Maastricht University

Stimulating balance: recent advances in vestibular stimulation for balance and gait

Citation for published version (APA):

Herssens, N., & Mccrum, C. (2019). Stimulating balance: recent advances in vestibular stimulation for balance and gait. *Journal of Neurophysiology*, *122*(2), 447-450. https://doi.org/10.1152/jn.00851.2018

Document status and date:
Published: 01/08/2019

DOI:
10.1152/jn.00851.2018

Document Version:
Publisher's PDF, also known as Version of record

Document license:
Taverne

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.umlib.nl/taverne-license

Take down policy
If you believe that this document breaches copyright please contact us at:

repository@maastrichtuniversity.nl

providing details and we will investigate your claim.

Download date: 06 May. 2021

J Neurophysiol 122: 447–450, 2019.
First published March 13, 2019; doi:10.1152/jn.00851.2018.

NEURO FORUM | *Advances in Vestibular Research: A Tribute to Bernard Cohen, MD*

Stimulating balance: recent advances in vestibular stimulation for balance and gait

Nolan Herssens[1,2] and **Christopher McCrum**[3,4]

[1]*MOVANT, Department of Rehabilitation Sciences and Physiotherapy, University of Antwerp, Antwerp, Belgium;* [2]*Multidisciplinary Motor Centre Antwerp (M²OCEAN), University of Antwerp, Antwerp, Belgium;* [3]*Department of Nutrition and Movement Sciences, NUTRIM School of Nutrition and Translational Research in Metabolism, Maastricht University Medical Center+, Maastricht, The Netherlands; and* [4]*Institute of Movement and Sport Gerontology, German Sport University Cologne, Cologne, Germany*

Submitted 19 December 2018; accepted in final form 7 March 2019

Herssens N, McCrum C. Stimulating balance: recent advances in vestibular stimulation for balance and gait. *J Neurophysiol* 122: 447–450, 2019. First published March 13, 2019; doi:10.1152/jn.00851.2018.—Noisy galvanic vestibular stimulation (nGVS) can boost vestibular sensory thresholds via stochastic resonance and research on nGVS as an intervention for vestibulopathy has accelerated recently. Recent research has investigated the effects and associated mechanisms of nGVS on balance and gait. nGVS has potential as an intervention for balance and gait-related deficits in vestibulopathy, but further research into the mechanisms underlying these effects and consensus on stimulation protocols are required.

galvanic vestibular stimulation; locomotion; stochastic resonance; vestibular system; vestibulopathy

INTRODUCTION

The vestibular system senses angular and linear accelerations of the head in space and thereby provides the central nervous system with information about self-motion, head position, and spatial orientation in relation to gravity. Although the function of the vestibular system remains mostly undetected during normal circumstances, it plays a key role in maintaining body balance and gaze stabilization through the vestibulospinal and vestibulo-ocular reflexes, respectively (Purves et al. 2012). Bilateral vestibulopathy (BVP) is a severe bilateral reduction or loss of vestibular function and was recently defined by the Bárány Society (Strupp et al. 2017). The bilateral reduction in peripheral vestibular function leads to debilitating effects that negatively affect vestibulo-ocular and vestibulospinal reflexes, which in turn affect quality of life, including severe balance deficits and an increased risk of falls (Strupp et al. 2017). Critically, most patients with BVP do not experience any improvement in their symptoms over time (Zingler et al. 2009). One potential intervention on which research has recently accelerated is noisy galvanic vestibular stimulation (nGVS).

With nGVS, an attempt to enhance the residual vestibular function is made by delivering an imperceptible electrical current to the vestibular end organs (i.e., semicircular canals, otolith organs) through electrodes placed over the mastoid processes. Thereby, the activity of the primary afferents and vestibular hair cells is modulated (Wuehr et al. 2017). The hypothesized benefit is that due to applying an appropriate amount of noise to the system, the processing of weak, subthreshold signals is facilitated (i.e., stochastic resonance), and, as a result, the vestibular detection thresholds are lowered (Fig. 1; also see Wuehr et al. 2017).

In this Neuro Forum, we discuss six recent articles (Inukai et al. 2018a, 2018b; Iwasaki et al. 2018; Keywan et al. 2018; Temple et al. 2018; Wuehr et al. 2018) that have explored the effects of nGVS on balance and gait in humans. Second, we discuss the potential mechanisms of the observed effects and, based on the current state of the art, give recommendations and directions for future research on nGVS for the purpose of improving balance and gait.

