



Full length article

Static monocular visual cues can decrease the vestibular-evoked balance response at low frequencies

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ABSTRACT

Background: The balance system continually integrates and processes diverse sensorimotor cues to maintain upright posture. Yet, little is known about how monocular visual cues may modulate the vestibular control of standing balance.

Research question: To determine how visual cues, specifically monocular vision, modulate the vestibular-evoked myogenic and whole-body balance response.

Methods: Seventeen (12 female) healthy subjects (age: 24.8 ± 5.3 years) were exposed to a random, continuous electrical vestibular stimulation (EVS) signal (± 3.5 mA, 0–20 Hz). Subjects stood quietly during four experimental (no vision, non-dominant eye, dominant eye, binocular) conditions. The EVS-medial-lateral ground reaction force (ML GRF) acting on the body and EVS-medial gastrocnemius electromyography (EMG, bilateral) responses were evaluated in the frequency (coherence) and time (cumulant density) domains.

Results: Coherence was increased for no vision compared to binocular, dominant eye, and non-dominant eye visual cues, respectively, with the most pronounced increases occurring at lower frequencies. For cumulant density, the EVS-ML GRF medium-latency peak amplitude was increased 45, 26 and 18% with no vision compared to binocular, dominant eye and non-dominant eye visual cues, respectively ($p < .05$). The EVS-EMG medium-latency peak amplitude during no vision was greater than binocular ($p < .05$) for both gastrocnemii, but binocular and dominant eye monocular vision was not different ($p > .05$). The EVS-ML GRF and EVS-EMG (right medial gastrocnemius) medium-latency peak amplitude was greater for non-dominant eye monocular vision compared to binocular vision ($p < .05$).

Significance: Monocular visual cues, at least for the dominant eye, can depress the vestibular-evoked balance response at low frequencies akin to binocular vision with limited differences exhibited between dominant and non-dominant eye.

1. Introduction

To maintain standing balance, the central nervous system (CNS) continually integrates and processes diverse sensorimotor cues [1,2]. Certainly, the visual system plays an important role in upright balance control [3], as emphasized by postural re-adjustments induced by moving visual environments [4] and removal of visual cues [3,5,6]. Further, when monocular vision is compared with binocular, whole-body sway is increased [5,6]. However, little is known regarding how the vestibular control of standing balance is altered when visual cues are reduced from binocular to monocular vision.

Electrical vestibular stimulation (EVS) can be used to probe the

vestibular control of standing balance by applying a small electrical current over the mastoid processes to modulate firing rates of the primary vestibular afferents [7]. Stochastic EVS induces reflexive activity within postural muscles, affording the characterization of vestibular-evoked balance responses in both frequency and time domains [8–10].

Reports describing how visual cues modulate vestibular-evoked balance responses are primarily limited to two conditions: vision (i.e., binocular) and no vision (i.e., eyes closed) [11–14]. Some studies have probed further and used a greater range of visual conditions [15,16]. Day and Guerraz [15] observed a progressive decrease in vestibular-evoked whole-body balance responses when visual cues were progressively increased from no vision to a 2D visual environment. Jessop and

