increased variability in speed, stride length, and stance time among the older participants following mental fatigue in the dual-task walking condition. Similarly, Kizony et al. [21] have also reported a significant decrease in gait speed among older participants following a cognitive task in a VE. In the context of the current study, we intended that the wayfinding task would place similar cognitive demands on the participants as dual-task conditions (e.g., mental fatigue), and that moments of disorientation will lead to heightened cognitive workload, as participants try to reorient themselves at the different locations, which could be observed in the variability of their gait patterns. This was the case considering the main effects observed. These outcomes are consistent with the well-known fact that aging is characterized by functional decline in selective cognitive domains [2] required for successful navigation due to anatomical alterations in the aging brain. One of such critical functions is executive function, which can be divided into different components, each having unique effects on gait [41]. Of particular importance to this discourse is the attention/dual-tasking component. Models put forward to explain the role attention/dual-tasking may have on gait gener-

Table 4. Sensitivity analysis

	Orientation			Location			Group			Orientation × location			Orientation × group		
	estimate	*t*	95% CI	estimate	*t*	95% CI	estimate	*t*	95% CI	estimate	*t*	95% CI	estimate	*t*	95% CI
Gait parameters															
Walking speed, m/s	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Step length, m	–	–	–	−0.06	−2.52	−0.10 to −0.01*	–	–	–	–	–	–	–	–	–
Stride time, s	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Stance time, s	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Walking speed CV (unitless)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Step length CV (unitless)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Stride time CV (unitless)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Stance time CV (unitless)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Psychophysiological parameters															
HRV RMSSD, ms	–	–	–	−52.60	−2.83	−94.3 to −14.8*	–	–	–	53.30	2.62	10.7–100*	–	–	–
SCR amplitude, µS	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
SCR count (unitless)	–	–	–	–	–	–	23.49	3.62	9.04–37.3***	–	–	–	−22.55	−3.51	−35.1 to −8.27***

Results of the final models are reported. CV, coefficient of variation; HRV, heart rate variability; RMSSD, root mean square of the successive differences of adjacent inter-heartbeat intervals; SCR, skin conductance response; CI, confidence interval (estimated from bootstrap simulations with 100 replications); m/s, meters per second; m, meters; s, seconds; ms, milliseconds; µS, microSiemens. *Denotes a significant effect (* $p < 0.05$, *** $p < 0.001$).

ally revolve around the capacity-sharing theory, the bottleneck theory or the multiple resource models theory [41]. The capacity-sharing theory [42], for instance, posits that attentional resources are limited in capacity, and so the performance of two attention-demanding tasks will cause deterioration of at least one of the tasks. In other words, the performance of an additional task (i.e., wayfinding) during walking alters gait (e.g., stability, speed) or the execution of the wayfinding task or both. These alterations in gait and secondary task performance have mainly been studied in the context of falls [43, 44]. In the current study, we were able to show that such alterations could also be indicative of moments of spatial disorientation in the absence of fall risks. However, contrary to our expectation, we found no main effects of spatial disorientation in the final models including location and group as additional predictors. There was also no main effect of group. Nonetheless, an effect of location was found for only step length. This could possibly be explained by the high collinearity of orientation, location, and group in the final models, which gives rise to the possibility of a confounding effect of the location and group predictors in the final model. Lastly, the lack of significant interaction effects of spatial disorientation and location or spatial disorientation and group suggests that the effect of disorientation on gait parameters among the older adults did not depend on participants' location (i.e., crossing vs. non-crossing) or group (i.e., older control vs. older experimental). Overall, the current findings of associations between spatial disorientation and gait changes are worth considering, in view of the fact that there was no major difference in confidence intervals between the outcomes of the initial analysis and the sensitivity analysis. Nonetheless, the main effects reported from the baseline model should be taken with a note of caution, considering that these effects were not replicated when location and group were included as additional predictors in the final models.

