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How a subclinical unilateral vestibular signal improves binocular vision

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Abstract: The present study aimed at determining if an infra-liminal asymmetric vestibular signal could account for some of the visual complaints commonly encountered in chronic vestibular patients. We used infra-liminal galvanic vestibular stimulation (GVS) to investigate its potential effects on visuo-oculomotor behavior. 78 healthy volunteers, 34 from 20 to 25 years old and 44 from 40 to 60 were included in a crossover study to assess the impact of infra-liminal stimulation on convergence, divergence, proximal convergence point, and stereopsis. Under GVS stimulation, the repeated measures ANOVA showed a significant variation of near convergence ($p < 0.001$), far convergence ($p < 0.001$), far divergence ($p = 0.052$). We also observed an unexpected effect of instantaneous blocking of the retest effect on far divergence measurement. Further investigations are necessary to establish causal relationships, but GVS could be considered as a behavioral modulator in non-pharmacological vestibular therapies.

Keywords: Galvanic vestibular stimulation, disconjugate eye movements, stereoscopic vision, vestibular error signal.

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1. Introduction

In the United States, 10 million patients seek medical consultations for vertigo each year **[1]**. According to various authors, this number could extend to 20 million individuals, including 3.9 million cases requiring emergency hospital visits **[2]**, accounting for approximately 3.3% to 4% of total visits to these services (3.3% **[3]**, 3.5% **[2]**, 4% **[4]**). In 2019, Hulse published a one-year prevalence of vertigo in Germany as 6.5%. Among the 70,315,919 patients included in the study, 3,406,169 (4.8%) were categorized with non-specific dizziness and 1,137,294 patients (1.6%) with peripheral vestibular disorders **[5]**. Patients' complaints are highly heterogeneous and significantly impact their quality of life. One of the most common complaints is visual discomfort experienced during movements, such as the sensation of blurred vision, vertigo in situations of intense visual flow, like in the presence of crowds in department stores, and visual fatigue during reading or screen use.

Vision plays a crucial role in spatial orientation and balance by detecting environmental variations. Working in synergy with the vestibular system (inner ear) and the somesthetic proprioceptive system (sensory receptors of muscles and joints), it contributes to

maintain body stability and coordination. The visual processing starts with the photoreception in the retina and is achieved at different levels of the cerebral cortex, allowing the central nervous system to distinguish shapes, colors, movements, distances, so as to elaborate mental representations of our environment.

The vestibular system differs from other sensory systems in three distinct aspects: i/ the existence of "vestibular noise," referring to random and unwanted fluctuations of sensory signals from the vestibular system; ii/ the permanent asymmetry of the bidirectional signal (or relative vestibular bias) weighted by somesthesis and vision **[6]**; iii/ the detection and discrimination thresholds corresponding to the extraction of a suprathreshold signal. The suprathreshold signal must be understood as the extraction of a "clear" signal, either arising from the variability of a unilateral signal (e.g., during caloric stimulation) or from the summation of an ipsilateral excitability signal coinciding with a contralateral inhibitory signal, amidst the ongoing discharge of sensory cells or "vestibular noise". These concepts must be introduced because they allow determining the physiological threshold beyond which a physical stimulus imposes an adaptive or behavioral response (i.e., avoidance strategies). In clinical practice, this threshold notion is well-established for exteroceptive senses such as hearing and vision **[7]**. For the vestibular system, determining thresholds is more complicate as the vestibular sense is generally implicit, operating automatically and unconsciously to maintain body balance and spatial orientation, and its output expression is multimodal. Detection thresholds are expressed by the absence or presence of motion perception, and discrimination thresholds distinguishes discrepancies in velocities, angles, internal/external movements, etc. In the context of unilateral peripheral vestibular clinical cases, the suprathreshold signal can be likened to a vestibular error signal (VES), either due to reduced excitability (e.g., total neurotomy) or excessive excitability (e.g., VPPB). In otoneurological practice, the analysis of VES is limited to its subcortical modulation expression, clinically observable through visuo-perceptivo-motor manifestations **[8,9]**.The study of the impact of artificial suprathreshold VES has been investigated through vestibular implant (VI) approaches and Galvanic Vestibular Stimulation (GVS) studies that suggest that the vestibular system has robust adaptability to electric stimulations induced by this procedure **[10–13]**. This adaptability depends on the type and pattern of stimulation used, such as frequency modulation, amplitude modulation, cross-channel stimulation of one or multiple channels, etc. However, some stimulations may be deleterious **[10–13]** and lead to the reproduction of a suprathreshold VES. The clinical adaptive response is observed by the emergence of a static and dynamic symptomatology that is almost identical to what is observed in the case of a unilateral lesion. These studies also demonstrate that prolonged stimulation induced by VIs alters the way vestibular signals are integrated in the brain, similar to what occurs in neighboring structures during chronic unilateral vestibular lesions. This engagement of neural plasticity and disturbances in vestibular compensation suggests that a suprathreshold unilateral peripheral VES may have significant implications in the central integration of sensory information, disrupting the construction of internal models for perceiving the environment.