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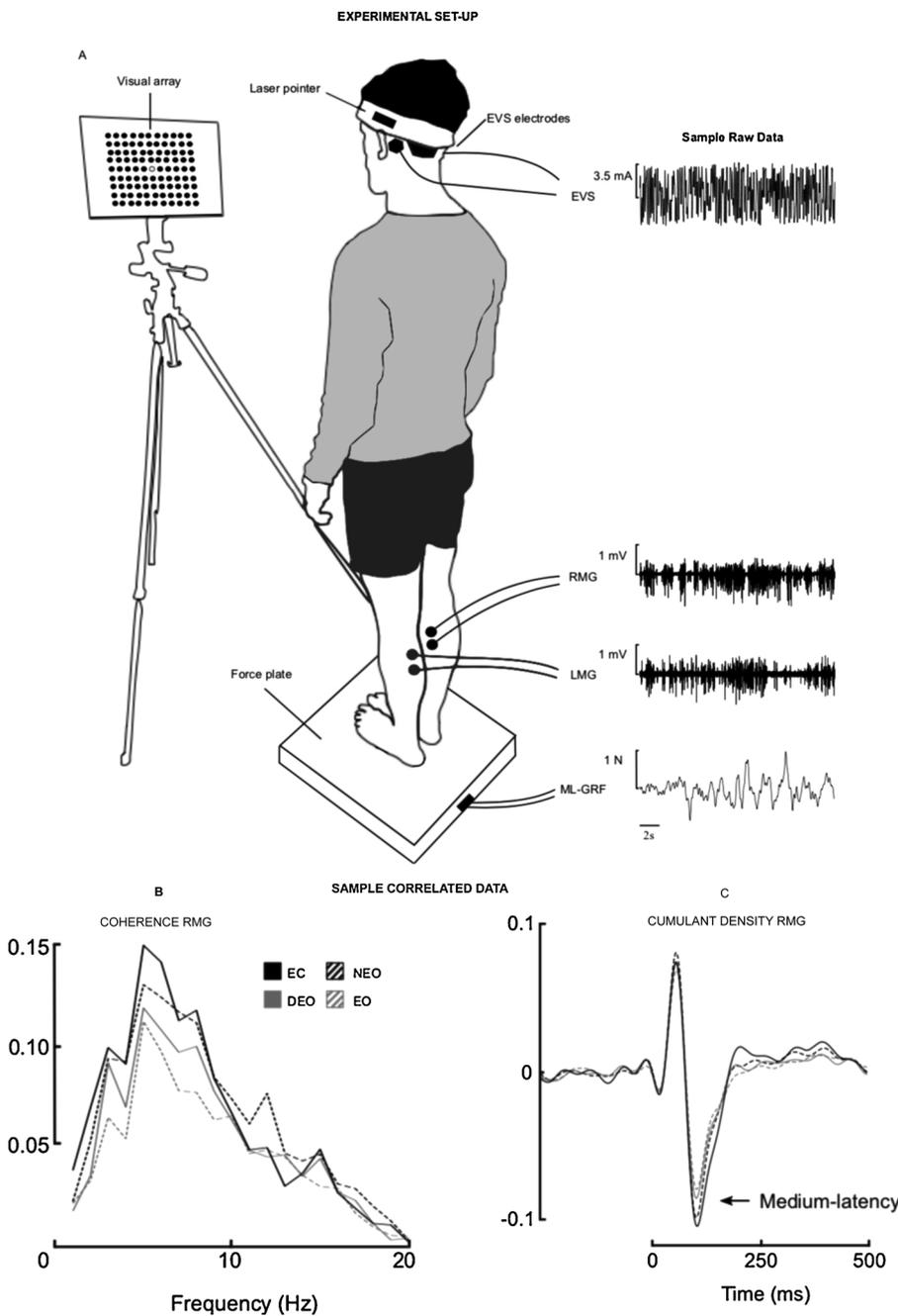


Fig. 1. Experimental setup (A) showing orientation of subject relative to the visual display. The electrical vestibular stimulation (EVS)-evoked muscle and whole-body balance responses are aligned in the frontal plane. Visual display dimensions were 25.4 × 25.4 cm, and was placed 69.7 cm in front of participants with a center dot oriented at eye level (not to scale). Laser is shown over left ear for illustrative purposes only. Sample unprocessed EVS, left (LMG) and right (RMG) medial gastrocnemius electromyography, and medial-lateral ground reaction force (ML-GRF; Fx) data are provided. Single-subject EVS-RMG coherence (B) and EVS-RMG cumulant density (C) functions for a 90-s trial. Visual conditions: eyes open (EO; grey hatched), monocular vision with the dominant eye (DEO; grey solid), monocular vision with the non-dominant eye (NEO; black hatched), and eyes closed (EC; black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

McFadyen [16] reported reduced vestibular-evoked angular trunk and head roll displacement with binocular compared with monocular or no vision. Interestingly, no differences were observed between monocular and no vision, suggesting that monocular vision alone is insufficient to reduce vestibular-evoked balance responses [16]. Thus, it appears that monocular visual cues are interpreted by the CNS as less reliable than binocular vision; thereby vestibular-evoked corrective balance responses during monocular vision are facilitated. The CNS may further discriminate between visual cues provided by the dominant and non-dominant eye [17]. For example, when static visual cues from the non-dominant eye were present, the vestibular-evoked balance response was greater than binocular vision [16]. However, owing to a low sample size ($n = 5$) and the use of traditional square-wave EVS [16], a complete characterization of the effect of monocular visual cues on the vestibular control of balance remains unclear.