Impact of Spatial Disorientation on Psychophysiological Response

We observed that spatial disorientation had an effect on psychophysiological response among the healthy older adults. This was evident in the main effects observed for SCR amplitude and SCR count in our baseline model, thereby confirming Hypothesis 2. These effects were, however, not replicated in the final models with location and group as additional predictors. Changes in the autonomic nervous system (ANS) activity in response to highly challenging situations have been observed in various conditions [22]. In principle, when faced with challenging situations, the ANS and hypothalamic-pituitary-adrenal axis are two major systems that respond in an attempt to re-establish balance on a psychophysiological level, through changes in cardiac activity, sweat gland activity, and skin temperature [26]. Two popular estimates of psychophysiological response are the HRV and SCR measures. In non-walking conditions, HRV has been associated with performance in a range of cognitive domains, including, but not limited to, executive and attention functions, memory functions, and visuospatial skills [45]. As for SCR, changes have been informative in the occurrence of spatial disorientation among pilots [33], and for algorithm-based detection of stress [26]. More importantly, in dual-task walking, Behrens et al. [22] reported a stronger psychophysiological workload response and a higher cognitive effort during a mental fatiguing task in the older adults based on a reduction in the RMSSD HRV measure. In the current study, increases in SCR amplitude and SCR count were observed during moments of spatial disorientation, which would indicate increases in cognitive effort [22, 26] as participants try to reorient themselves. Contrary to our expectation, however, we found no main effects for spatial disorientation in the final models including location and group as additional predictors. This could be explained by the high collinearity of orientation, location, and group in the final models, which gives rise to the possibility of a confounding effect of the location and group predictors in the final model. Nonetheless, the main effects of location and group were found for RMSSD and SCR count, respectively, in the final model. These observations signify that in the case of RMSSD, being at crossings was associated with a reduced psychophysiological response in comparison to being at non-crossings regardless of orientation. To some extent, this might be driven by the tendency of the participants to reduce physical effort when they slow down or stop walking at crossings. Untangling physical from mental effort in psychophysiological studies remains a topic of discussion [46]. In the case of SCR count, the observation signifies an overall increased cognitive effort in the experimental group following the induction of disorientation. Furthermore, an orientation by location interaction was also observed for RMSSD. However, contrary to the findings from Behrens et al. [22], a lower RMSSD was only observed when disorientation occurred at non-crossings; when disorientation occurred at crossings, a higher RMSSD was rather observed. A possible explanation could be that due to the physiological latency [26, 47] between activation of the ANS and changes in HRV (about 1 s) or SCR (1–5 s) detected by the worn sensors, activations resulting from instances of spatial disorientation at crossings may have only been picked up "post facto" in moments after which the participant could have already traversed the crossing. Additionally, we found significantly more SCR counts when disorientation occurred in the experimental group (compared to the control group) irrespective of location. To a fair extent, this supports the earlier notion that disorientation was successfully induced by manipulating the environment in the experimental group. The follow-up sensitivity analysis done while removing data points which were systematically determined as outliers yielded similar results as the initial analysis with the original sample, thereby confirming that the findings were not in any way biased by the presence or absence of the outliers. Nevertheless, the main effects reported from the baseline model should be taken with a note of caution, considering that these effects were not replicated when location and group were included as additional predictors in the final models.

Implication for Independent Wayfinding and Assistive Technology

A central aim of gerontological research in recent times has been to identify markers for designing effective intervention. In the area of assistive technology, this means, first, identifying the most relevant indicators of the challenging situation (i.e., spatial disorientation), and second, designing situation-adaptive and subsidiary assistive devices, which could leverage upon existing cognitive resources by only providing assistance when needed [48]. In the current study, results showed that changes in the pattern of gait (i.e., walking speed, step length, stride time, stance time, walking speed CV, and stance time CV) and psychophysiological arousal (i.e., SCR amplitude and count) corresponded to instances of spatial disorientation during wayfinding among older adults. Additionally, we were able to provide evidence for the argument that crossings are important "hotspots" for spatial disorientation as more instances of spatial disorientation were observed at crossings. However, as regards the interdependence of spatial disorientation and location, our results rather showed effect for RMSSD (i.e., HRV) at non-crossings. These outcomes suggest that in designing ATDs for navigation support, a more adaptive approach might be needed in selecting relevant features for detecting spatial disorientation, considering that on a general level, changes in our gait and psychophysiological parameters had implications for the detection of spatial disorientation. On a more specific level, however, while our psychophysiological feature (RMSSD) was more reflective of spatial disorientation at non-crossings, it remains unclear what features might be more informative for spatial disorientation detection at crossings. Nonetheless, identifying the relevant features for spatial disorientation at non-crossings arguably provides the benefit of proactively detecting navigation errors in time and intervening prior to moments when their consequences could be more dire (e.g., at crossings). In this case, a situation-adaptive ATD should be able to recognize and adapt to the user's location (derivable from global positioning system coordinates) in both detecting disorientation and providing assistance. A hypothetical ATD could then employ a combined evaluation of the user's gait and psychophysiological arousal level in general, but prioritize evaluation of psychophysiological arousal level while at non-crossings, as well as further location-based features at crossings when available.