GVS consists in transcranial stimulation that can modulate vestibular afferences by inhibiting (anodic current) or stimulating (cathodic current) them **[14,15]**. By polarizing the peripheral loop (semicircular canals, otolithic organs, vestibular nerves, and vestibular nuclei), it affects balance, oculomotor function, and spatial orientation. The GVS effect is comparable to the clinically observable suprathreshold unilateral peripheral VES **[16]**. Abundant literature in the field shows that GVS facilitates partial or complete neural connections, allowing for progressive recovery of lost vestibular function through synaptic circuit reorganization **[17,18]**. It also has a reweighting effect on the connection between vestibular pathways and the limbic system. For some authors, GVS acts on all pathways involved in the vestibular system response **[12,19–21]**. Depending on the use of subliminal

or supraliminal thresholds and the duration of stimulation, a VES effect is described, leading to modifications in the plasticity of vestibular and postural reflexes **[12,19–22]**.

The present work investigates what happens on oculomotir indicators when an subthreshold VES (below discrimination thresholds) that does not generate measurable clinical manifestations is applied. This question is worth addressing since otoneurological consultations often encounter complaints that only partially correspond to the already established clinical model of unilateral peripheral deficit. We can draw parallels with unilateral hydrops which induces an erroneous signal with slow and subthreshold progression due to: 1/ the high plasticity of peripheral vestibular synaptic circuits; 2/ central modulation of detection and discrimination thresholds. The questioning of the effect of subthreshold GVS stimulation is relevant: can it modify any visuo-oculomotor indicators without perceptual and behavioral manifestations? Our study was undertaken to describe the visuo-oculomotor consequences of an subthreshold VES artificially and transiently administered unilaterally through GVS in healthy subjects, to identify specific marker evolutions over time and assess the effect of aging on these phenomenon.

2. Materials and Methods

2.1. Study Design:

A crossover experiment was conducted at the Center for Brain and Cognition Research (CerCo) in collaboration with the Orthoptics School of Toulouse, France, from 2018 to 2022. Healthy male and female subjects aged between 18 to 60 years were recruited on a voluntary basis. The study was approved by the INSERM Ethics Evaluation Committee (INSERM n°14-155ter). Before participation, subjects read the information sheet and provided written consent. Subjects underwent an initial questionnaire and orthoptic evaluation to verify their eligibility based on exclusion criteria (see Appendix A, Table 1-2). The inclusion procedure is described in Figure 1.

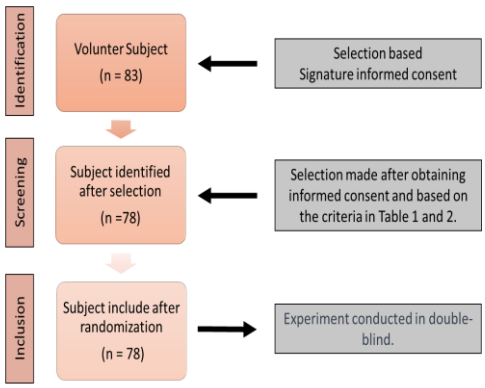

Figure 1. Flow diagram for subject inclusion in the stimulation test.

2.2. Experimental Protocol:

Galvanic vestibular stimulation (GVS) was performed using a DIGITIMER DS-5 stimulator delivering a square wave signal with a maximum intensity of 1mAthrough disposable adhesive electrodes. We chose a 1mA intensity, for which we did not observe any consistent behavioral response in our experimental conditions. The stimulation protocol consisted of 10 bursts of 2 seconds, separated by 10 seconds, for a total duration of 120 seconds. Two categories of stimulations were performed (1) unilateral vestibular an-

odal stimulation on the right side (GVS) via a mastoid electrode and a cervical one (spinous process of C7) (2) sham or control stimulation via 2 electrodes placed on both sides of the spinous process of C7. Eight orthoptics student operators conducted the manipulations, supervised by a senior to improve reliability, validity, control of variability, and reproducibility of measurements. Subjects were placed in a Romberg position on a flat surface. Optometry measurements were taken before (T0), during (T1), after (T2), and 15 minutes after the stimulation (T3). The measured follow-up indicators included: far convergence at 5m (C), near convergence at 40cm (C'), far divergence at 5m (D), near divergence at 40cm (D'), near point of convergence (PPC), far stereoscopic acuity at 2.5m (Kratsa-Barron-Laraudogoitia), and near stereoscopic acuity at 40cm (TNO; see Appendix A, Table 3). The subjects went twice, on 2 different days, the order of GVS or Sham stimulation was randomized to avoid biases.

2.3. Statistical Analysis:

A baseline correction (T-T0) was applied to rule out the initial effect. Statistical analysis was performed using JASP software version 0.17.1. Repeated measures ANOVA was used to determine whether the type of stimulation (GVS and/or Sham) influenced the evolution of follow-up indicators over time based on subjects' age category. A sphericity test was conducted, and a Huynh-Feldt correction was applied when $\varepsilon \geq 0.75$. A post hoc analysis with the Student's test was proposed with a Holm correction to adjust the significance level. The significance level for tests was set at $p \leq 0.05$, and the Holm procedure was applied to adjust the significance level based on the number of independent comparisons.

3. Results

3.1. Indicators evolution according to the stimulation factor.

Table 1: Evolution of indicators according to the stimulation factor.