The vestibular-evoked whole-body balance response may be graded based on the amount [15] and/or type [16] of visual information

available. Yet, whole-body balance adjustments are the summation of all muscles actively engaged in the postural task [9]. Owing to mechanical filtering, the whole-body balance response may be impervious to low-amplitude or short-duration effects [18], and may not translate to alterations within individual muscles. The purpose here was to determine whether the transformation of an isolated vestibular error signal to the bilateral gastrocnemii, and subsequently, whole-body forces, is modulated by a range of static visual cues using both frequency (coherence) and time (cumulant density) approaches. We hypothesized that increasing visual cues (no vision, monocular vision, binocular vision) will progressively decrease the vestibular-evoked balance response.

2. Methods

2.1. Participants

Seventeen (12 female) right-eye and right-leg dominant, healthy participants (age: 24.8 ± 5.3 years, height: 1.7 ± 0.9 m, mass: 65.0 ± 8.8 kg) granted written, informed consent and completed the study. All procedures were approved by the University of Oregon's Institutional Review Board for the Protection of Human Subjects.

2.2. Visual acuity and eye dominance

Normal or corrected-to-normal binocular and monocular vision was confirmed 20/20 using a Snellen visual acuity test. Eye dominance was determined using variations of the Miles and Porta tests [17]. All participants included were right eye dominant on both tests. Four volunteers, who were not right eye dominant, were excluded from data analysis.

2.3. Electromyography

Surface electromyography (EMG) were collected from the right (RMG) and left (LMG) medial gastrocnemius. The medial gastrocnemii have been shown to contribute to vestibular-evoked whole-body balance responses directed medial-laterally [10]. Prior to electrode placement, the skin surface was cleaned using isopropyl alcohol. A pair of self-adhesive Ag-AgCl surface electrodes (Blue Sensor M, M-00-S, Ambu A/S, Ballerup, Denmark) were placed over the muscle bellies – in line with the muscle fibers – with an inter-electrode distance of 2 cm center-to-center. Ground electrodes were placed over the lateral malleoli. Surface EMG signals were pre-amplified ($\times 1000$, NL844, Digitimer Ltd., Welwyn Garden City, United Kingdom), amplified ($\times 2$, NL802 A, Digitimer Ltd., Welwyn Garden City, United Kingdom), and band-pass filtered (30–1000 Hz, NL136 and NL 144, Digitimer Ltd., Welwyn Garden City, United Kingdom). All signals were sampled at 2048 Hz (PXI-6289, National Instruments, Austin, TX, United States).

2.4. Vestibular stimulation

The EVS signal comprised of a continuous, randomly varying current in both frequency (0–20 Hz) and amplitude (± 3.5 mA; RMS = 1.7 mA) with a duration of 90 s (Fig. 1). Binaural, bipolar EVS was delivered using carbon rubber electrodes (9 cm^2) coated in electrode gel (Spectra 360, Parker Laboratories, Fairfield, NJ, United States) and placed over the mastoid processes. The electrodes were secured using Durapore tape (3M Innovations, St. Paul, MN, United States) and an elastic headband. The EVS signal was created on a PC computer using LabVIEW software (National Instruments, Austin, TX, United States) and sent to an isolated, bipolar constant current stimulator (DS5, Digitimer Ltd., Welwyn Garden City, United Kingdom).

2.5. Visual display

A visual display was created in PowerPoint (Microsoft Corporation, Redmond, WA, United States) and projected onto a computer monitor (Fig. 1). The display (dimensions: 25.4×25.4 cm) consisted of an 11×11 grid of circles (2 mm in diameter with a spacing of 2.2 cm) superimposed over a black background and positioned 69.7 cm in front of the participant. All circles were white except for a central blue circle.

2.6. Experimental set-up

In a dark room, participants stood barefoot on a force platform (OR6-5-2000, Advanced Mechanical Technology Inc., Watertown, MA, USA) with feet parallel, medial malleoli < 3 cm apart, and arms relaxed at their sides (Fig. 1). During all trials, the participant's head faced

forward and Reid's plane tilted $\sim 19^\circ$ above horizontal, such that the EVS-evoked postural response was directed medial-laterally [7,10]. Head position was confirmed using a bubble inclinometer, and was maintained during all trials using a laser (Fig. 1).

