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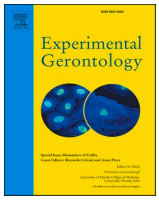

Impact of repetitive home-based galvanic vestibular stimulation on cognitive skills in healthy older adults

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ABSTRACT

The human vestibular system is adversely affected by the aging process. Recent evidence indicates that vestibular information and cognitive functions are related, suggesting that age-related vestibular loss may contribute to cognitive impairment. In this study, we aimed to investigate the effects of repetitive, home-based galvanic vestibular stimulation (GVS) on cognitive functions in healthy older adults. Twenty-one participants (age = 64.66 ± 2.97 years, 12 females) were randomly allocated to either a home-based GVS or an active control group. The GVS intervention lasted 20 min per session, five times a week, for two weeks (10 sessions). Cognitive functions were assessed before and after the intervention using the Stroop Test, Trail Making Test A&B, and Dual-Task (digit recall and paper-pencil tracking test). Our findings revealed a significant group-by-time interaction effect for the tracking accuracy ($F(1,18) = 7.713$, $p = 0.012$, $\eta_p^2 = 0.30$), with only the home-based GVS group showing significant improvement ($t = -2.544$, $p = 0.029$). The proposed home-based GVS protocol offers a promising non-pharmacological avenue for enhancing visuospatial ability in healthy older adults. Further research is needed to investigate the effects of different GVS protocols on various cognitive functions, particularly in older individuals with different health conditions.

1. Introduction

The vestibular system is an evolutionarily old sensory system comprising the peripheral apparatus, the vestibular nerve, the brainstem, cerebellar processing circuits, and vestibular pathways to the thalamus and cortex (Jamon, 2014). As we have gained a deeper understanding of the vestibular system, it has become clear that it plays a role not only in the detection of head acceleration, gaze stability, and postural control but also in various higher cognitive functions (Smith, 2017). Human neuroimaging studies have revealed the cortical projection areas that are activated during selective stimulation of the vestibular system, including the somatosensory cortex, frontal cortex, parietal cortex, hippocampus, and temporoparietal junction (Shinder and Taube, 2010; Lobel et al., 1998; Lopez and Blanke, 2011). Evidence of transmitting vestibular information to cortical areas responsible for specific cognitive functions has raised questions about potential cognitive decline in the absence of vestibular input. Indeed, cognitive complaints in patients with vestibular symptoms are not rare. A growing body of literature suggests a causal link between vestibular dysfunction and cognitive impairment, including spatial navigation, attention, perception, executive function, and memory (Smith et al., 2005; Rizk et al., 2020; Zwergal et al., 2024). Furthermore, research has demonstrated that vestibular symptoms' severity, duration, and degree of compensation can impact cognitive impairment (Rizk et al., 2020; Lacroix et al., 2021).

Although the exact mechanism linking vestibular dysfunction to cognitive impairment remains uncertain, vestibular dysfunction might cause atrophy in regions of the cortical vestibular network, including the hippocampus, potentially leading to deficits in memory and visuospatial abilities (Brandt et al., 2005; Hüfner et al., 2009). Another proposed mechanism is that the increased postural instability accompanying vestibular loss may demand more attentional resources to maintain balance, thus reducing the resources available for cognitive functions (Bigelow and Agrawal, 2015). Additionally, the high prevalence of emotional disturbances in individuals with vestibular disorders has been suggested to contribute to cognitive dysfunction (Gurvich et al., 2013).

Aging has deteriorating effects on all structures relevant to vestibular function, including the otolith organs, semicircular canal, central

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vestibular system, and vestibular-cortical projections (Arshad and Seemungal, 2016). Early histological reports confirm that hair cell counts decline in vestibular end organs as people age (Rosenhall, 1973; Richter, 1980), and the vestibular nerve fibers undergo a degenerative process that results in a 40 % decrease around the seventh decade (Bergström, 1973). A study on individuals aged 40–93 years has demonstrated a loss of 3 % of neurons per decade in the vestibular nuclei (Lopez et al., 1997). Furthermore, the volume of the vestibulospinal tract and parieto-insular vestibular cortex is lower in older adults than in young individuals (Yeo et al., 2020). In parallel with these histological and imaging studies, a cross-sectional analysis including 5086 adults demonstrated that the incidence of vestibular dysfunction increased significantly with advancing age (Agrawal et al., 2009).