Measurements	Stimulation	ANOVA results	p	Significant post hoc analysis
GVS	C′	F (2.613, 198.569) = 10.073	P<0.001	μ(T0) - μ(T2) = -2.407; p<0.002
				μ(T0) - μ(T3) = -3.432; p<0.001
				μ(T1) - μ(T3) = -2.527; p<0.001
Sham	C′	F (2.755, 209.389) = 2.358	p=0.078	
GVS	C	F (2.772, 210.642) = 13.027	p<0.001	μ(T0) - μ(T2) = -2.116; p<0.001
				μ(T0) - μ(T3) = -2.685; p<0.001
				μ(T1) - μ(T2) = -1.522; p=0.007
				μ(T1) - μ(T3) = -2.092; p<0.001
Sham	C	F (2.492, 189.425) = 1.556	p=0.208	
GVS	D′	F (2.596, 197.322) = 0.460	p=0.683	
Sham	D′	F (2.587, 205.090) = 2.006	p=0.124	
GVS	D	F (2.134, 162.208) = 2.942	p=0.052	
Sham	D	F (2.699, 205.090) = 7.641	p=0.001	μ(T0) - μ(T1) = 0.460; p=0.004
				μ(T0) - μ(T2) = 0.622; p<0.001
				μ(T0) - μ(T3) = 0.401; p=0.013
GVS	NPC	F (2.236, 169.964) = 2.523	p=0.077	
Sham	NPC	F (1.270, 96.528) = 0.155	p=0.755	
GVS	TNO	F (2.450, 186.182) = 1.281	p=0.282	
Sham	TNO	F (1.797, 136.554) = 2.736	p=0.074	
GVS	KBL	F (2.959, 224.850) = 9.003	P<0.001	μ(T0) - μ(T1) = 11.200; p=0.012
				μ(T0) - μ(T2) = 16.634; p<0.001
				μ(T0) - μ(T3) = 16.955; p<0.001
C7	KBL	F (2.526, 192.010) = 1.435	p = 0.238	

Legends. C: Far convergence at 5 meters; C': Near convergence at 40 cm ; D: Far divergence at 5 meters ; D': Near divergence at 40 cm ; NPC: Near Point of Convergence ; KBL: Kratsa-Barron-Laraudogoitia ; TNO: Stereopsis with Graded Circle, GVS : galvanic vestibular stimulation ; C7 : C7 spine stimulation.

3.1.1. Near convergence indicator (C'; Figure 2A; Table 1)

Repeated measures ANOVA confirms that the variation in C' measurements under GVS stimulation is statistically significant, ($F(2.613, 198.569) = 10.073$; $p < 0.001$). Post hoc analysis reveals a significant mean difference in the Student's t-test between T0 and T2 ($\mu(T0) - \mu(T2) = -2.407$; $p < 0.002$); T0 and T3 ($\mu(T0) - \mu(T3) = -3.432$; $p < 0.001$); T1 and T3

(μ(T1) - μ(T3) = -2.527; p < 0.001). Under Sham stimulation, non-significant variation in C' measurements was found (F (2.755, 209.389) = 2.358; p = 0.078). Post hoc analysis does not reveal significant links in the Student's t-test (p > 0.007).

3.1.2 Far convergence indicator (C; Figure 2B; Table 1)

Under GVS stimulation, repeated measures ANOVA shows a significant variation in C measurements (F (2.772, 210.642) = 13.027; p < 0.001). Post hoc analysis reveals a significant mean difference in the Student's t-test between T0-T2 (μ(T0) - μ(T2) = -2.116; p < 0.001); T0-T3 (μ(T0) - μ(T3) = -2.685; p < 0.001); T1-T2 (μ(T1) - μ(T2) = -1.522; p = 0.007); T1-T3 (μ(T1) - μ(T3) = -2.092; p < 0.001). Under Sham stimulation, repeated measures ANOVA shows a non-significant variation in C measurements (F (2.492, 189.425) = 1.556; p = 0.208). Post hoc analysis does not reveal significant links in the Student's t-test (p > 0.007).

3.1.3. Near divergence indicator (D')

Statistical analysis does not show a significant link (Figure 2C; Table 1).

3.1.4. Far divergence indicator (D, Figure 2D; Table 1)

The variation measured for D under GVS stimulation, fails t reach statistical significance (repeated measures ANOVA F (2.134, 162.208) = 2.942; p = 0.052 for main effect and post hoc analysis. In contrast, under Sham stimulation, repeated measures ANOVA shows a significant variation in D measurements (F (2.699, 205.090) = 7.641; p = 0.001). Post hoc analysis shows a significant link in the Student's t-test between T0-T1 (μ(T0) - μ(T1) = 0.460; p = 0.004); T0-T2 (μ(T0) - μ(T2) = 0.622; p < 0.001). The interval analysis T0-T3 (μ(T0) - μ(T3) = 0.013; p < 0.013) is debatable.

3.1.5. Near Point of Convergence (NPC) and Stereopsis with Graded Circle (TNO) indicators

Statistical analysis does not show a significant link (Figure 2 E and F; Table 1).