2.7. Experimental procedures

Four experimental visual conditions with two 90-s trials each were conducted randomly. The four conditions included eyes open/binocular vision (EO), monocular vision with dominant eye (DEO), monocular vision with non-dominant eye (NEO), and eyes closed/no vision (EC). The EVS electrodes were positioned in an anode right, cathode left configuration. To reduce visual cues for the no vision and monocular vision conditions, participants wore a blindfold or eye patch, respectively. One min of rest was provided between trials.

2.8. Data analyses

Surface EMG were full-wave rectified and high-pass filtered at 30 Hz [19], and ML GRF data were mean-removed and low-pass filtered at 10 Hz (digital 5th order zero-phase shift Butterworth filter, MATLAB, Mathworks, Natick, MA, United States). To characterize the vestibular-evoked balance response, both ML GRF and EMG were time-locked to the onset of the EVS signal. For each condition, data were pooled into a single 180-s time series per participant, which consisted of 90 and 180 segments of 2048 data points per segment for the ML GRF (segment length = 2.0 s, resolution = 0.5 Hz) and EMG (segment length = 1.0 s, resolution = 1.0 Hz), respectively. For frequency analysis and visual representation, individual subject data were then pooled across all participants to yield a single data series of 1530 and 3060 segments per condition for ML GRF and EMG, respectively. Time and frequency domain analyses were performed using an archive of MATLAB functions (Neurospec 2.0; <http://neurospec.org>) based on multivariate Fourier analyses.

Coherence estimates evaluated the linear relationship between the input (EVS) and output (EMG or ML GRF), and is a unit-less value bound between 0 and 1, with '1' indicating a perfect linear relationship, and '0' indicating independence [20,21]. Coherence for each visual condition per subject were determined significant and used for further analyses when values exceeded a 95% confidence limit that was based on the total number of data segments [20].

The cumulant density function was derived from a transformation of the cross-spectra between the EVS signal and the motor responses (GRF and EMG) and is a correlation-like measure that represents an associative relationship between the input (EVS) and output (GRF and EMG). The amplitudes of the cumulant density function were normalized by the product of the vector norms of the input (EVS) and output (GRF and EMG) signals. Thus, the cumulant density function is bound between 1 and -1 and can provide meaningful magnitude units [22–24]. Further, the medium-latency peak amplitude is used to describe the vestibular control of standing balance [9,25,26], and seems to be more sensitive to vision-related alterations than the short-latency peak amplitude [11,13]. Significance was determined when the medium-latency peak amplitude exceeded the 95% confidence intervals that were constructed from the total number of data segments [20].

2.9. Statistical analyses

Significant differences in coherence between visual conditions were identified using the difference of coherence (DoC) function in MATLAB [27]. This analysis compares the standardized differences between coherence for two visual conditions and frequencies exceeding the 95% confidence limits are deemed statistically different [21,27].

To analyze cumulant density main effects for visual condition, the medium-latency peak amplitudes were compared using one-way, repeated-measures analysis of variances. Post-hoc analyses were

