Using Galvanic Vestibular Stimulation to Induce Post-Roll Illusion in a Fixed-Base Flight Simulator

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INTRODUCTION: The illusions of head motion induced by galvanic vestibular stimulation (GVS) can be used to compromise flight performance of pilots in fixed-base simulators. However, the stimuli used in the majority of studies fail to mimic disorientation in realistic flight because they are independent from the simulated aircraft motion. This study investigated the potential of bilateral-bipolar GVS coupled to aircraft roll in a fixed-base simulator to mimic vestibular spatial disorientation illusions, specifically the "post-roll illusion" observed during flight.

METHODS: There were 14 nonpilot subjects exposed to roll stimuli in a flight simulator operating in a fixed-base mode. GVS was delivered via carbon rubber electrodes on the mastoid processes. The electrical stimulus was driven by the high-pass filtered aircraft roll rate to mimic the semicircular canals' physiological response. The post-roll test scenarios excluded outside visual cues or instruments and required subjects to actively maintain a constant bank angle after an abrupt stop following a passive prolonged roll maneuver. The anticipated outcome was an overshot in roll elicited by the GVS signal.

RESULTS: The responses across subjects showed large variability, with less than a third aligning with the post-roll illusion. Subjective ratings suggest that the high-pass filtered GVS stimuli were mild and did not induce a clear sense of roll direction. However, uncontrolled head movements during stimulation might have obscured the intended effects of GVS-evoked illusory head movements.

CONCLUSION: The mild and transient GVS stimuli used in this study, together with the uncontrolled head movements, did not convincingly mimic the post-roll illusion.

KEYWORDS: galvanic vestibular stimulation, vestibular illusion, spatial disorientation, simulation.

Houben MMJ, Stuldreher IV, Forbes PA, Groen EL. *Using galvanic vestibular stimulation to induce post-roll illusion in a fixed-base flight simulator*. Aerosp Med Hum Perform. 2024; 95(2):84–92.

During flight, misleading vestibular cues can lead to spatial disorientation (SD) of the flight crew, which is a serious contributing factor to aviation accidents.[19,32] SD awareness programs, offering pilots an opportunity to experience the confusing and potentially overwhelming sensation of being disoriented, greatly improve the pilots' understanding of the risks of SD and the conditions in which it is most likely to occur.[3,34] The challenge in recreating conditions of SD is that vestibular illusions are difficult to reproduce in conventional flight simulators operating on a hexapod-type motion platform.[11] To address this problem, the simulator industry has designed so-called SD devices, i.e., flight simulators equipped with motion platforms capable of continuous rotation, or even centrifugation, to induce vestibular illusions.[26,33] Still, the operational use of these special devices is very limited, because the training requirements (e.g., STANAG 3114[40]) on pilot SD do not prescribe a specific simulator type. This makes the investment in an SD device unattractive. Recent advancements in sensory manipulation techniques[37] may provide a low-cost alternative to allow all pilots to experience SD without the need of an expensive motion platform.

An increasingly popular method for evoking artificial sensations of self-motion is galvanic vestibular stimulation (GVS).[13,18]

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This manuscript was received for review in June 2023. It was accepted for publication in December 2023.

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DOI: https://doi.org/10.3357/AMHP.6325.2024

The application of GVS modulates the ongoing firing rate of all vestibular primary afferents by delivering mild electrical currents to the mastoid processes.[20,22,24] For the most commonly used electrode arrangement (i.e., binaural-bipolar), the imposed vestibular activity primarily evokes a sensation of head-roll velocity about a naso-occipital axis elevated about 17–19° from Reid's plane.[8,13] Although numerous studies have addressed the psychophysiological effects of GVS on vestibular processing for the control of gaze,[1,6,39] balance,[7,16,27] head-neck stability,[10,14,17] perception,[8,35,43] mental spatial transformation,[25] visual memory recall,[38,42] and motion sickness,[5,9,36] few have addressed the applicability of GVS as an analog to induce SD. As an early attempt to induce SD, Malcik[29] applied bilateral-bipolar GVS signals, with an amplitude of 3 mA and a duration of 30 s, to 350 pilots who performed a series of ascents and descents during instrument flight. All pilots reported sensations of tilting and turning, which they judged to be similar to the sensations expected during real flight. In another study, Moore et al.[31] used bilateral bipolar GVS in pilots while they had to perform simulated space shuttle landings. GVS was applied as an oscillating pseudorandom (i.e., sum-of-sines) waveform, leading to decrements in pilot performance during landing consistent with that observed after microgravity exposure in the NASA Shuttle program. While both studies show that GVS may compromise vestibular sensations and affect flight performance in a simulator, the induced stimuli were non-physiological and were not coupled to either the motion of the aircraft or the actions of the pilots. As such, these general GVS signals seem inadequate to mimic vestibular illusions produced by specific aircraft motions.