FUNCTIONAL EFFECTS OF NGVS ON BALANCE

Two recent studies have explored the effects of nGVS on standing balance control using center of pressure (COP) measures. The COP represents the weighted average of all the pressures under the surface of the foot in contact with the ground; an increase in common COP measures (amplitude, path length, sway area, and velocity) implies a reduced stability [see Winter (1995) for review]. Inukai et al. (2018b) investigated the effects of different stimulation protocols on the COP behavior during quiet standing and Inukai et al. (2018a) conducted a randomized controlled trial (RCT) investigating the effects of nGVS on COP characteristics during standing in community-dwelling older adults. Inukai et al. (2018b) conducted three experiments within their study, the first of which examined the effects of three different stimulation conditions (sham, low intensity, and high intensity) on COP behavior during 30-s quiet standing. The second experiment compared

---

Address for reprint requests and other correspondence: C. McCrum, Department of Nutrition and Movement Sciences, Maastricht University, PO Box 616, Maastricht, 6200 MD, The Netherlands (e-mail: chris.mccrum@maastrichtuniversity.nl).

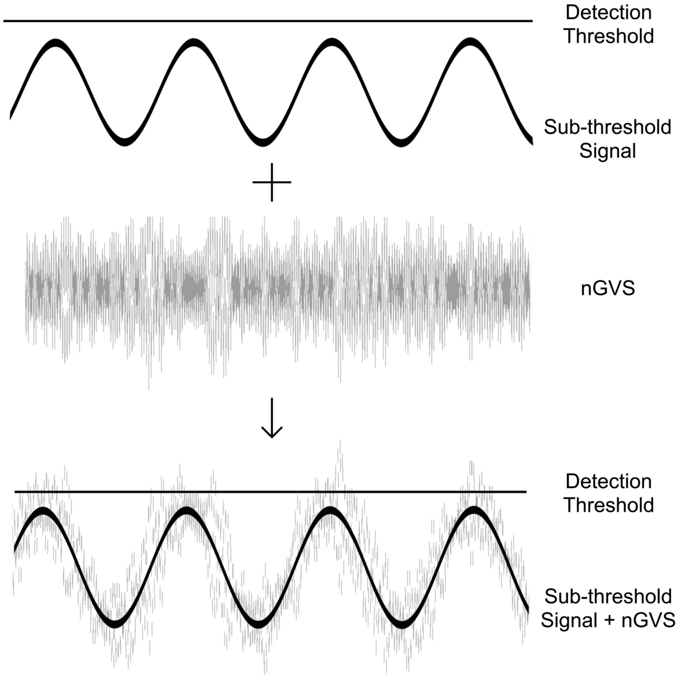

Fig. 1. When noisy galvanic vestibular stimulation (nGVS) is applied to the vestibular system, the processing of subthreshold signals is facilitated through stochastic resonance.

low-intensity stimulation for 5-s duration at the beginning of the 30-s standing measurement, with low-intensity and high-intensity stimulation for 30 s. The third experiment repeated the second experiment, but with the electrodes placed on top of the head and not on the mastoid processes. With these experiments, Inukai et al. (2018b) could confirm that nGVS reduces COP sway path length and anteroposterior mean COP velocity during eyes-open stance in healthy young adults and that in less stable participants the effects are more pronounced, with the addition of reducing mediolateral mean COP velocity. Reduction in COP sway path length was also observed after only 5 s of stimulation. The third experiment, by performing an identical protocol but with the electrodes placed so that the vestibular apparatus was not stimulated, excluded the possibility that the effects seen with nGVS were due to motor learning, arousal, attention, or physical tension due to stimulation, as no change in COP sway path length was seen in this condition. In their RCT, Inukai et al. (2018a) found results in agreement with Inukai et al. (2018b), as the older adults randomized to the low-intensity condition demonstrated significantly reduced COP path length, as well as anteroposterior and mediolateral mean COP velocities, whereas the sham stimulation group showed no changes.