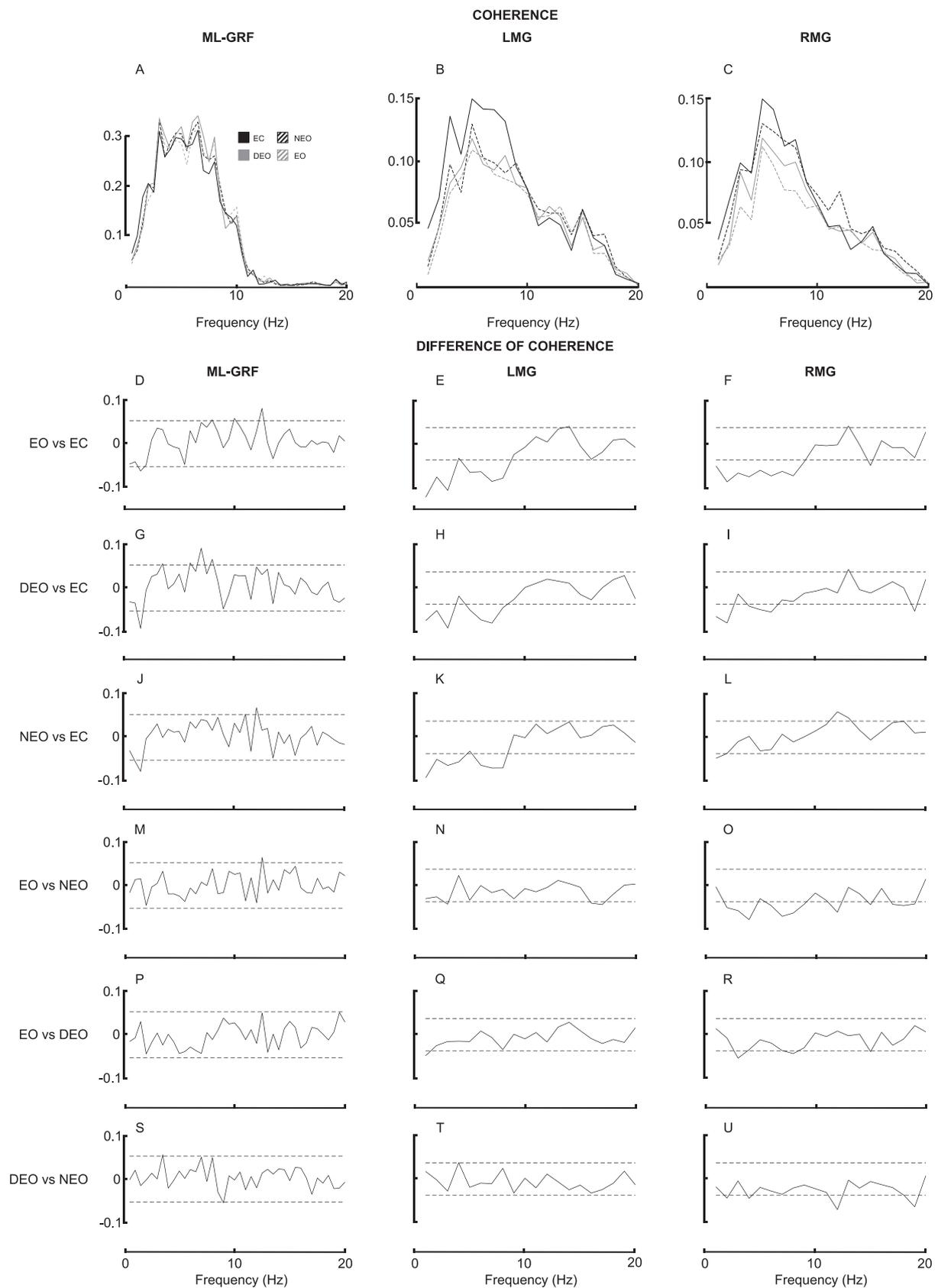


Fig. 2. Pooled data for coherence estimates and difference of coherence across all visual comparisons showing modulations of the vestibular-evoked balance response across the electrical vestibular stimulation frequency bandwidth (0–20 Hz). Visual conditions: eyes open (EO; grey hatched), monocular vision with the dominant eye (DEO; grey solid), monocular vision with the non-dominant eye (NEO; black hatched), and eyes closed (EC; black). Top row depicts coherence estimates for medial-lateral ground reaction force (ML-GRF), and left (LMG) and right (RMG) medial gastrocnemius, respectively. Difference of coherence (D–U) for ML-GRF (left column), LMG (middle column) and RMG (right column) for all six visual comparisons. A negative value for the difference of coherence indicates that coherence was increased for the second dependent variable for each comparison. Values exceeding the 95% confidence limits (dashed horizontal lines) were considered statistically significant (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

conducted using a Bonferroni correction factor. Planned contrasts between monocular visual conditions were analyzed using paired *t*-tests. Time domain statistical analyses were conducted using SPSS version 25. Significance was set at $p < .05$. Effect sizes were calculated using partial eta squared (η_p^2) to determine the strength of main effects. Descriptive statistics within the text are reported as means \pm standard deviations and figures are reported as means \pm standard errors.

3. Results

The EVS-EMG coherence was significant over the entire frequency bandwidth of the vestibular error signal (i.e., 0–20 Hz) for all subjects, yet significant operational frequencies were distributed over a lower and narrower bandwidth for EVS-ML GRF (Fig. 2A–C). With vision occluded, EVS-ML GRF coherence was greater than binocular (Fig. 2D, 1–2 Hz), dominant eye (Fig. 2G, 1–2 Hz) and non-dominant eye (Fig. 2J, 1–2 Hz) visual cues at low frequencies. The EVS-ML GRF coherence was not different between binocular and monocular vision (Fig. 2M & P), nor between dominant and non-dominant eye (Fig. 2S). Taken together, the vestibular-evoked whole-body balance response is increased at select low frequencies when vision is occluded compared to binocular and monocular vision.