A topic of inquiry within the literature pertains to the potential deteriorating impact of age-related vestibular dysfunction on cognitive function. Relatedly, an epidemiological study conducted on a sample of 1303 adults aged ≥60 years reported that vestibular dysfunction accounted for 14.3 % of the cognitive decline associated with aging (Semenov et al., 2016). Moreover, a study with a sample size of 5107 patients (mean age: 57.9) found that individuals with vestibular dysfunction are more likely to experience cognitive processing difficulties rather than mobility-based tasks (Harun et al., 2015). Vestibular-related cognitive declines in aging may be linked to reduced vestibular stimulation projecting to brain structures involved in these cognitive functions, possibly related to vestibular hypofunction and the sedentary lifestyle of older adults.

Galvanic vestibular stimulation (GVS) is a non-invasive method that allows motion-free activation of the vestibular system (Dlugaiczyk et al., 2019). The utilization of GVS in clinical settings is increasing due to its objectivity, safety, easy implementation, low cost, and minimal patient discomfort (Pires et al., 2022). Currently, GVS has been used as a diagnostic and rehabilitative tool, not only exerting an effect on vestibular system-related mobility like postural control during standing but also engaging mood and cognition. Since the deterioration of vestibular structures may worsen cognitive aging, increasing vestibular input may be expected to improve cognitive functions in older adults. However, available findings demonstrated that the effect of GVS on cognitive and locomotor function depends on the application protocol, including electrode size, wave configuration, polarity, intensity, duration, and stimulation frequency (Pires et al., 2022; Truong et al., 2023). Therefore, conducting research to evaluate the effectiveness of GVS and developing a suitable protocol could have significant clinical implications and contribute to the well-being of the aging population.

Although previous studies examined the effects of a single GVS session on cognition in humans, no study has investigated the effects of repeated GVS on cognitive functions in older adults. The aim of the current study is thus to investigate the effects of repeated, home-based GVS on cognitive functions in healthy older adults. Home-based intervention programs may constitute a feasible strategy to improve the participant's engagement and compliance with health-related experimental research. In addition, it ensures the availability of outpatient treatment options if the results indicate any therapeutic properties. Therefore, for the first time to our knowledge, we created a home-based GVS program to self-administer the participants and selected a range of cognitive functions to assess the effects of ten sessions of GVS. We hypothesized that repeated sessions of GVS would improve cognitive functions in healthy older adults.

2. Material and methods

2.1. Participants

The current sample is a subsample of participants from the VELOCCE study, investigating the effect of exercise, bright light exposure, and GVS on sleep habits. Therefore, Participants were recruited through advertisements in the local newspapers and media reports between September 2021 and January 2023. The inclusion criteria were: (i) age of at least 60, (ii) being retired, (iii) being right-handed, (iv) having Pittsburgh Sleep Quality Index (PSQI) score < 5. The exclusion criteria were: (i) diagnosis of acute psychiatric, vestibular, neurologic, endocrine, or cardiovascular disorders, (ii) taking psychotropic or bradicardizing medication, (iii) alcohol, drug, or caffeine abuse, (iv) recent hospitalization (<30 days) (v) Mini-Mental State Examination score below 26/30, (vi) having health enhancing physical activity (HEPA) active level (International Physical Activity Questionnaire short-form score ≥ 1500 MET), (vii) inability to use the computerized tool. This study analyzed the GVS and control groups, however, the VELOCCE project also included exercise and exercise plus light exposure groups. Therefore, the randomization process was performed based on four groups. Eligible participants were allocated to one of the study groups using simple randomization from a computer-generated numbered sequence with 25 blocks of 4, performed by a researcher. Participants received a number based on the order of their registration for the study after enrolling and signing the informed consent form. While the researchers and participants were not blinded, the data analyst remained blinded. The study was approved by the local ethical committee (Comité de Protection des Personnes, CPP Nord Ouest III, Caen) - number IDRCB: 20206A01578–31. All participants gave written informed consent before participation and received financial compensation.

Table 1 provides the demographic, physical, and mental characteristics of the participants.