A common result from these studies was that participants with initially poorer balance control tended to demonstrate improvements of greater magnitude with nGVS than those with better initial balance performance. These results imply that the reason for these participants' less stable stance was in part due to processes that can be affected by the nGVS. However, there are several mechanisms that could be responsible for such effects, related not only to stimulation of the vestibular apparatus, but also activation of cortical regions (e.g., vestibular nucleus, brainstem, vestibular thalamus, multisensory input areas 2, 3a/b, 7, parieto-insular vestibular cortex). Additionally, it is unclear from these studies the extent to which frequency band or stimulation intensity could play a role in the effectiveness of nGVS on balance control, as both studies applied the same frequency band, and no differences were found by Inukai et al. (2018b) between low and high intensities. It is reassuring that consistent results in these studies are found, but alone they do not provide clear insight into the potential mechanisms and how those mechanisms can be most optimally targeted. Finally, as these studies only analyzed eyes-open quiet standing, it is unclear whether and how the observed benefit of nGVS transfers to other tasks with different sensorimotor demands and restrictions. With changes in sensorimotor task requirements, the optimum stimulation frequency and intensity may vary.

FUNCTIONAL EFFECTS OF NGVS ON GAIT

Two recent studies have analyzed the effects of nGVS on gait (Iwasaki et al. 2018; Temple et al. 2018). Iwasaki et al. (2018) investigated the effects of nGVS on walking speed in healthy people and people with BVP. Using an accelerometer placed on the trunk, Iwasaki et al. (2018) observed significant increases in gait velocity and stride length and decreases in stride time at the optimal nGVS in both healthy participants and patients with BVP. However, variability of stride time and vertical and lateral movement were not affected in either group (Iwasaki et al. 2018). As the walking trials comprised of 15-m walking with the middle 10 m taken for analysis, it is likely that the number of strides taken was not sufficient to reliably evaluate gait variability. This is worth highlighting, as it could be argued that increased gait variability (indicating potentially increased fall risk) is of greater clinical relevance than mean stride length and time in patients with BVP. It is also unclear how the optimal stimulation intensity found for walking speed is related to other gait and balance tasks or parameters and indeed whether determining the optimal stimulation intensity based on single 10-m walking trials is reliable.

Temple et al. (2018) examined the effect of nGVS in healthy participants completing a functional mobility test conducted on 10-cm-thick foam, which included a course with multiple obstacles requiring different negotiating movements. The first three trials established a baseline, and these were followed by nine more trials while wearing vision-distorting goggles (prism vertically flipping the visual field). Participants were randomized to either a stimulation group or a control group. nGVS led to significantly faster rates of adaptive improvement in the time to complete the test at group level; however, further analysis revealed that only 7 of the 12 participants to receive nGVS "responded" in this manner. Similar to the study of Iwasaki et al. (2018), it is unclear whether the outcome measure (adaptation rate of time to complete the test) is reliable or sensitive to detect the specific effects of nGVS. Taken together, these two studies looking into gait and mobility while applying nGVS do not give clear experimental support for specific mechanisms of the responses (and variation in responses) observed, although they certainly give indications that such an intervention could positively influence gait and mobility in BVP. The nGVS protocols also differ substantially, both from each other and from the previously described studies on standing balance. This results in difficulties drawing general conclusions from the literature, without considering potential mechanisms for improvements in gait and balance seen with nGVS more specifically.

POTENTIAL MECHANISMS OF BALANCE AND GAIT IMPROVEMENTS IN NGVS

The most frequently hypothesized working mechanism to explain the ameliorating effects of nGVS has been linked to stochastic resonance (Fig. 1; see also Wuehr et al. 2017). During application of nGVS, the neuronal activity of the primary vestibular afferents (semicircular canals and otolith organs) and vestibular hair cells is thought to be altered through stochastic resonance, i.e., noise (Gensberger et al. 2016). The presence of noise is believed to lower the vestibulospinal detection threshold, which enables the ability of the subject to detect and process the otherwise undetectable, subthreshold, vestibular signals (Fig. 1; Wuehr et al. 2018). Keywan et al. (2018) examined whether effects of nGVS on vestibulospinal function during quiet standing, assessed by COP measures, are accompanied by changes in vestibuloperceptual function, assessed by roll-tilt motion perception. However, they did not find any correlations between the nGVS-induced improvements in the COP measures and the improved roll-tilt motion perception. These results might indicate a frequency dependency of nGVS on vestibular motion perception. Nevertheless, these improvements indicate that the same nGVS mode might be able to induce improvements of both reflexive and perceptual functions, which are both vital in controlling upright balance.