The EVS-EMG coherence estimates increased during no vision than binocular (Fig. 2E & F, LMG: 1–9 Hz, RMG: 1–9, 15 Hz), dominant eye (Fig. 2H & I, LMG: 1–4, 5–8 Hz, RMG: 1–3, 4–7, 19 Hz), and non-dominant eye (Fig. 2K & L, LMG: 1–4, 5–8 Hz, RMG: < 2 Hz) visual cues, whereby most differences occurred at low frequencies. Greater EVS-EMG coherence was observed for the non-dominant eye than binocular vision for RMG (Fig. 2O) over multiple frequencies (1–5, 6–9, 11–12, 15, 16–19 Hz), but limited differences were observed for LMG (Fig. 2N, 2–3, 16–19 Hz). There were minimal increases observed for EVS-EMG coherence for dominant eye visual cues compared to binocular vision (Fig. 2Q & R, LMG: < 1 Hz, RMG: 2–4, 7–9 Hz). Non-dominant eye EVS-EMG coherence was greater than dominant eye, but only for RMG (Fig. 2U, 2, 4, 11–13, 18–19 Hz).

For EVS-ML GRF medium-latency peak amplitude, there was a main effect of vision ($F(3,48) = 16.10$, $p < .001$, $\eta_p^2 = .50$). The medium-latency peak amplitude increased by 45 ($p < .001$), 26 ($p < .01$) and 18% ($p = .01$) with no vision than binocular, dominant eye and non-dominant eye, respectively (Fig. 3A & D). The EVS-ML GRF medium-latency peak amplitude was also 23% ($p = .02$) greater for non-dominant eye than binocular vision, but not different between dominant eye and binocular vision ($p = .16$; Fig. 3A & D). These data indicate that the vestibular-evoked whole-body balance response was largest for no vision compared with all other static visual cues.

For EVS-LMG medium-latency peak amplitude, a main effect of vision was detected ($F(3,48) = 9.29$, $p < .001$, $\eta_p^2 = .37$). The medium-latency peak amplitude was 30 ($p < .01$), 24 ($p < .01$) and 18% ($p = .02$) greater for no vision compared to binocular, dominant and non-dominant eye, respectively (Fig. 3B & E). No other pairwise comparisons were detected for EVS-LMG medium latency peak amplitude ($p > .05$).

A main effect of vision was also detected for the EVS-RMG medium-latency peak amplitude ($F(3,48) = 8.39$, $p < .001$, $\eta_p^2 = .34$). The EVS-RMG medium-latency peak amplitude during no vision was 31 ($p = .001$) and 21% ($p = .03$) greater than binocular and dominant eye visual cues, respectively, but no differences between non-dominant eye and eyes closed ($p = .94$) were detected (Fig. 3C & F). Yet, non-dominant eye medium-latency peak amplitude was 21% ($p = .04$) greater than eyes open (Fig. 3C & F) with no other significant pairwise comparisons detected ($p > .05$). The EVS-EMG medium-latency peak amplitude results indicate that as static visual cue information increases, the vestibular-evoked balance response decreases.

4. Discussion

The aim of the present study was to determine how a range of visual cues, specifically static monocular visual cues, modulate the vestibular-evoked myogenic and whole-body balance response. Similar to binocular, monocular visual cues reduced EVS-EMG and EVS-ML GRF coherence over mostly low frequencies, and decreased the medium-latency peak amplitude compared with occluded vision. Although monocular visual cues were sufficient to reduce the vestibular-evoked whole-body balance response compared to no vision, it was not as reliable as binocular vision, specifically the non-dominant eye (Fig. 3D & F). Our results emphasize that monocular and binocular visual cues can depress the vestibular-evoked myogenic and whole-body balance response, while static visual cues from the non-dominant eye alone may not modulate this response as well as binocular vision.