In the current study, we evaluate the capability for bilateral-bipolar GVS to mimic a flight-specific SD event, namely the "post-roll illusion". This false sensation of roll motion is related to the decay in semicircular canal signals of motion that occur during prolonged periods of roll. When the rotation is abruptly stopped, an illusory roll motion opposite to the preceding aircraft roll is evoked and often triggers pilots to make erroneous counter-roll motions despite the aircraft being level.[11,33] We hypothesized that a GVS stimulus designed to mimic the vestibular post-roll effect would consistently induce erroneous counter-roll inputs similar to the response to real motion. In a survey among 368 military pilots, the post-roll illusion was in the top 10 of most frequently reported SD events, experienced by 48% of all respondents. As such, it would be valuable if this illusion could be reproduced with GVS in a ground-based set-up in SD awareness programs. With this application in mind, we chose not to fixate the subjects' head, allowing them to look freely around, similar to normal flight simulation conditions.

METHODS

Subjects

The study protocol was approved in advance by TNO's review board (reference: 2019-091). Each subject provided written informed consent before participating. Inclusion criteria for subjects included: being 18–45 yr old; not being pregnant; not being sensitive to motion sickness; and not having any health issues (cardiovascular, neurological or psychiatric, chronic headache or migraine, or vestibular). There were 14 nonpilot subjects (9 women, 5 men) between 19–41 yr old (mean = 24 yr, SD = 6 yr) recruited, and each received a monetary compensation for their time and travel costs. Two subjects did not complete the "post-roll test" phase of the experiment due to complaints about discomfort behind the ears caused by GVS. In the analysis of this phase of the experiment, data from only 12 subjects are used.

Equipment

The study was performed in the Advanced Spatial Disorientation (manufactured by AMST, Ranshofen, Austria) simulator at TNO. Although this is a moving base flight simulator, the simulator was operated in fixed-base mode for most of the experiment, using only the out-the-window visual system and the flight controls. The simulator motion was activated only during the familiarization phase of the experiment.

Electrical vestibular stimulation was delivered using carbon rubber electrodes coated with Spectra 360 electrode gel (Parker Laboratories, Fairfield, NJ, United States). Electrodes were placed over the mastoid processes on either side of the head with tape and a headcap. We used a binaural-bipolar configuration to modulate the firing rate of vestibular afferents in our participants.[20,22,24] In this arrangement, the stimulus evokes a perception of head-roll velocity[35] with a craniocentric sensation centered on an axis tilted 17–19° posteriorly and superiorly relative to Reid's plane.[8,13] This net signal of virtual rotation is estimated based on the responses of afferent populations within the labyrinth, assuming that both canal and otolith afferents respond to the electrical stimulus.[15,24] The expectation of a minimal signal related to translation was based on the near symmetry of otolith afferents across the macular striola of the utricles.[41] To minimize cutaneous cues of GVS, we applied an anesthetizing skin cream [Lidocaine ($25\,mg \cdot g^{-1}$) and Prilocaine ($25\,mg \cdot g^{-1}$), TEVA, Haarlem, Netherlands] on the skin 30 min prior to the experimental phase. The stimuli were delivered as analog signals via a data acquisition board (Labjack T4, LJTick-DAC, Lakewood, CO, United States) to an isolated constant current stimulator (STMISOLA, Biopac Systems Inc, Goletta, CA, United States). Using hardware and software measures, the maximum output current was limited to ±5 mA.

The electrical stimulus was coupled to the roll motion of the simulated aircraft. It was designed to mimic the dynamics of the semicircular canals for roll motion, represented by a first-order high-pass filter with a time constant (τ) of 5 s, based on a study by Fernandez and Goldberg.[12] The relationship between current (I) and simulated aircraft roll motion (ω_{ac}) is given by:

$$I = K_i \cdot G \cdot \frac{\tau s}{\tau s + 1} \cdot \omega_{ac}$$

where *s* is the complex frequency in the *s*-domain (Laplace transform). *G* is a gain factor to map roll rates to electrical currents and was set to $5/30 = 0.167\,mA/(° \cdot s^{-1})$, based on a maximum current of 5 mA, and simulated aircraft turns with a maximum roll rate of $30° \cdot s^{-1}$. Note, however, that the manually flown maneuvers (see Procedure) could exceed this maximum roll rate, resulting in saturated GVS stimuli. We further note that although more advanced transfer functions replicating the dynamics of canal afferent responses to GVS were available,[24] we chose to implement the more straightforward transfer function as the difference between these two were minimal over the movement frequencies tested here. K_i is the gain to explore the effect of stimulus intensity in the motion perception phase as described below (in the test phase, a fixed gain of $K_i = 1$ was used). The direction of stimulation was such that the assumed sensation is in the same direction as the physical motion of the simulator.