3.1.6. Kratsa-Barron-Laraudogoitia indicator (KBL; Figure 2G; Table 1)

Under GVS stimulation, repeated measures ANOVA shows a significant decrease in KBL measurements (F (2.959, 224.850) = 9.003; P < 0.001), also found in post hoc analysis (Student's t-test between T0-T2 (T0-T1 (μ(T0) - μ(T1) = 11.200; p = 0.012) μ(T0) - μ(T2) = 16.634; p < 0.001); T0-T3 (μ(T0) - μ(T3) = 16.955; p < 0.001). . Under Sham stimulation, repeated measures ANOVA shows a non-significant variation in C measurements (F (2.526, 192.010) = 1.435; p = 0.238). Post hoc analysis does not reveal significant links in the Student's t-test (p > 0.012).

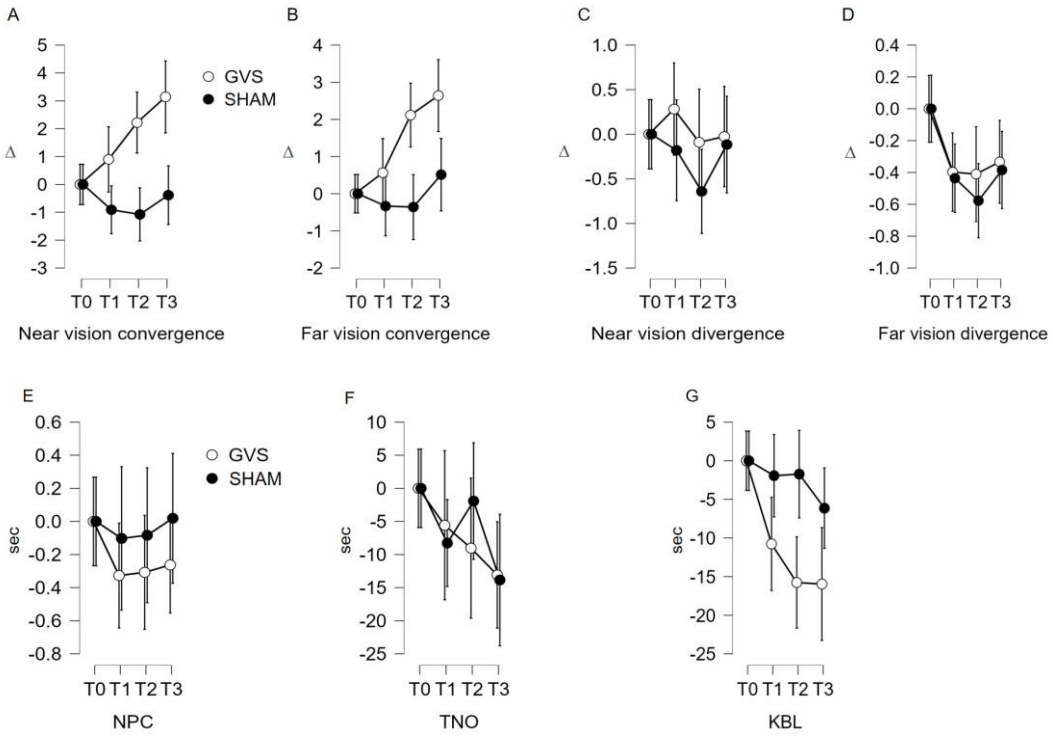

Figure 2 A-G. Evolution of monitoring indicators according to the stimulation site. GVS**:** vestibular galvanic stimulation; C7: Stimulation on either side of the C7 spine; NPC: Near point of convergence; TNO: Stereopsis with graded circle. Distance stereoscopy test (0.40m); KBL: Kratsa-Barron-Laraudogoitia. Distance stereoscopy test (2.5m); Δ: diopter, sec: second. The error bars indicate the 95% confidence intervals.

3.2. Evolution of follow-up indicators in both age groups.

Table 2: Evolution of monitoring indicators according to age group.

Measurements	Stimulation	ANOVA results	p	Significant post hoc analysis
C′	GVS	F (2.613, 198.569) = 6.327	p = 0. 002	20-25 ans: T0-T2 (p=0.005) T0-T3 (p<0.001) T1-T3 (p<0.001)
C′	Sham	F (2.755, 209.389) = 2.251	p = 0.089	
C	GVS	F (2.772, 210.642) = 0.242	p = 0.852	
C	Sham	F (2.492, 189.425) = 0.059	p = 0.967	
D′	GVS	F (2.596, 197.322) = 0.584	p = 0.602	
D′	Sham	F (2.587, 196.629) = 1.360	p = 0.258	
D	GVS	F (2.134, 162.208) = 0.338	p = 0.720	
D	Sham	F (2.699, 205.090) = 2.296	p = 0.086	
NPC	GVS	F (2.236, 1169.964) = 0.351	p = 0.728	
NPC	Sham	F (1.270, 96.528) = 0.290	p = 0.647	
TNO	GVS	F (2.450, 186.182) = 1.847	p = 0.151	
TNO	Sham	F (1.797, 136.554) = 1.709	p = 0.188	
KBL	GVS	F (2.959, 224.850) = 1.779	p = 0.153	
KBL	Sham	F (2.526, 192.010) = 0.226	p = 0.846	

Legends. C: Far convergence at 5 meters; C: Near convergence at 40 cm; D: Far divergence at 5 meters; D': Near divergence at 40 cm; NPC: Near Point of Convergence; KBL: Kratsa-Barron-Laraudogoitia; TNO: Stereopsis with Graded Circle, GVS : galvanic vestibular stimulation ; Sham : C7 spine stimulation.