Here, we chose to examine the medium-latency peak, owing to its relevance in the direction and amplitude of the vestibular-evoked whole-body corrective balance response [9,26]. We found that the medium-latency peak amplitude decreased with visual cues compared to without for both EVS-EMG and EVS-ML GRF. These results confirm those reported previously for the time domain [11–14,16]. Although the medium-latency peak is composed of a range of frequencies, it is predominantly comprised of lower frequencies [8,28]. Here, we observed less coherence with binocular than occluded vision at lower frequencies, similar to a recent report [13]. The visual system operates at a frequency bandwidth of < 1 Hz [29], suppresses whole-body sway at frequencies < 0.4 Hz [30], and has limited impact on those frequencies > 0.5 Hz [30]. Complete and partial visual occlusion reduced the amount of information available to the CNS for maintaining standing balance. Thus, removal of visual cues may necessitate that the CNS rely more heavily on vestibular sources at lower frequencies, thereby facilitating the increased whole-body vestibular-evoked balance response observed in the present study (Fig. 3).

Previously, Jessop and McFadyen [16] found greater vestibular-evoked whole-body postural perturbations in the presence of monocular than binocular vision, yet monocular visual cues were not different compared to occluded vision. This previous finding suggests monocular visual cues are likely disregarded, or considered unreliable by the balance system when establishing a corrective response to a vestibular error. The whole-body balance response could be insensitive to low-amplitude or short-duration effects owing to mechanical filtering [18]. Therefore, the present study included vestibular-evoked whole-body and myogenic balance responses. In contrast to Jessop and McFadyen [16], our study demonstrated that the EVS-EMG and EVS-ML GRF coherence and medium-latency peak amplitude were depressed in the presence of monocular than no vision. Surprisingly, the medial gastrocnemii EVS-EMG medium-latency peak amplitude was not different between the dominant eye and binocular vision, but differences were detected in coherence between the non-dominant eye and binocular vision. Our coherence findings indicate the low-frequency content of monocular visual cues are relevant to the balance system, thereby leading to a decreased vestibular control of standing when compared with no vision. It is unlikely that in young healthy adults, the balance system would interpret monocular visual cues as irrelevant sensory information. Instead, our results suggest any amount of visual information – regardless of monocular or binocular vision – is sufficient to suppress reliance on the vestibular control of standing balance. It is worth noting that we examined only one postural muscle. Because the whole-body balance response is the summation of all muscle activity engaged in maintaining upright balance, evaluating the whole-body balance response, in combination with multiple muscle recordings would more accurately reflect how visual cues modulate the vestibular control of standing when the perturbation is directed medial-laterally.

Not only is the vestibular-evoked balance response decreased with the addition of monocular vision from occluded vision, monocular cues are likely not as reliable as binocular vision. For example, the EVS-GRF