Procedure and Design

After explanation of the experimental procedures, the subject signed an informed consent. Subsequently, the experimenter applied a small amount of anesthetizing skin cream to the left and right mastoid of the subject. In the 20 min needed to fully absorb the cream, the subject was seated in the flight simulator to get familiarized with the flight controls and task. As part of this simulator familiarization period, the subject was exposed to a predefined set of roll maneuvers using the outside visuals and the instruments. The subject also practiced stabilizing the aircraft and maintaining attitude after the operator had ended the roll motion and gave the voice command "you have control." Throughout this familiarization phase, the simulator's motion platform was active to allow subjects to experience natural physical motion feedback during simulated flight. The motion cues were generated by the stimulator's standard built-in motion-cueing algorithm.

Following the simulator familiarization period, the subject stepped out of the simulator and the GVS electrodes were applied on the left and right mastoid. Subjects then returned to the simulator and underwent a second familiarization period to expose them to GVS without administering any flight procedure. This GVS stimulus consisted of a 0.2-Hz sine wave signal that varied in intensity from 2.5–5 mA. When the subject agreed to continue, and no unnecessary discomfort was experienced, the experimental trials were carried out in two successive phases. Note, during these subsequent phases, the simulator remained stationary at all times.

First, in the "motion perception" phase, we investigated the subjects' motion perception during sinusoidal aircraft roll motions, with a maximum roll rate of $30° \cdot s^{-1}$, a frequency of 0.2 Hz, and a total duration of 10 s (i.e., two cycles). The purpose of this phase was to familiarize subjects with GVS, and to get more insight into the provoked sensations in a more controlled manner than in the next phase. The aircraft was flown manually by the simulator operator, and the participants were asked to judge how well the whole-body motion sensation delivered through GVS matched the visual motion observed in the outside view, a scenery of a typical daytime Dutch landscape. In five separate GVS conditions, the gain K_i of the GVS signal (parameter in the equation above) was varied between 0, 0.5, 0.75, and 1 to investigate the effect of GVS stimulus magnitude on the motion sensation. One condition with a negative GVS gain of −0.5 was added to investigate whether a reversed current would diminish the subject's perception of how well the GVS-evoked sensations of motion matched the visual cues of motion. All conditions were presented in random order and without simulator motion.

After each GVS condition, the subjects answered the following questions on an 11-point scale (0 = not at all; 10 = completely):

a) How well could you feel the GVS-induced roll sensation? This will be referred to as "motion intensity".
b) How well did the magnitude of the GVS-induced whole-body roll sensation match the magnitude of the visual motion?
c) How well did the direction of the GVS-induced whole-body roll sensation match the direction of the visual stimulus?
d) How uncomfortable did you find the GVS stimulus?

Next, in the "post-roll test" phase, the subjects were exposed to prolonged roll angle changes with a sudden stop. Because the simulator was stationary during this period and the GVS-coupled stimulus delivers primarily a sensation of head roll, we considered these conditions as analogous to the roll stimulus applied to supine participants in a previous simulator study.[33] Each maneuver was flown manually by an experienced simulator operator, at one of two different magnitudes: a "small roll maneuver" with an intended roll angle change of 40° (starting at 20° roll tilt in one direction to 20° roll tilt in the other direction), or a "large roll maneuver" with an intended roll angle change of 90° (from 45° roll tilt in one direction to 45° roll tilt in the other direction). The simulator operator tried to perform each maneuver in 5 s, so that these two magnitudes theoretically corresponded to average roll rates of $8° \cdot s^{-1}$, and $18° \cdot s^{-1}$, respectively. Both roll magnitudes were presented during leftward and rightward maneuvers, resulting in four test conditions. All test conditions were presented without simulator motion, without instruments, and without outside visual references (as if flying in dense fog). Although the cockpit lights were dimmed, the reflection of the outside visual display made it possible to vaguely see the cockpit interior. Each condition was performed once, and the order of conditions was randomized between subjects. The subjects' task was to take over the control at the end of each maneuver (upon a voice command after both the small and large roll maneuver), and to keep the aircraft's orientation constant (that is, a constant roll angle) by moving the control stick left and right. Our hypothesis was that the GVS stimulus would produce an erroneous sensation of roll rate resulting in an overshoot of roll angle when subjects regained control.