3.2.1. Near convergence indicator (C')

Under GVS stimulation, repeated measures ANOVA shows a significant variation in C' measurements based on age (F (2.613, 198.569) = 6.327; p = 0. 002). Post hoc analysis using the Student's t-test shows a significant mean difference for the 20-25 age group between T0-T2 (p = 0.005), T0-T3 (p < 0.001), T1-T3 (p < 0.001). Interval analysis for the 40-60 age group does not show significant links in the Student's t-test: p = 1 among the intervals studied in this group (Figure 3A; Table 2). Under Sham stimulation, repeated measures ANOVA shows a non-significant variation in C' measurements based on age (F (2.755, 209.389) = 2.251; p = 0.089). Post hoc analysis using the Student's t-test does not show a significant mean difference for both age groups (Figure 3A; Table 2).

3.2.2. Analysis of Indicators C, D', D, NPC, TNO, KBL

Under both GVS and C7 stimulation, repeated measures ANOVA does not show 7significant variations for these 7 indicators (Figure 3C-G; Table 2).

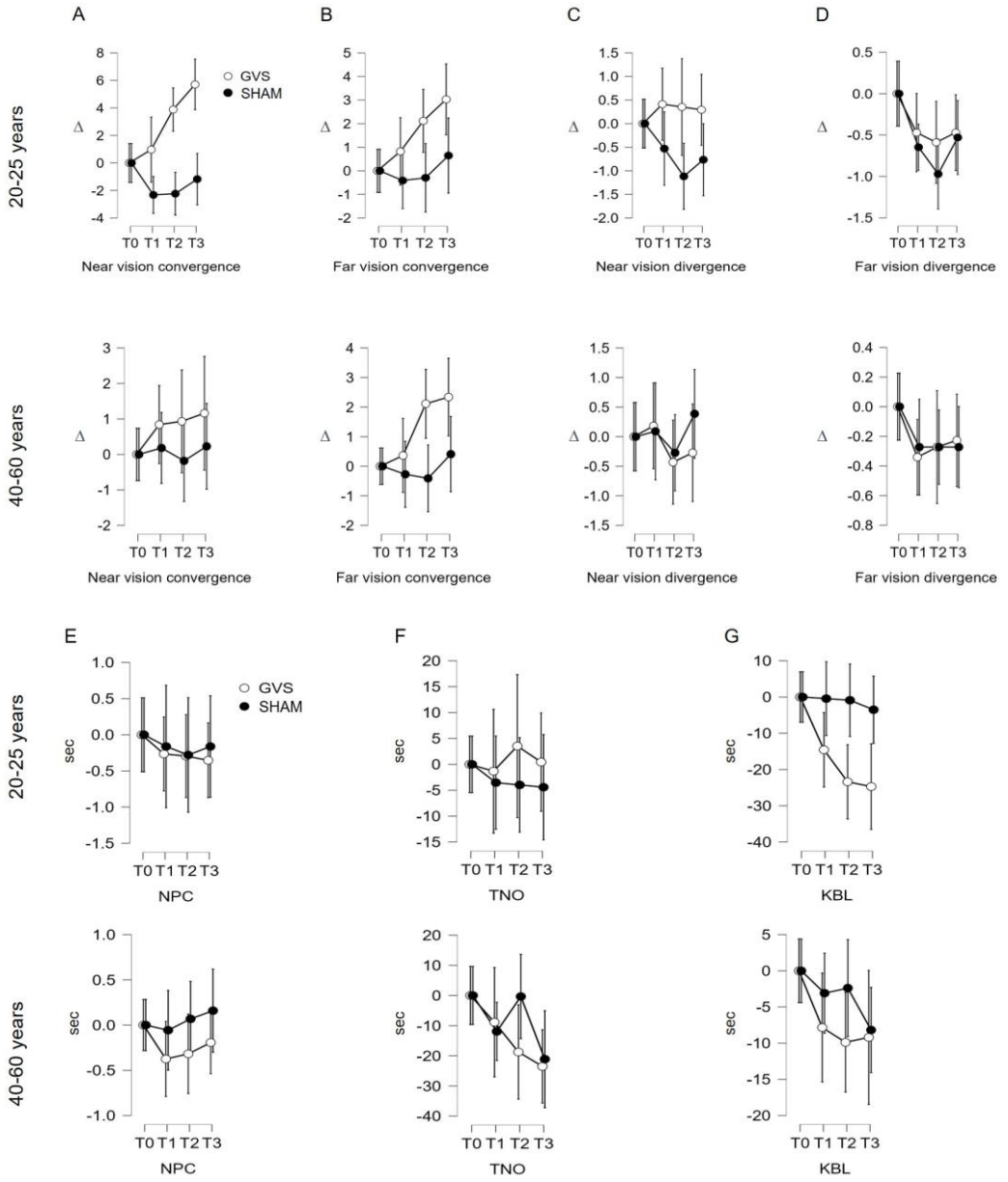

Figure 3 A-G. Evolution of measured indicators according to age category. GVS: vestibular galvanic stimulation; Sham: Stimulation on either side of the C7 spine; NPC: Near point of convergence; TNO: Stereopsis with graded circle. Distance stereoscopy test (0.40m); KBL: Kratsa-Barron-Laraudogoitia. Distance stereoscopy test (2.5m); Δ: diopter, sec: second. The error bars indicate the 95% confidence intervals.