Strengths and Limitations

A key strength of the current study is the combined setup of an adequately immersive VE and a well-instrumented treadmill [16]. This gives the advantage of a naturalistic interactive setting while ensuring a high degree of control and standardization. With the current setup, we were able to explore associated changes in gait and psychophysiological features resulting from instances of spatial disorientation among older adults during wayfinding while overcoming two major challenges: (1) the lack of control and standardization in real-world environments and (2) the limited ecological validity in non-ambulatory VR navigation studies. This gives confidence to the validity of the study findings. On the contrary, a major limitation of the current study is the limited sample size. Further studies with larger sample sizes are still recommended to confirm the findings of the current study. A further limitation is the use of psychophysiological measures from the exact moment as the occurrence of spatial disorientation. Although this was done to ensure perfect temporal synchronization with the gait features, it might be a better approach to derive psychophysiological measures from a short duration after the occurrence of spatial disorientation due to the required physiological latency between ANS activation and changes in heart rate or SCR. Nevertheless, these measures were not derived here for practical reasons – one being that such psychophysiological measures will have to be derived from a post-disorientation latency. This goes against the rationale of the study, as we were more interested in changes in these measures within the latency of disorientation occurrence, considering that our ATD of interest should be proactive (i.e., identify characteristics of disorientation and provide intervention prior to the consequences, e.g., getting lost) rather than retroactive. Also, although the VE used in the current study was a low-detail rendition of the Rostock city center, we acknowledge that the extent of participant prior familiarity with the city center (which was not investigated in the current study) might be a contributing factor to disorientation worth investigating in future studies. Additionally, we acknowledge that the unusual walking pattern due to the experimental setup limits the ecological validity of the current study. Omnidirectional treadmills which allow free movement in all directions could be an alternative for future wayfinding research.

Conclusion

The present study highlighted the effect of spatial disorientation on gait variability and psychophysiological response among healthy older adults during wayfinding in a VE. Informative findings of variations in gait and psychophysiological response following moments of spatial disorientation provide valuable insight into the behavioral substrates of navigation challenges among older adults, thereby highlighting viable features for designing situation-adaptive interventional ATDs.

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Statement of Ethics

The study followed the guidelines of the Declaration of Helsinki [28]. All participants have given their written informed consent before participating in any study related activity. Written consent was also obtained for the publication of the participant image depicted in Figure 1. The study protocol has been approved by the Ethics Committee of the University Medicine Rostock (Approval number: A 2019-0062).

Conflict of Interest Statement

Part of the presented material arises from the doctoral theses of A. Klostermann, C. A. Hinz, and I. Kampa.

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Author Contributions

Chimezie O. Amaefule, Stefan Lüdtke, Anne Klostermann, Charlotte A. Hinz, and Isabell Kampa contributed towards data acquisition. Chimezie O. Amaefule analyzed the data and wrote substantial parts of the manuscript. Stefan Teipel, Thomas Kirste, Stefan Lüdtke, and Chimezie O. Amaefule provided substantial contributions to the conception and design of the work, analysis, and interpretation of data for the work. Chimezie O. Amaefule, Stefan Lüdtke, Anne Klostermann, Charlotte A. Hinz, Isabell Kampa, Thomas Kirste, and Stefan Teipel participated in drafting the work and revising it critically for important intellectual content and finally approved the version to be published and agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Data Availability Statement

All data generated or analyzed during this study are not included in this article due to ethical reasons. Further inquiries can be directed to the corresponding author.

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