Both after the motion perception phase and post-roll test phase, subjects were asked to rate possible discomforts. Furthermore, subjects were instructed to report any symptoms of motion sickness immediately to the experiment leader.

Three individuals reported some minor motion sickness symptoms of dizziness. For one of these individuals, the experiment was paused for 15 min after reports of nausea. The complete study took about 105 min for each subject. Subjects performed the study at varying times of the day throughout the morning or afternoon.

We first simulated the predicted outcome by passing an artificial roll signal through the GVS transfer function (upper panel of **Fig. 1**). In the period prior to $t = 0$, a subject experiences an imposed motion by the operator, and, after $t = 0$, the subject takes over control. As shown in the middle panel of Fig. 1, the GVS stimulus peaks at the roll onset but quickly begins to decay. After 5 s of sustained roll the GVS signal is about half the peak response at roll onset, such that stopping the roll maneuver (at $t = 0$ s) results in a GVS signal of reversed sign, i.e., the post-roll effect. The simulation at $t = 1$ s represents a control input to counter this GVS-induced post-roll effect. Because this roll input is in the same direction as the preceding roll maneuver, it results in an overshot of bank angle, as is shown in the lower panel of Fig. 1.

Statistical Analysis

To analyze the subjective responses in the motion perception phase, Kruskal-Wallis tests (a nonparametric variant of a one-way analysis of variance, because the variables were not normally distributed) and nonparametric post hoc tests were used. We tested whether there was a main effect of GVS gain on the subjects' perception of whole-body motion and performed post hoc tests (Wilcoxon signed-rank tests, corrected for multiple comparisons using Bonferroni corrections) to compare results between the different gains, $K_i \neq 0$ to $K_i = 0$, and to each other. We expected that all subjective responses would be highest at the largest GVS gain. A planned comparison of the negative GVS gain (i.e., $K_i = -0.5$) was made to the equivalent positive GVS gain (i.e., $K_i = 0.5$).

The dependent variable in the post-roll test phase, designated "roll response", was computed as the change in roll angle 3 s (t = 3 s) after the moment at which the subject was given control ($t = 0$ s), i.e., the roll angle at $t = 3$ s minus the roll angle at $t = 0$ s. This analysis window was chosen because most subjects produced a response within this period when given control. Subsequently, this response was categorized as one of three types of behavior: 1) a response in the same direction as the preceding roll motion, corresponding to a post-roll effect; 2) a response in the opposite direction; and 3) a neutral response, with no noticeable response at all or a change in roll angle smaller than 6° (corresponding to a mean roll rate of $2° \cdot s^{-1}$). For both roll maneuvers, the percentage of roll responses within each category was computed.