4. Discussion

In our study, galvanic vestibular stimulation (GVS) improves most of the visuo-oculomotor indicators studied(Table 3).

Table 3: Evolution of indicators according to the stimulation factor.

Indicator	Between-group variation	Within-group variation of the mean measurements taken at each time point (T)					
	T0- T3	T0-T1	T0-T2	T0-T3	T1-T2	T1-T3	T2-T3
C′	Continuous +	+	+	+	+	+	+
cC′	Discontinuous	-	-	-	-	+	+
C	Continuous +	+	+	+	+	+	+
cC	Discontinuous	-	-	+	-	+	+
D′	Discontinuous	+	-	-	-	-	+
cD′	Discontinuous	-	-	-	-	+	+
D	Discontinuous	-	-	-	-	+	+
cD	Discontinuous	-	-	-	-	+	+
NPC	Discontinuous	-	-	-	+	+	+
cNPC	Discontinuous	-	-	+	+	+	+
TNO	Continuous -	-	-	-	-	-	-
cTNO	Discontinuous	-	-	-	+	-	-
KBL	Continuous -	-	-	-	-	-	-
cKBL	Discontinuous	-	-	-	+	-	-

Legends. p < 0.001 P > 0.012 + = Rising variation - = Decreasing variation

C: Far convergence at 5 meters; C': Near convergence at 40 cm ; D: Far divergence at 5 meters ; D': Near divergence at 40 cm ; NPC: Near Point of Convergence ; KBL: Kratsa-Barron-Laraudogoitia ; TNO: Stereopsis with Graded Circle.

Our study revealed a beneficial effect of GVS on the indicators C', C, D, and KBL The analysis on the control data sets the robustness of the results, ruling out any test-retest effect, in all cases except from far divergence (D), which decreases with repeated measures (Figure 2D-3D; Table 1). The age-stratified analysis concludes that age is a confounding factor only for the C' indicator, evidencing that the effects of GVS on near convergence occur only in younger subjects (20-25 years). This can be explained by: 1) More efficient neural plasticity and sensory adaptation capacity in younger subjects, allowing more pronounced changes in near convergence; 2) Visual system alterations (loss of vergence abilities) and vestibular changes (reduced sensitivity of the system) that limit the effects of GVS in older individuals.

Firstly, the significant increase in far convergence (C) during and after after GVS can be interpreted as an improvement in the ability to converge the eyes at a distance in subjects following GVS stimulation. This suggests that the subjects were able to effectively converge their eyes to fixate distant objects after being subjected to GVS stimulation. It is essential to note that this increase in C (convergence at distance) was observed post-GVS and appears to be enduring over time, as it persists for up to 15 minutes after stimulation. (Table 3; Figure 4). This suggests that GVS stimulation has both an immediate and lasting effect on the ability to converge at a distance in the study subjects.

Secondly, we observed an increasing trend in near convergence (C') measurements, demonstrating that GVS influences this indicator during and after its application, seemingly lasting for at least 15 minutes (Table 3, Figure 4). Similar to far convergence, the

results indicate the lasting effect of GVS on this indicator. The increase in C' values suggests an increase in the amplitude of eye convergence movement during near gaze, indicating that the eyes have a greater capacity to perform this movement when focusing on a nearby object. . Nevertheless, this beneficial effect of GVS was only found significant for younger.

Furthermore, it is also noteworthy to mention the results of far divergence (D) in the control condition. The shape of the control data curve differs from that of the GVS, especially from T1 to T2 (Figure 2D and 3D), and significant values are recorded in the statistical analysis, indicating a significant alteration in this measurement at T2. Assessing the natural variability of an indicator under a control condition, allows a safer interpretation of the results obtained following a particular intervention or stimulation, in this case, GVS. Literature suggests that repeated measurement of vergence can lead to adaptation of the oculomotor system, but it does not directly conclude that far divergence decays with repeated measures **[23]**. However, in the conditions of this study, the repetition of far divergence measurements deteriorates the D indicator in the control condition. Thus, the dissociation of the curve pattern between the two conditions could imply that GVS may prevent from the spontaneous adaptive impact on far divergence during repeated measures.

Finally, we observed a significant decrease in the KBL value during the application of GVS, demonstrating an improvement in far stereopsis during the per-stimulation period (Figure 4). However, it is important to note that the decrease in the KBL value at T2 and T3 (5 and 15 minutes after GVS stimulation) is visible in the curve in Figure 2G but did not reach statistical significance during the analysis (Table 4 and 5). This observation suggests that the effect of GVS on far steroscopic perception is immediate, and may reach a ceiling effect.