2.2. Measures

2.2.1. Cognitive assessment

A trained researcher administered subtests of the GREFEX battery (Godefroy, 2008), including the Stroop Color and Word Test, Trail Making Test A and B, and Baddeley's dual-task paradigm. Prior to all cognitive tests, familiarization sessions were conducted.

2.2.1.1. Trail making test. We used the paper-and-pencil version of Trail Making Test A&B to assess cognitive flexibility. Participants were required to draw a line to connect 25 encircled numbers distributed randomly on a paper in the Trail Making Test Part A, whereas to connect alternating numbers and letters (e.g., 1-A, 2-B, 3-C) in Part B. Total time to complete the task, including corrections prompted by the examiner, was calculated.

2.2.1.2. Stroop test. We used the Stroop Color and Word Test to assess inhibitory control. Participants were presented with three cards, including the "color card" (X), on which there are patches of three different colors; the "word card" (Y), on which are printed (in black and white) the names of the colors, and the "color-word card" (Z) on which are printed the names of the colors, printed in an ink of a conflicting color. Each card has 100 items to be named. The participant's task on

Table 1
Demographic and clinical characteristics of participants.

	Total (n = 21)	GVS (*n* = 11)	Control (*n* = 10)	*p* value
Age (years)	64.66 (2.97)	65.00 (0.85)	64.30 (1.02)	0.60
Sex (m|f)	9|12	3|7	6|5	
BMI (kg/m^2)	27.33 (5.36)	25.81 (1.46)	29.00 (1.78)	0.18
IPAQ (MET)	1158.45 (890.38)	1060.95 (261.68)	1265.70 (300.00)	0.61
MMSE	28.61 (1.68)	28.63 (0.50)	28.60 (0.56)	0.96
Education (years)	13.0 (2.66)	13.09 (0.71)	12.90 (0.97)	0.87

Note. Continuous data is presented as mean and standard deviation with corresponding *p*-values. BMI, body mass index; GVS, galvanic vestibular stimulation; IPAQ, International Physical Activity Questionnaire; MET, metabolic equivalent; MMSE, Mini-Mental State Examination.

card X was to name the color of the patch (red, green, blue) as rapidly as possible, scanning the rows from left to right. On card Y, the participant read the words (color names) aloud. On card Z, the participant was required to name the colors of the inks while ignoring the conflicting printed color names. Participants were asked to respond as fast and correctly as possible. Total time to complete the task on each card, interference and error scores were calculated. Interference score was calculated as follows: Interference score = [Total time Z − Total time X].

2.2.1.3. Dual-tasking test. We used a dual-task paradigm consisting of performing digit recall and paper-pencil tracking tasks separately (single task) and simultaneously (dual-task) (Baddeley et al., 1997). In the digit recall task, participants heard a sequence of digits at a rate of one per second and then asked to repeat them back in the same order. Before starting the task, the digit span of each individual was established, and the sequence of digits that each participant heard during the task varied depending on the span score. The paper-pencil tracking task was to cross a predetermined path on an A4 sheet as quickly as possible by placing an X in 1 cm squares that formed a predetermined path in 120 s. The accuracy score was calculated for both single and dual-task trials. A dual-task mu score, a combined score computing the dual-task cost, was calculated as follows: 100 − [(Percent change digit task + Percent change tracking task) /2] (Baddeley et al., 1997, 2001).

2.3. Galvanic vestibular stimulation

Bipolar, sinusoidal GVS current was delivered by a mini-CT portable box device (Soterix Medical®, USA). The GVS sessions were scheduled five times per week over two weeks, from Monday to Friday, at a fixed time in the morning. Two square electrodes (5 × 5 cm) were placed behind the ears on the mastoid bone after soaking in serum physiologic (Fig. 1). A headband was used to ensure optimal contact between the skin and the electrodes. The duration of the stimulation was 20 min, initiated by a 60-s ramp-up and terminated by a 60-s ramp-down, with a set sinusoidal current of the frequency of 1 Hz and intensity of 1 mA.

Fig. 1. GVS application.