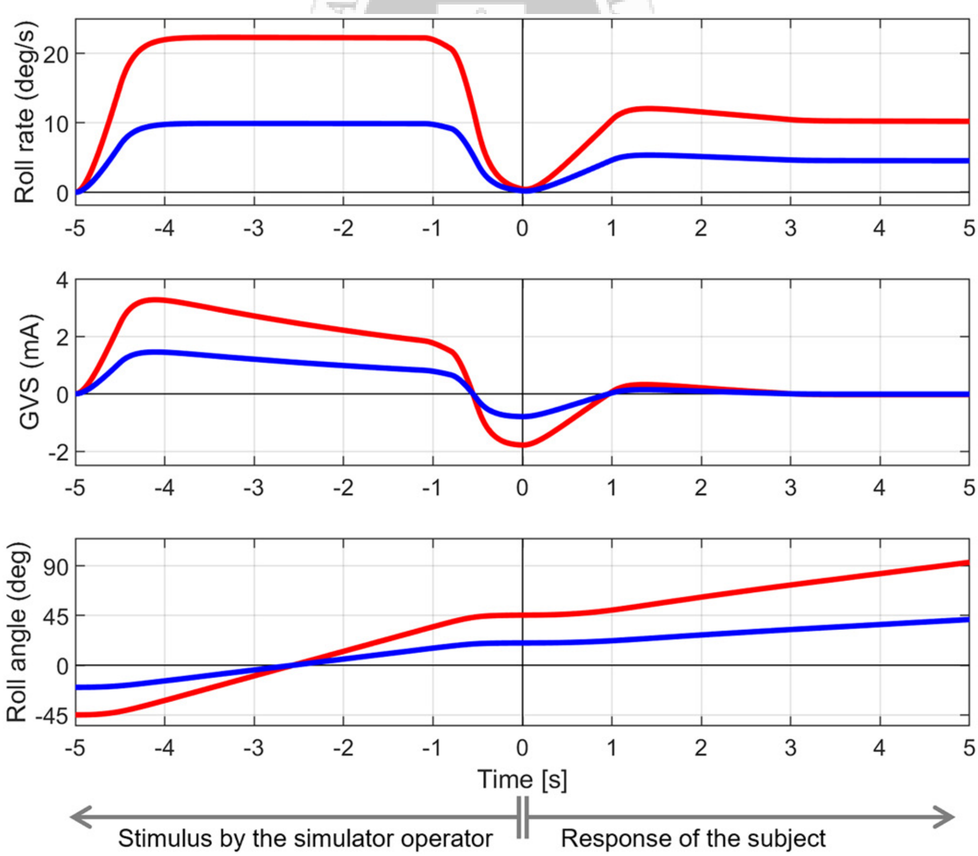

Fig. 1. Artificial stimulus by the simulator operator (the period up to time = 0, indicated as "Stimulus by the simulator operator") and subject response (the period after taking over control at time = 0, indicated as "Response of the subject") to a small roll maneuver (−20–20° roll tilt; blue lines) and a large roll maneuver (−45–45° roll tilt; red lines). The mimicked response illustrates what is qualitatively expected if the subject experiences a post-roll illusion. The upper panel shows the roll rates, the middle panel shows the GVS current, and the lower panel shows the roll angle.

RESULTS

Motion Perception Phase

We first examined the subjects' ratings on the four aspects of the motion sensation induced by the GVS stimulus in the motion perception phase (see **Fig. 2**). The Kruskal-Wallis test showed a main effect of GVS gain on the perceived intensity of the motion sensation ($H(4) = 20.46$, $P < 0.001$; see Fig. 2A). The post hoc test revealed that relative to the control condition (i.e., $K_i = 0$: median = 2.5), the perceived intensity was significantly larger for only the two high-gain GVS conditions ($K_i = 0.75$: median = 6.0, $Z = 2.77$, $P = 0.014$; and $K_i = 1.0$: median = 7.0, $Z = 3.22$, $P < 0.001$). Furthermore, the perceived intensities of motion sensation across all conditions with GVS (i.e., $K_i > 0$) were not significantly different from one another (all $Z < 2.20$, $P > 0.05$). The effect of GVS gain on the match of perceived whole-body motion magnitude with visual motion was also significant ($H(4) = 16.62$, $P = 0.004$). According to the post hoc test, only the two high-gain GVS conditions ($K_i = 0.75$: median = 6.5; and $K_i = 1.0$: median = 7.5) were significantly different, and, thus, better matched in magnitude to the visual motion when compared to the control condition ($K_i = 0$: median = 3.0) ($Z = 3.09$, $P = 0.031$; $Z = -3.09$, $P = 0.003$, respectively). This means that for these two gains ($K_i = 0.75$ and $K_i = 1.0$), the GVS produces the closest sensation to that of real (visually perceived) motion. However, the comparison of perceived match in magnitude to visual motion across all GVS conditions ($K_i > 0$) showed no difference between each other (all $Z < 2.05$, $P > 0.05$). We further found no significant main effect of GVS gain on the perceived match between the direction of the sensed motion and the direction of the visual motion ($H(4) = 3.75$, $P = 0.441$). Surprisingly, when we compared the condition with a negative gain ($K_i = -0.5$) with that of a positive gain ($K_i = 0.5$), there were no significant differences in perceived intensity of the motion sensation ($Z = 1.52$, $P = 0.129$) or the matching of whole-body motion magnitude or direction with the visual motion as compared to equivalent positive GVS gain (magnitude: $Z = 1.08$, $P = 0.280$; direction: $Z = 0.41$, $P = 0.682$). Finally, there was a main effect of GVS gain on the discomfort ratings ($H(4) = 34.65$, $P < 0.001$), where stronger GVS stimuli gave more discomfort. Similar to all other measures, we found no difference in discomfort ratings between the positive and negative GVS gain conditions ($Z = 0.07$, $P = 0.942$).