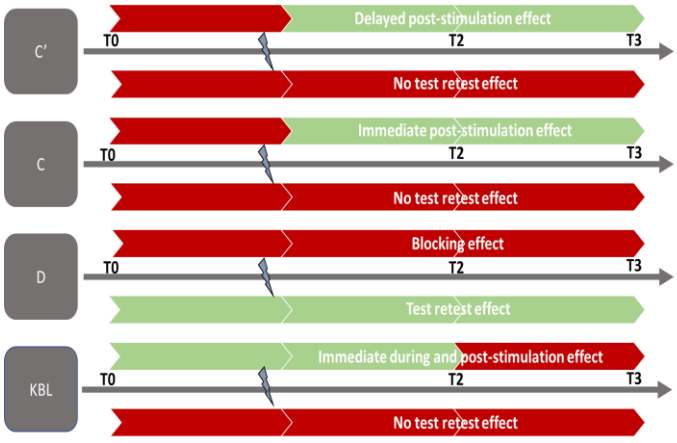

Figure 4. GVS Effect. C' : near vision convergence ; C : Far vision convergence ; D : Far vision divergence ; KL : Krats Laraudou Test. Colors : No significant effect Significant effect

Before their cortical integration, visual and vestibular signals are already processed together at the level of several subcortical structures, such as the vestibular nuclei (NV) in the brainstem and the thalamus in the diencephalon **[24,25]**. The vestibulo-ocular reflex (VOR) involves the NV and oculomotor nuclei to maintain stable binocular vision during head and/or body motion. The cerebellum is a key structure that receives vestibular information from the NV to ensure body coordination and balance maintenance, but it also receives visual information (e.g. retinal slips) enabling it to modulate the VOR to stabilize gaze **[26,27]**. Furthermore, there are subcortical connections that provide tracking or saccade movements during head movements **[26,28]**.

Morover, the vestibular system interacts with different visual system structures, at the other levels: i) Oculomotor pathways responsible for controlling and coordinating eye movements. The cortico-nuclear tract links cortical associative areas receiving visual information to the vestibular nuclei (NV), allowing coordination between eye movements and body movements to maintain balance **[29,30]**. ii) Collicular pathways involving motion receptors and retinal ganglion cells. The Superior Colliculus is linked to the NV through the tecto-vestibular pathway, enabling precise coordination of eye and body movements in response to visual and vestibular stimuli **[31,32]**. iii) Accommodation pathways enabling image clarity regardless of the distance of the fixated object. The link between the oculomotor (II, IV and V) nucleus and the NV are mainly mediated through the **medial longitudinal fasciculus**, which maintains precise focus on the object, even during head movements **[33]**. iv) Pupillary reflex pathways, which function in coordination to adjust eye focus and pupil size based on environmental visual conditions. The vestibular system detects head rotation movements and sends signals to the nucleus of the trigeminal nerve, which impacts pupil size, triggering constriction of the pupil on the side opposite to the direction of head movement. This is known as the vestibular pupillary reflex, improving vision sharpness by reducing optical aberrations induced by head movements **[33,34]**.

In our study, the application of low-intensity current in a repeated manner had the primary effect of disrupting the activity of vestibular neurons by modifying the sensory signals transmitted to the NV without causing the appearance of clinical signs. It is important not to confuse the electrophysiological consequences of subthreshold GVS with those of suprathreshold GVS. The latter leads to sufficient neuronal inhibition or excitation to reach the perceptual clinical threshold (vertigo, nausea, and vomiting) and induces measurable behavioral (oculomotor and postural) responses **[16,35]**. Dlugoiczyk in 2019 and Apba in 2022 **[19,20]** both proposed an exhaustive review of advances in GVS. Their work addressed cellular and neurophysiological mechanisms as well as clinical applications of this technique. However, how GVS acts on neuronal structures and the most appropriate forms of stimulation for specific applications remain debated. While there are currently few studies in humans that identify the exact electrophysiological modifications after the application of subthreshold GVS, our results show that visuo-oculomotor indicators are sensitive to this stimulation, suggesting an adaptive neuronal processes during and after GVS. This neuronal plasticity may allow the system to find a spontaneous resolution to GVS stimulation, explaining the immediate effects observed on visuo-oculomotor indicators. Two studies have tested GVS at subliminal and supraliminal intensity levels and recorded induced brain activity through fMRI for each. Bense et al. **[36]** showed distinct activation of frontal eye fields (FEF) and the area anterior to FEF by suprathreshold GVS. Helmchen et al. **[37]** observed an increase in resting activity of the visual cortex in patients with bilateral vestibular areflexia and a decrease in healthy subjects after subthreshold GVS. The discrepancies in study's conclusions can be attributed to factors such as intensity and form of current used, the type of threshold studied, etc. This allows us to consider a specific spontaneous reorganization of the subliminal signal between vestibular neurons and higher centers of the visuo-oculomotor system. This observation is supported by our results, particularly the persistence of modifications in convergence for both near and far distances even 15 minutes after subthreshold GVS. Currently, only studies using prolonged stimulation at perceptual thresholds by GVS and IV show reorganization of synaptic circuits up to structural and functional modifications of brain regions involved in processing vestibular and visual information **[17,18]**. These results offer promising prospects for improving our understanding of the Subliminal Vestibular Error (SVE) signal.