Before the intervention, we programmed the GVS device according to the parameters above and generated ten codes for each participant, aligning with the ten stimulation sessions. Participants were instructed to sit relaxed with their eyes open during the intervention and to enter the day's code for each session. After the instructional program was completed, the participants self-administered the first vestibular stimulation session in the laboratory under the guidance of the experimenter. The remaining sessions were conducted at home, and the intervention was remotely monitored via the SAPATIC digital platform. The stimulator screen provided systematic feedback on contact quality and stopped the stimulation if the quality was "poor".

2.4. Procedure

Participants visited the laboratory four times during the experimental process. The assessment dates were established based on all the research questions of VELOCCE, not only on the GVS but also on exercise and light therapy interventions. Therefore, the GVS and control groups underwent a 12-week inactive control and health education program, respectively, prior to the GVS intervention. Further measurements, which were taken but not included in the analysis, involved assessment of sleep, circadian rhythm, cardiorespiratory fitness, and motor tasks, including mobility, balance, grip, and lower limb strength, in addition to a quality of life questionnaire. To prevent any confounding factors that could arise due to motivational factors during the GVS intervention, participants in the control group received a one-hour health education session via video conference every week for two weeks. These sessions covered topics related to physical activity, healthy lifestyle practices such as sleep habits and dietary balance, and cardiovascular risk factors. The experimental flow diagram can be seen in Fig. 2. For a comprehensive overview of the VELOCCE study procedure, refer to the study protocol by Milot et al. (2024).

2.5. Statistical analysis

Statistical analyses were conducted with IBM SPSS Statistics for Windows (Version.

25.0; Armonk, NY, USA). Data normality was confirmed using the Shapiro-Wilk test. Descriptive statistics for the baseline characteristics were presented as means ± standard deviations (SDs) for the continuous factors, and assessed by two sample *t*-test. A mixed model analysis of covariance (ANCOVA) with one within-subject factor (time: pre (visit 3rd) and post (visit 4th)) and one between-subject factor (group: GVS and control) were examined for the cognitive measurements. The baseline cognitive score (visit 2nd) was included as a covariate for each outcome since baseline covariates increase power in randomized studies (Van Breukelen, 2006). In case of significant group-by-time interactions, Bonferroni adjusted paired (within-group) *t*-tests were conducted for post-hoc analyses. $p < 0.05$ was the statistical significance cutoff level. The effect size was estimated by partial eta squared coefficient (η_p^2), and Cohen's *d* values were interpreted as follows: large ≥0.8, medium ≥0.5, small ≥0.2, and trivial <0.2 (Cohen, 1998).

3. Results

We analyzed a subsample of $n = 21$ participants (age: $M = 64.66$ years, $SD = 2.97$) who participated in the GVS intervention and control sessions. Any participant who failed to complete the intervention program or attend all assessments was excluded from the analysis. One participant dropped out of the GVS group due to an inability to apply GVS, and one participant in the control group dropped out due to an

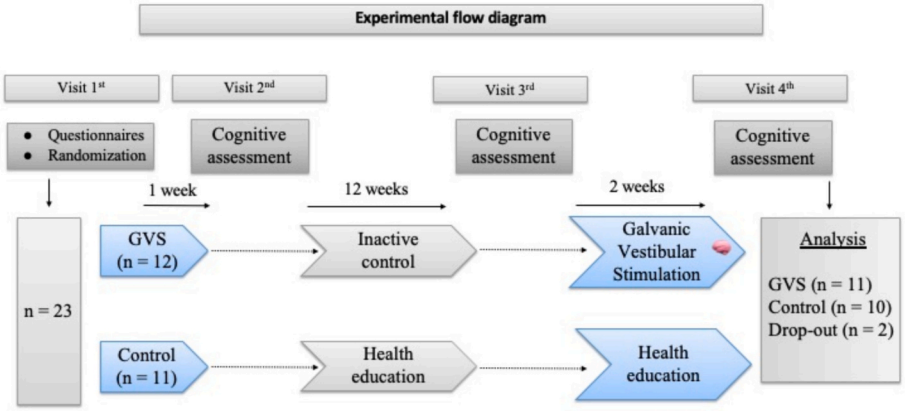

Fig. 2. Experimental flow diagram.

inability to attend the assessments. No adverse effects were reported by any of the participants while using home-based GVS.