Furthermore, the afferent vestibular signals that are induced through nGVS are believed to pass through the vestibular nucleus of the brainstem and the vestibular thalamus and to activate brain areas that are associated with multisensory input (area 2, area 3a/b, area 7, and the parieto-insular vestibular cortex) (Inukai et al. 2018a, 2018b). The activation of these cortical areas associated with multisensory input may also affect postural sway during stimulation (Inukai et al. 2018b). Additionally, it has been hypothesized that nGVS might alter the cerebellar activity, which might, in turn, induce changes to the locomotor pattern (Iwasaki et al. 2018).

Moreover, post-nGVS-stimulation improvements of postural stability of up to four hours in BVP and healthy elderly might be induced by neuroplasticity in the central vestibular system (Fujimoto et al. 2016; Iwasaki et al. 2018). This mechanism of neuroplasticity in the vestibular system involves both the cerebellar circuits and the vestibular nuclei. Long-term depression at the parallel fiber to the Purkinje cell synapses in the cerebellum underlies the early stages of vestibular learning. The vestibular nuclei, providing excitatory input to the ipsilateral extensor motor neurons and inhibitory input to the reciprocal flexor motor neurons of the legs through the lateral vestibulospinal tract, show long-term potentiation and depression, respectively, induced through the high-frequency vestibular nerve stimulation. These neuroplastic changes are thought to underlie the storage of consolidated memories of the vestibular system. Therefore, the improvements of postural stability associated with nGVS might be attributed to the induction of neuroplasticity in the vestibular nucleus and/or cerebellum (Fujimoto et al. 2016).

FUTURE DIRECTIONS FOR VESTIBULAR STIMULATION

In general, nGVS can be beneficial for balance performance, but it remains unclear which mechanisms are involved. Whether these ameliorating effects are only related to the improvement of vestibular information processing through the activation of the primary vestibular afferents due to stochastic resonance or also induce the activation of cortical regions related to multisensory integration and/or the cerebellum is still uncertain for the moment. Some hypotheses even attribute these effects to the neuroplasticity of the central vestibular system. Moreover, while there is early evidence that nGVS can modulate the vestibular hair cell activity, it could be possible that only specific hair cells with frequency bands corresponding to the stimulation frequency will profit from nGVS. Similarly, it may be important to adjust the stimulation frequency to the frequency of head movement experienced during specific tasks. Additionally, responsiveness to nGVS in BVP may also depend on the presence and extent of residual vestibular function. Furthermore, people with BVP who are more visually dependent could be differentially affected by nGVS; the improved vestibular input could either be added to the existing visual reliance, or the residual vestibular information could be down-weighted to the extent that the improved vestibular function is not integrated. Whether only one of the hypothesized mechanisms is responsible for the effects that are demonstrated or whether a combination of mechanisms induce these changes remains a question for future research.

In addition to the uncertainty in working mechanisms of nGVS, a wide variety of stimulation procedures have been applied. Therefore, it is difficult to define the “optimal” way to use nGVS in healthy controls or in people with BVP. Answers should be sought with regards to which frequencies are most suited, whether different balance tasks demand different frequency bands, or whether different types and responses of hair cells to specific frequencies are activated or not. Furthermore, methods to determine the optimal stimulation intensity vary widely, from predetermined, fixed stimulation intensities (Inukai et al. 2018a, 2018b), to assessment of the perceptual cutaneous threshold (Temple et al. 2018; Wuehr et al. 2018) or based on the performance of a postural task (Iwasaki et al. 2018; Keywan et al. 2018). Therefore, future studies should more thoroughly examine whether susceptibility to nGVS depends on certain individual traits (e.g., full or partial vestibular function loss in BVP or sensory weighting) or anatomical or physiological characteristics (e.g., frequency dependency of vestibular hair cells or activation of cortical regions).

In conclusion, recent work on nGVS for improving balance and gait shows promise and has the potential to be a beneficial intervention for people with vestibulopathy in the future. However, to reach this goal, further research into the mechanistic underpinnings of the effects of nGVS and consensus on stimulation protocols are needed.

ACKNOWLEDGMENTS

The authors thank Prof. Dr. Ann Hallemans and Prof. Dr. Vincent Van Rompaey for helpful comments on the manuscript and Prof. Dr. Wim Saeys and Prof. Dr. Luc Vereeck for helpful discussions.