Post-Roll Test

Inspection of the simulated aircraft roll motions showed considerable variability in the test maneuvers flown by the simulator operator in the post-roll test phase. On average, the small roll maneuver with an intended roll change of 40° and roll rate of $8° \cdot s^{-1}$ was performed with a roll change of 47.6° (±4.6°), a roll rate of $13.2° \cdot s^{-1}$ ($\pm 2.1° \cdot s^{-1}$), and a duration of 3.71 s (±0.68). The large roll maneuver with an intended roll change of 90° and a roll rate of $18° \cdot s^{-1}$ was performed with a mean change of 127.8° (±11.2°), a roll rate of $26.1° \cdot s^{-1}$ ($\pm 4.7° \cdot s^{-1}$), and a duration of 5.33 s (±1.00).

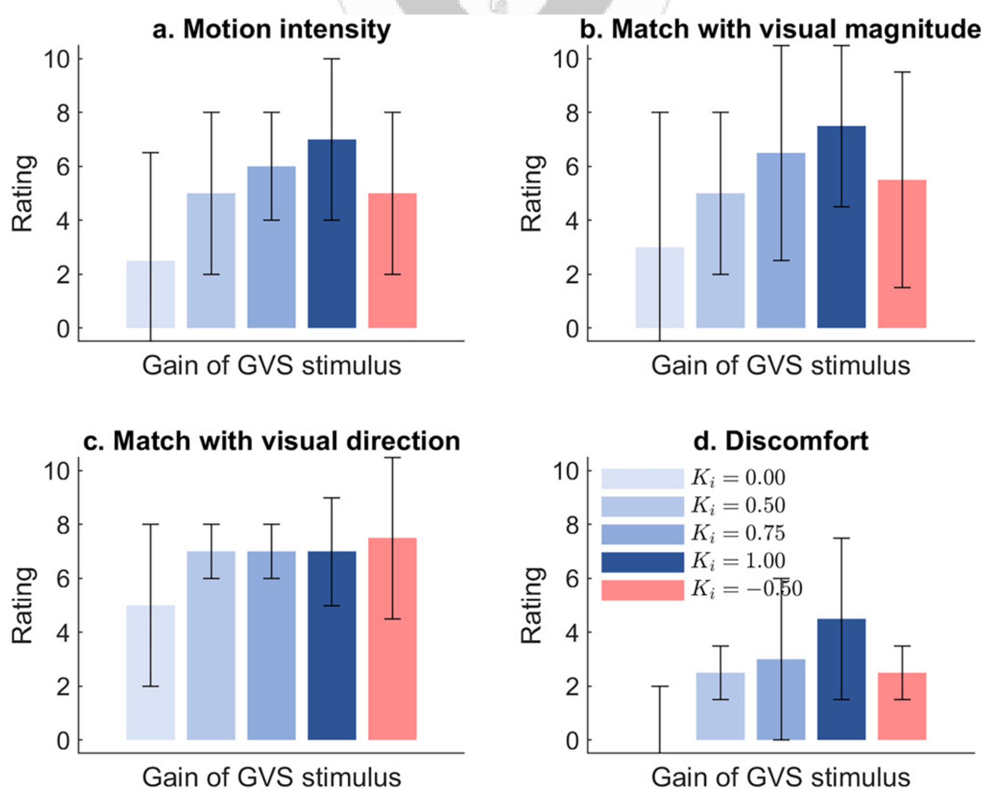

Fig. 2. Median and interquartile range of the subjective ratings on four aspects in the motion perception phase as function of gain K_i. (In Panel D, there is no bar for the condition with gain = 0 because the median discomfort is zero.)