A mixed model ANCOVA revealed a significant group-by-time interaction effect for the tracking accuracy ($F(1,18) = 7.713$, $p = 0.012$, $\eta_p^2 = 0.30$), where the interaction was driven by an increased accuracy for the GVS group only ($t = -2.544$, $p = 0.029$) (Fig. 3).

Although there was a main effect of group for dual-task accuracy ($F = 7.293$, $p = 0.01$, $\eta_p^2 = 0.28$), follow-up testing revealed no significant changes in either group.

There was also a significant main effect of time on Stroop Interference ($F = 7.964$, $p = 0.01$, $\eta_p^2 = 0.33$) with decreased reaction time both in GVS ($t = 2.424$, $p = 0.042$) and Control ($t = 2.367$, $p = 0.042$) groups.

There were no group-by-time interactions or main effects for the other outcomes. Tables 2, 3, 4 present group-specific pre-post intervention values and ANCOVA results for each cognitive test.

An additional table (Supplementary Table 1) is provided to report baseline cognitive values and statistics.

4. Discussion

In this study, we aimed to investigate the potential for improving cognitive functions by means of repetitive GVS sessions in healthy older adults. We demonstrated that ten sessions of GVS improved visuospatial ability but did not affect cognitive flexibility, inhibitory control, and dual-tasking.

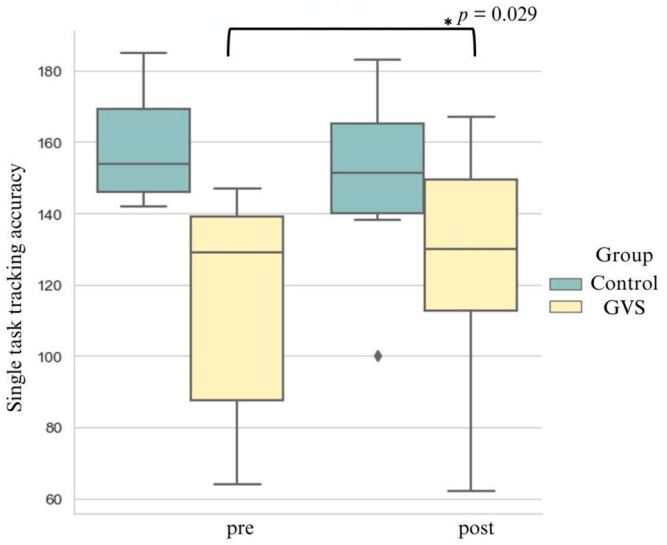

Fig. 3. Single task tracking accuracy scores before and after the intervention. *Significant results, ($p < 0.05$).

Given that repetitive GVS resulted in visuospatial improvement in our sample, our findings are consistent with the literature suggesting an association between vestibular input and visuospatial skills (Smith, 2017). Recent animal studies have shown that five sessions of subthreshold GVS had beneficial effects on visuospatial cognition in mice with vestibular dysfunction (Nguyen et al., 2021, 2022). There are also human studies utilizing acute GVS models, demonstrating the positive effects of vestibular input on visuospatial skills (Wilkinson et al., 2008; Dilda et al., 2012; Hilliard et al., 2019). However, our study extends these prior observations and suggests that increasing vestibular input through repetitive GVS may contribute to visuospatial ability in older adults. To the best of our knowledge, the current findings provide the first empirical evidence of the effects of repetitive GVS on modulating visuospatial skills in older adults.

The vestibular input has been shown to activate a broad cortical network, including the temporoparietal junction, hippocampus, and intraparietal sulcus, which are part of a complex neural network for visuospatial processing (Ventre-Dominey, 2014; Miyamoto et al., 2007). Patients with vestibular disorders have developed significant hippocampal atrophy, resulting in deficits in visuospatial tasks (Brandt et al., 2005; Lee et al., 2023). Relatedly, it has been suggested that galvanic stimulation of the medial vestibular nuclei increased the firing rates of hippocampal place cells, which in turn may contribute to spatial information processing in the hippocampus (Horii et al., 2004). Atrophy of the hippocampus can have a significant impact on the ventral cortical conduction pathway responsible for visual processing, as well as the corresponding vestibular thalamic cortical pathway (Huang et al., 2023). Indeed, the vestibular thalamic cortical pathway has been reported to affect spatial cognitive processing through vestibular information (Hitier et al., 2014). Hence, one possible mechanism of improving visuospatial performance through GVS may be to excite the related areas within the cortical vestibular network and to protect against neuronal atrophy. Eventually, it is possible to suggest that repetitive GVS may improve spatial cognitive processing through the anatomical connections mentioned above.