5. Perspectives and Conclusion:

The results of this study highlight the effects of subthreshold GVS on visuo-oculomotor indicators, emphasizing the importance of considering the concept of Subliminal Vestibular Error (SVE) in our understanding of the vestibular system. The existence of an SVE below discrimination thresholds can lead to subtle modifications in visuo-oculomotor coordination mechanisms without manifesting obvious clinical symptoms. This phenomenon finds an interesting parallel with vestibular schwannomas, which can induce a subliminal erroneous signal. In the case of vestibular schwannomas, this configuration is made possible by the slow evolution of the tumor, high plasticity of peripheral vestibular circuitry, and central modulation of detection and discrimination thresholds. Similarly, the subthreshold SVE induced by GVS could engage subtle adaptive neuronal processes, initially localized in the vestibular nuclei and visuo-oculomotor structures, allowing the system to spontaneously adjust to the stimulation. However, further studies will be necessary to confirm our observations and extend them to the population of vestibular patients.

Thus, studying the effects of SVE could be essential for understanding the mechanisms of adaptation and compensation of the vestibular system in response to mild but potentially efficient stimulations on visuo-oculomotor coordination. This improvement in our understanding of SVE could have important clinical implications, particularly for the monitoring and management of patients with subtle complaints related to vestibular dysfunctions. Just as with vestibular schwannomas, where slow progression can initially mask symptoms, SVE could also contribute to compensate sensory deficits, affecting environmental perception and balance maintenance. The results suggest that the vestibular system possesses robust adaptability to electrical stimulations, even when they do not exceed clinical perception thresholds. These adaptations could manifest as electrophysiological changes, brain reorganization, and adjustments in synaptic connections of visuo-vestibular structures.

In summary, the study of SVE opens up exciting new research perspectives to better understand the complexity of the vestibular system and its interactions with the visual system, paving the way for potential therapeutic and clinical developments aimed at improving the quality of life for patients with vestibular dysfunctions.

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Appendix A

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Table 1: Baseline assessment

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Items
Visual acuity measurement (at 5m: Monoyer chart and at 40cm: Parinaud chart)
Phoric deviation assessment using the Cover Test (at 5m and 40cm) with horizontal and vertical prism bars
Evaluation of ocular motility and conjugate eye movements using a fixation target
Phoric deviation measurement using the Maddox rod (at 5m and 40cm)
Measurement of the Near Point of Convergence using the Mawas ruler
Assessment of convergence and divergence fusional amplitudes (at 5m and 40cm)
Stereo vision examination using the TNO test (at 40cm) and Laroudoux and Kratz stereograms (at 2.5m)

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Tables 2: Exclusion criteria

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Items
Heterotropia
Abnormal retinal correspondence (ARC)
Visual acuity less than 10/10 in both eyes
Abnormal fixation (nystagmus)
Abnormal eye movements (paresis, paralysis, alphabetic syndrome)
Positive diagnosis of an ocular pathology
Positive diagnosis of a general pathology that can impact oculomotor function
Positive diagnosis of a neurological or neurodegenerative pathology
Positive diagnosis of a vestibular pathology
Regular presence of vertigo or motion sickness
Ongoing orthodontic and/or orthopedic treatment

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Table 3: Description of optometric tests used in the study.

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Items	*Description*
Far convergence at 5 meters: C	The subject fixates the light and sees only one, without neutralization. The horizontal prism bar is placed with the base-in position in front of one eye. The operator increases the power of the prism until the subject can no longer fuse. The measurement of convergence is given by the strongest prism that could be compensated, indicated as C + value in diopters (Δ). **Norms range from 8 to 10 Δ.**
Near convergence at 40 cm: C′	Same procedure: The measurement of convergence is given by the strongest prism that could be compensated, indicated as C' Δ. **Norms range from 30 to 40 Δ.**
Far divergence at 5 meters: D	Same procedure, but the horizontal prism bar is placed base-out in front of one eye: the measurement of divergence is given by the strongest prism that could be compensated, indicated as D Δ. **Norms range from 2 to 4 Δ.**
Near divergence at 40 cm: D'	Same procedure, but the horizontal prism bar is placed base-out in front of one eye: the measurement of divergence is given by the strongest prism that could be compensated, indicated as D' Δ.

	Norms range from 6 to 8 Δ.
Near Point of Convergence: NPC	An object is brought closer until one eye deviates outward, and the NPC (Near Point of Convergence) is measured using a ruler. **Its normal value is around 8 to 10 cm from the orbital rim**. It is trainable and can be modified voluntarily.
Far Stereoscopic Acuity at 2.5m: Kratsa-Barron-Laraudogoitia (KBL)	It consists of random red-green dot patterns and is performed using red and green filters. The stereoscopic acuity is measured at 250 seconds of arc at 5 meters and 500 seconds of arc at 2.50 meters. At 5 meters, it is a central test, while closer distances involve peripheral fusion. **Norms: Stereoscopic vision less than 100 seconds of arc is considered good**.
Near Stereoscopic Acuity at 40 cm: Stereopsis with Graded Circle (TNO).)	The TNO Stereotest consists of 6 plates (ranging from 480 to 15 seconds of arc) of anaglyph random-dot stereograms. They should be viewed through red-green glasses. This test measures very fine stereoscopic acuity. Norms: **The average stereoscopic acuity in the population is 20 seconds of arc. For individuals over forty years old, the average value is 58 seconds of arc.**

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