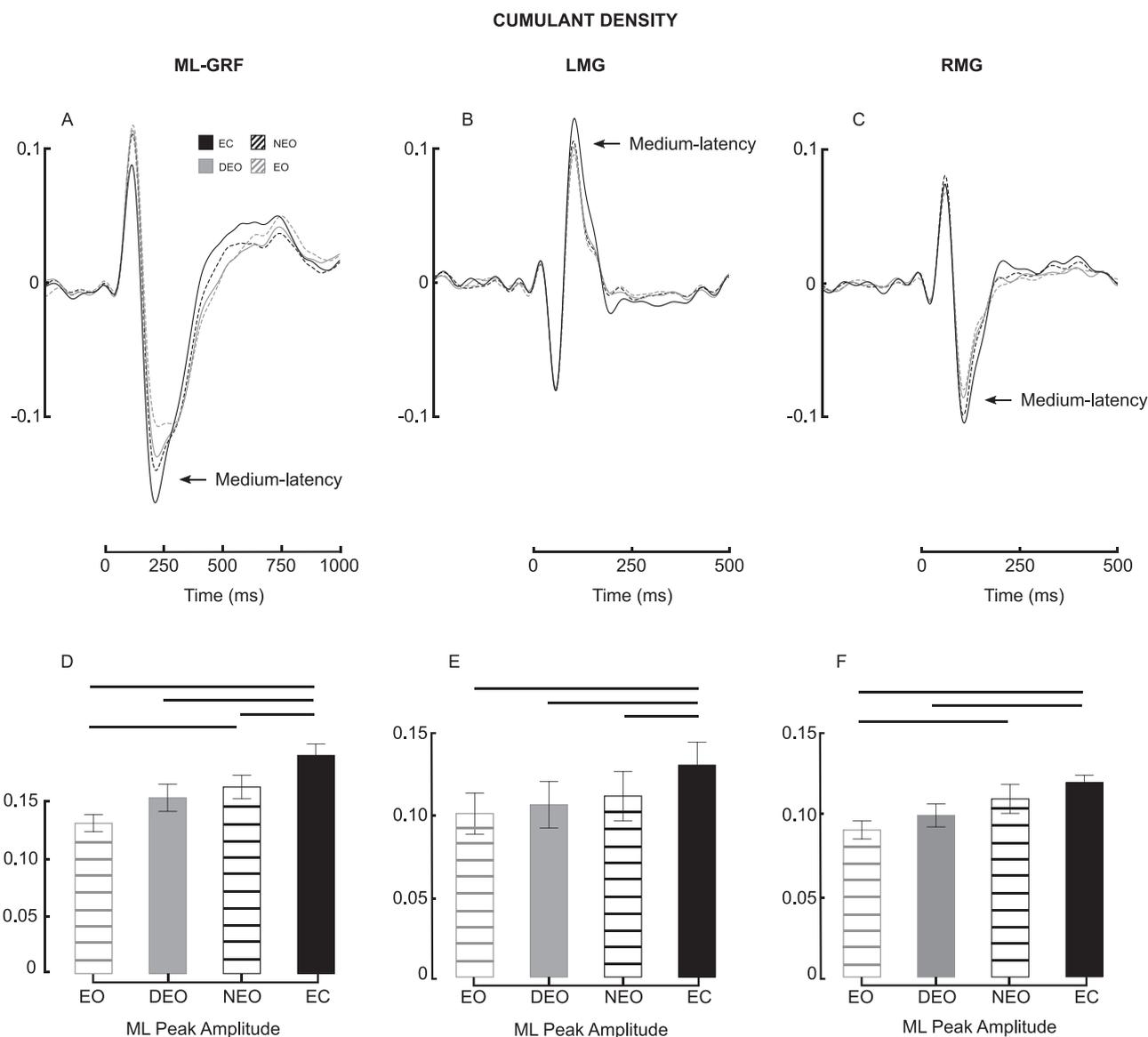


Fig. 3. Pooled cumulant density plots (top row) and mean medium-latency peak amplitudes (bottom row) across all participants. Visual conditions: eyes open (EO; grey hatched), monocular vision with the dominant eye (DEO; grey solid), monocular vision with the non-dominant eye (NEO; black hatched), and eyes closed (EC; black). Columns, from left to right, depict medial-lateral ground reaction force (ML-GRF), left medial gastrocnemius (LMG) and right medial gastrocnemius (RMG), respectively. Horizontal bars indicate significant differences between visual conditions (Bonferroni: $p < .05$) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

ML medium-latency peak amplitude increased progressively as visual cues decreased from binocular, monocular, and no vision (Fig. 3A and D). Similar results have been reported previously [15], as a graded attenuation of the vestibular-evoked balance response was shown to occur with an increase in available visual information. Interestingly, presenting static visual cues with the non-dominant eye led to a greater vestibular-evoked whole-body balance response than binocular vision (Figs. 2O, 3 D and F), but this was not the case for the dominant eye. This indicates that visual cues from the non-dominant eye may not be as reliable as binocular vision in suppressing the vestibular-evoked balance response.

Each eye may communicate an independent coordinate system for the body’s position in space to the CNS [6]. Therefore, we also performed an *a priori* statistical analysis comparing the effect of non-dominant to dominant eye visual cues on the vestibular-evoked balance response, but no differences were detected for the time domain. For those with a dominant right eye, visual dominance may not play a significant factor in how the balance system responds to a vestibular

error signal to maintain upright standing per se. However, caution should be taken when interpreting the lack of statistical differences between monocular vision conditions, as there were differences detected when comparing non-dominant eye and binocular visual cues, but not between dominant eye and binocular vision.

It is still unclear whether the visual stimuli investigated here is modulating the vestibular-evoked balance response directly. Thus, manipulating visual cues may have led to alterations in whole-body sway or changes in other sensory cues, which could have potentially influenced the vestibular control of balance. Nevertheless, our results indicate that monocular visual cues are indeed interpreted differently by the balance system compared with no vision, and are therefore sufficient to decrease the vestibular control of standing balance. As well, monocular visual cues originating from the non-dominant eye may not be as reliable as binocular vision in maintaining upright postural control.

Conflict of interest statement

The authors have no conflicts of interests to disclose.

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