Another possible explanation of the GVS effect on visuospatial ability might be related to non-specific arousal (Nguyen et al., 2021). Smith et al. (2024) have suggested that vestibular inputs modify the integration of other sensory cues, affecting the development of internal representations of allocentric and egocentric space. Therefore, GVS is likely to contribute to visuospatial skills by stimulating non-spatial domains. Future investigations are needed to understand how multimodal mechanisms influence performance in specific cognitive domains.

Visuospatial ability refers to understanding and organizing visual and spatial information among objects in two- and three-dimensional space. Considering spatial ability is not a unitary function but rather a

Table 2
Stroop test outcomes at pretest (visit 3rd) and after the intervention (visit 4th), and mixed ANCOVA results.

Stroop Test	Group	*pre*	*post*	Group			Time			GroupTime		
				F	*p*	η_p^2	F	*p*	η_p^2	F	*p*	η_p^2
	GVS	61.35 ± 10.00	58.75 ± 10.04									
Denomination (s)	Control	55.09 ± 7.94	53.64 ± 6.74	2.031	0.17	0.11	0.593	0.45	0.03	0.36	0.55	0.02
	GVS	44.26 ± 6.99	43.15 ± 7.25									
Lecture (s)	Control	40.25 ± 6.10	39.53 ± 4.48	0.677	0.42	0.04	0.65	0.43	0.03	0.302	0.59	0.01
	GVS	103.20 ± 43.36	102.82 ± 20.35									
Interference (s)	Control	103.56 ± 29.64	97.09 ± 24.00	3818	0.06	0.19	7964	**0.01**	0.33	1118	0.3	0.06
	GVS	52.12 ± 21.59	44.03 ± 17.82									
Indices (s)	Control	48.43 ± 25.10	43.41 ± 19.51	0.738	0.4	0.04	4,31	0.054	0.21	1273	0.27	0.07
	GVS	1.30 ± 0.94	1.11 ± 1.26									
Error rate	Control	2.00 ± 1.82	1.00 ± 1.05	0.538	0.47	0.03	2865	0.11	0.15	1167	0.29	0.06

Note. Baseline measurement (visit 2nd) is included as a covariate in the mixed ANCOVA model. GVS, Galvanic vestibular stimulation. Cognitive data are presented as mean ± standard deviation. *Significant results are printed in bold ($p < 0.05$).

Table 3
TMT outcomes at pretest (visit 3rd) and after the intervention (visit 4th), and mixed ANCOVA results.

TMT	Group	*pre*	*post*	Group			Time			GroupTime		
				F	*p*	η_p^2	F	*p*	η_p^2	F	*p*	η_p^2
	GVS	29.80 ± 6.05	26.82 ± 5.55									
TMT A (s)	Control	24.69 ± 6.11	23.92 ± 5.31	2.459	0.13	0.12	0.19	0.66	0.01	0.919	0.35	0.04
	GVS	63.67 ± 20.51	63.39 ± 24.10									
TMT B (s)	Control	59.72 ± 20.13	60.73 ± 23.69	0.114	0.7	0.006	0.337	0.56	0.01	0.154	0.7	0.008
	GVS	33.87 ± 19.87	36.57 ± 22.16									
Indices (s)	Control	35.03 ± 15.82	36.81 ± 23.63	0.31	0.58	0.01	0.006	0.94	0	0.005	0.94	0
	GVS	2.18 ± 0.68	2.38 ± 0.78									
TMT A/B	Control	2.40 ± 0.44	2.61 ± 1.09	0.605	0.44	0.03	0.33	0.57	0.01	0.001	0.97	0

Note. Baseline measurement (visit 2nd) is included as a covariate in the mixed ANCOVA model. GVS, Galvanic vestibular stimulation; TMT, Trail making test. Cognitive data are presented as mean ± standard deviation.

Table 4
Dual-tasking outcomes at pretest (visit 3rd) and after the intervention (visit 4th), and mixed ANCOVA results.