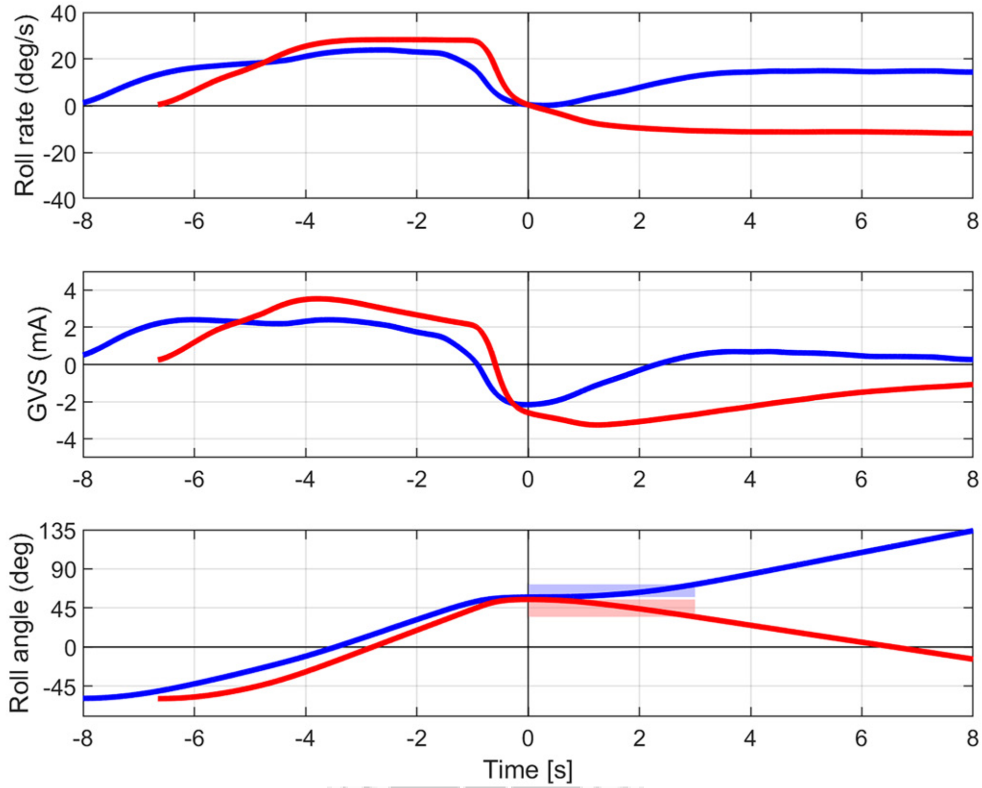

Fig. 3. Two example trials in the post-roll test phase for large roll maneuvers. Test maneuver and subject response are shown for a large rightward (red lines) and leftward (blue lines) maneuver for one subject. The leftward signals are inverted to overlay the graphs. The upper, middle, and lower panels show the roll rate, GVS current, and roll angle, respectively. At time = 0, the subject took over control from the simulator operator. The colored patches indicate the roll-angle change 3 s after taking over.

Fig. 3 shows two examples of an individual response to a large roll maneuver (a rightward maneuver shown in red and a leftward maneuver shown in blue and inverted for easier comparison). Roll rate, GVS current, and roll angle are shown in separate panels. The moment that the simulator operator handed control over to the subject is represented by $t = 0$. After this hand-over, the subject had to keep the aircraft's orientation constant, based solely on the motion sensation induced by the GVS stimulus. One can see that the GVS current slightly decays during the operator-controlled roll maneuver ($t < 0$ s). At the end of the maneuver, when the subject takes over control (at $t = 0$ s), the GVS current overshoots (to −2.2 mA and −2.6 mA in these two examples) in the opposite direction. Averaged over all subjects, the GVS level at the onset of the subject taking control amounted to −1.24 mA (±0.14 mA) for the small roll maneuvers and −2.87 mA (±0.53 mA) for the large roll maneuvers. In the blue example in Fig. 3, the stimulus resulted in a continued roll input to the right, which is in accordance with the predicted post-roll effect. In the red example, however, the subject's response was in the opposite direction from the preceding roll maneuver, meaning opposite the expected direction for a post-roll effect. Furthermore, in 25% of the trials, we also observed that the subject's steering control led to clipping of the GVS signal to the safety limit of 5 mA, though this was not the case for the two examples in Fig. 3. This clipping primarily took place after longer durations of control input by the subject, outside the analysis window of 3 s.

Fig. 4 plots the individual roll responses relative to the GVS current at the moment of control handover for all subjects. Responses with a negative GVS current at onset were rightward maneuvers, while responses with a positive GVS current were leftward maneuvers. The GVS current values corresponding to small roll maneuvers (gray circles) and large roll maneuvers (black squares) cluster around ±1 mA and ±3 mA, respectively, with some scatter on account of the manual operation by the simulator operator. The change in roll angle shows large variability across subjects, especially for the large maneuvers, and the responses are uncorrelated with the GVS stimulus (Pearson correlation for all trials pooled is −0.0163; small roll maneuvers only −0.0403; large roll maneuvers only −0.0146). For the small roll maneuver, only 13% of the responses were in the post-roll direction (responses in upper left and lower right quadrant), 33% were in the opposite direction (responses in upper right or lower left quadrants), and 54% of the responses showed no noticeable response at all (responses in the horizontal band). For the large roll maneuver, these percentages were 33%, 46%, and 21%, respectively. These results indicate that a larger roll maneuver induced a larger number of trials containing a post-roll effect compared to the smaller roll maneuver, but the majority of responses in both maneuvers did not show a post-roll effect.