GRANTS

N. Herssens is supported by the University of Antwerp Research Council [grant number ID33586]. C. McCrum is supported by the NUTRIM Graduate Programme of Maastricht University Medical Center+.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

N.H. and C.M. conceived and designed research; N.H. and C.M. drafted manuscript; N.H. and C.M. edited and revised manuscript; N.H. and C.M. approved final version of manuscript.

REFERENCES

Fujimoto C, Yamamoto Y, Kamogashira T, Kinoshita M, Egami N, Uemura Y, Togo F, Yamasoba T, Iwasaki S. Noisy galvanic vestibular stimulation induces a sustained improvement in body balance in elderly adults. *Sci Rep* 6: 37575, 2016. doi:10.1038/srep37575.

Gensberger KD, Kaufmann AK, Dietrich H, Branoner F, Banchi R, Chagnaud BP, Straka H. Galvanic vestibular stimulation: cellular substrates and response patterns of neurons in the vestibulo-ocular network. *J Neurosci* 36: 9097–9110, 2016. doi:10.1523/JNEUROSCI.4239-15.2016.

Inukai Y, Masaki M, Otsuru N, Saito K, Miyaguchi S, Kojima S, Onishi H. Effect of noisy galvanic vestibular stimulation in community-dwelling elderly people: a randomised controlled trial. *J Neuroeng Rehabil* 15: 63, 2018a. doi:10.1186/s12984-018-0407-6.

Inukai Y, Otsuru N, Masaki M, Saito K, Miyaguchi S, Kojima S, Onishi H. Effect of noisy galvanic vestibular stimulation on center of pressure sway of static standing posture. *Brain Stimul* 11: 85–93, 2018b. doi:10.1016/j.brs.2017.10.007.

Iwasaki S, Fujimoto C, Egami N, Kinoshita M, Togo F, Yamamoto Y, Yamasoba T. Noisy vestibular stimulation increases gait speed in normals and in bilateral vestibulopathy. *Brain Stimul* 11: 709–715, 2018. doi:10.1016/j.brs.2018.03.005.

Keywan A, Wuehr M, Pradhan C, Jahn K. Noisy galvanic stimulation improves roll-tilt vestibular perception in healthy subjects. *Front Neurol* 9: 83, 2018. doi:10.3389/fneur.2018.00083.

Purves D, Augustine J, Fitzpatrick D, Hall WC, LaMatia AS, White LE (Editors). *Neuroscience* (5th ed.). Sunderland, MA: Sinauer, 2012.

Strupp M, Kim JS, Murofushi T, Straumann D, Jen JC, Rosengren SM, Della Santina CC, Kingma H. Bilateral vestibulopathy: diagnostic criteria consensus document of the Classification Committee of the Bárány Society. *J Vestib Res* 27: 177–189, 2017. doi:10.3233/VES-170619.

Temple DR, De Dios YE, Layne CS, Bloomberg JJ, Mulavara AP. Efficacy of stochastic vestibular stimulation to improve locomotor performance during adaptation to visuomotor and somatosensory distortion. *Front Physiol* 9: 301, 2018. doi:10.3389/fphys.2018.00301.

Winter DA. Human balance and posture control during standing and walking. *Gait Posture* 3: 193–214, 1995. doi:10.1016/0966-6362(96)82849-9.

Wuehr M, Boerner JC, Pradhan C, Decker J, Jahn K, Brandt T, Schniepp R. Stochastic resonance in the human vestibular system—Noise-induced facilitation of vestibulospinal reflexes. *Brain Stimul* 11: 261–263, 2018. doi:10.1016/j.brs.2017.10.016.

Wuehr M, Decker J, Schniepp R. Noisy galvanic vestibular stimulation: an emerging treatment option for bilateral vestibulopathy. *J Neurol* 264, *Suppl* 1: 81–86, 2017. doi:10.1007/s00415-017-8481-4.

Zingler VC, Weintz E, Jahn K, Huppert D, Cnyrim C, Brandt T, Strupp M. Causative factors, epidemiology, and follow-up of bilateral vestibulopathy. *Ann N Y Acad Sci* 1164: 505–508, 2009. doi:10.1111/j.1749-6632.2009.03765.x.