Dual-tasking	Group	*pre*	*post*	Group			Time			GroupTime		
				F	*p*	η_p^2	F	*p*	η_p^2	F	*p*	η_p^2
	GVS	5.90 ± 0.94	5.81 ± 0.60									
ST-digit recall (span)	Control	5.90 ± 0.95	6.10 ± 1.19	0.92	0.35	0.04	1.388	0.25	0.07	0.49	0.49	0.02
	GVS	114.18 ± 30.16	129.31 ± 30.32									
ST-tracking	Control	158.15 ± 14.72	150.25 ± 22.55	7.928	**0.011**	0.31	0.09	0.76	0.005	7.713	**0.012**	0.30
	GVS	109.54 ± 21.36	117.77 ± 24.06									
Dual-task	Control	140.50 ± 19.21	0.34 ± 0.15	7.293	**0.01**	0.28	0.458	0.5	0.02	0.844	0.37	0.04
	GVS	5.90 ± 0.100	97.47 ± 12.64									
mu score	Control	5.90 ± 0.101	94.51 ± 15.10	0.937	0.34	0.04	0.187	0.67	0.01	0.705	0.41	0.03

Note. Baseline measurement (visit 2nd) is included as a covariate in the mixed ANCOVA model. GVS, Galvanic vestibular stimulation; ST, Single task. Cognitive data are presented as mean ± standard deviation. The unit of ST-tracking and dual-task outcomes is the number of correct responses. *Significant results are printed in bold ($p < 0.05$).

combination of categories such as spatial visualization, spatial perception, and mental rotation, it is possible to classify the tracking task we used in this study as spatial visualization (de Bruin et al., 2016). In the paper-pencil tracking task, our participants were requested to locate the target square in a predetermined path (visuospatial search) and mark it. Spatial visualization refers to the ability to mentally manipulate complex spatial information when several steps are required to complete a spatial task, such as in the paper-pencil tracking test (Voyer et al., 1995). However, the relatively low visual motor requirement of the 2D tracking test may be inadequate to represent the physical interactions we experience with the objects around us in daily life. Therefore, future studies employing more complex visuospatial tasks into single- and dual-task designs will provide more ecologically valid information about the effects of GVS on visuospatial skills.

Although studies have suggested that GVS positively affects visuospatial cognition (Wilkinson et al., 2008; Dilda et al., 2012; Hilliard et al., 2019), the various protocols utilized in GVS research make it difficult to compare the results. These protocols differ in terms of frequency (single-session or repetitive GVS), timing (before and during the task), and whether noisy or direct current, making it challenging to draw comprehensive generalizations from the literature. Moreover, although the concept of sub/suprathreshold is frequently used in literature, the different approaches to determining the threshold (e.g., cutaneous or motion-specific) also increase the challenge (Piccolo et al., 2020). For instance, Wilkinson et al. (2008) reported that one session, subthreshold (determined by cutaneous approach), noisy GVS improved visual memory recall speed whereas non-noisy GVS did not. Relatedly, Dilda et al. (2012) reported improved performance in visuospatial tasks during subthreshold (determined by motion approach) GVS. However, although both studies employ subthreshold classification, the approaches taken to determine the threshold differ. In this study, we utilized a repetitive, sinusoidal galvanic stimulation protocol, administered by subjects at home. We applied the same current intensity to each participant without choosing any specific technique to determine the

motion or cutaneous threshold. Therefore, our findings need to be confirmed by GVS protocols with different frequencies, application times, and threshold-setting methodologies. Further research is needed to find the optimal stimulating parameter of GVS in health and disease conditions, as visuospatial ability loss can contribute to falls, accidents, and difficulties in daily living activities for older adults.

It has been suggested that visuospatial ability is more closely related to the vestibular system than other cognitive functions (Zhang et al., 2022). Indeed, an increasing number of studies have reported failures in different domains of visuospatial skills in patients with vestibular disorders (Hüfner et al., 2007; Grabherr et al., 2011; Deroualle et al., 2019; Ayar et al., 2020). Supportingly, a study of 183 older adults demonstrated that vestibular function was associated with visuospatial ability (Bigelow and Agrawal, 2015). Moreover, it has been demonstrated that older adults with vestibular dysfunction have worse visuospatial skills than their healthy counterparts (Zhang et al., 2022). Although our results support this perspective and point out visuospatial skills, further research with larger sample sizes is necessary to confirm these findings.

Our results showed a significant time effect for the Stroop interference effect, indicating a significant reduction in both the GVS and control groups in the follow-up analysis. This finding is likely due to a learning effect rather than an improvement in inhibitory control. However, Dilda et al. (2012) reported that one-session GVS improved inhibitory control in healthy adults. Regarding cognitive flexibility, we did not find any significant effect of GVS. Similarly, the only study available on the effect of GVS on cognitive flexibility showed that a single session of GVS with 0.8 mA had no effect (Schöne and Mast, 2023).

As a general note, it is important to consider that older adults may experience vestibular input deficiency due to a lack of physical activity (Van Laer et al., 2023), which can result in cognitive consequences even without a diagnosed vestibular impairment. Thus, it may be reasonable to use GVS as an alternative approach to support cognition when increasing physical activity is not feasible.

Our study offers benefits by pointing out a non-pharmacological, easy-to-access, home-based intervention to improve cognitive performance in older adults. Given that older individuals often experience polypharmacy due to multimorbidity (Doumat et al., 2023), non-pharmacological approaches, which have fewer contraindications and side-effect risks than pharmacological interventions, merit greater consideration for target-specific interventions. In addition, home-based interventions can facilitate older adults' access to health assistance by addressing obstacles like mobility challenges, limited transportation, and community infrastructure. In this regard, our findings have demonstrated that GVS could be an effective non-pharmacological and home-based tool for targeting cognition in older adults. On a cautionary note, however, our results are based on a healthy older adult population, and the generalizability of the outcomes should be investigated in different populations.

Given that cognitive functioning tends to decline in older adults, it is important to consider how long the effects of GVS on cognition can last. Various factors, including individual differences, intensity, and duration of stimulation, can influence the persistence of GVS effects (Nguyen et al., 2023). For instance, Fujimoto et al. (2016) reported that repeated GVS sessions can have long-lasting impacts, possibly through vestibular neuroplasticity; however, their study specifically focused on postural balance. While it is likely that repetitive vestibular input could lead to long-lasting changes in the extensive cortical areas it engages, resulting in potential enduring effects on cognition, our research design is not sufficient to support this claim. On the other hand, the literature still needs to define the optimal parameters of GVS application for enhancing cognition. Therefore, further longitudinal research is required to determine the optimal intervention strategy and to clarify the long-term effects of GVS on cognitive functions.

Our study has several limitations. First, cognitive measurements were performed three times since we used a subsample of the VELOCCE project, which might have caused both a learning effect and demotivated the subjects from performing their best in the cognitive tests. Second, during the 12 weeks between the first and second measurements, the GVS group remained inactive while the control group received health education. This could have resulted in differences in social input and motivation. Therefore, we included the first measurement as a covariate in the analysis to minimize this effect. Third, we did not recruit any sham group to exclude the practice effects. Finally, our findings, which provide evidence for repetitive GVS effects on cognition, are characterized by a small effect size, probably due to the small sample size. Given that small sample sizes limit the generalizability of the findings (Charter, 1999), we suggest replicating these preliminary findings with sham control sessions in a larger sample size.

5. Conclusions

Our preliminary findings support that repetitive, home-based GVS improves visuospatial ability in healthy older adults. Since visuospatial skills allow us to safely navigate in space through the accurate judgment of direction and distance, this is particularly significant for the independent daily life of older adults. We also note that our findings support the idea that this non-pharmacological, low-cost, safe, easy-to-apply technique could be self-administered by older adults. Future studies with larger samples are warranted to gain a better understanding of how different GVS protocols affect cognitive functions in healthy older adults and those with vestibular dysfunction, and follow-up analyses are needed to explore the long-term effects.

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CRediT authorship contribution statement

Evrim Gökçe: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Emma Milot:** Writing – review & editing, Software, Investigation, Data curation. **Antoine Langeard:** Writing – review & editing, Validation, Supervision, Project administration. **Gaëlle Quarck:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors report there are no competing interests to declare.

Data availability

Data will be made available on request.

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