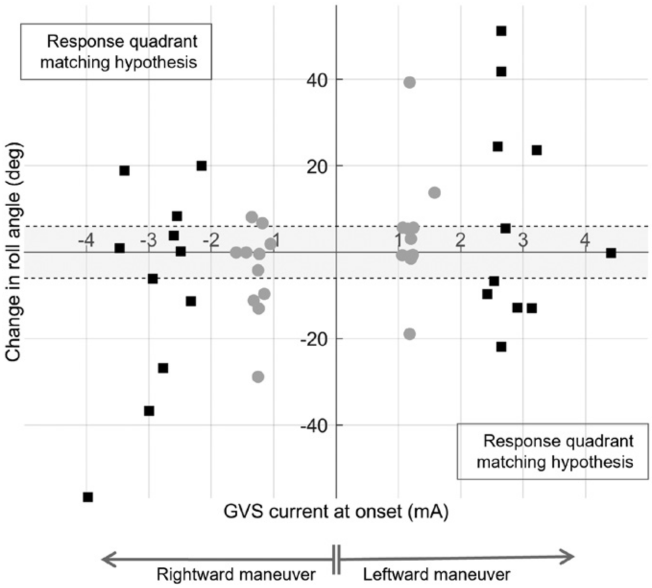

Fig. 4. Scatterplot of roll responses (change in roll angle (°) after 3 s) plotted relative to the imposed stimulus (GVS current (mA) at onset) for small (gray circles) and large (black squares) roll maneuvers. Four trials (two small and two large maneuvers) with extreme responses (>80°) were omitted for visual clarity. The horizontal band depicts the classification criterion of 6° change in roll angle.

DISCUSSION

In this study, we attempted to induce a post-roll effect in a fixed-base simulator using a GVS stimulus that was designed to approximate the first-order response of the semicircular canals to the deceleration of a prolonged roll maneuver. Our aim was to mimic normal flight simulation conditions; therefore, we did not control for head movements or lighting conditions, as is often the case with perception-based GVS research. Under these conditions, however, we observed evidence of post-roll illusions in only 13% of the responses to the small roll maneuver, and only 33% of the responses to the large roll maneuver. Overall, our results demonstrate poor reliability in evoking post-roll illusions using simulation-coupled GVS during normal fixed-base flight simulation conditions, as well as that additional experimental control may be needed to achieve this aim.

Even in the large roll maneuver, almost 50% of the subjects gave a control input in a direction opposite to the predicted post-roll effect (see Fig. 3, red trace). One explanation for this is that the GVS setup used here did not induce a pure sense of roll rotation as intended,[21] thereby masking the intended effects of a sustained roll. Specifically, in the heads-up position chosen for this experiment, bilateral-bipolar GVS evokes sensations of lateral acceleration in the direction opposite to the anode (i.e., in the same direction as the evoked head roll)[21] and is predicted to be slightly out of phase with the primary sensation of roll rotation.[21] This linear acceleration arises when the net GVS-evoked sensation of pure roll is orthogonal to gravity. The brain infers a sensation of linear motion that arises through the integration of otolith and canal inputs and an internal model of gravity.[1,4,30] Another contributing factor may be that since the subjects were free to move their heads during our experiment, they perceived only the direction of their compensatory head-neck movements as opposed to the intended virtual signal of head motion.[10] Wardman et al.[43] showed that when standing subjects are free to balance, they only perceive their motion in the direction of the evoked balance response, but when fixed upright, subjects perceive the expected direction of the GVS-evoked head roll.[8,21,35] These two potentially confounding motion sensations in our experiment may explain why the reversed GVS signal did not result in lower ratings for the perceived match between the direction of the GVS-induced motion and the observed visual motion. More consistent roll sensations may be achieved with the subject's head oriented with the GVS-evoked roll signal parallel to gravity and also fixed against a head rest. This, however, is not representative of how pilots orient and move their head during flight simulator training.

In 54% of the small-roll trials, and 21% of the large-roll trials, no control input was observed at all (see Fig. 4). This may indicate that the GVS stimulus was too small to produce a distinct roll sensation. The results of the motion perception phase showed that, for a sinusoidal GVS signal, the motion intensity ratings increased with GVS amplitude, where a GVS signal of 5 mA was rated a 6.5 out of 10 on an 11-point perception scale (see Fig. 2). However, in the post-roll phase, we noted that the GVS signal at the moment of control handover often did not reach the intended 5 mA. In the small roll maneuver, the GVS signal varied close to ±1 mA, and in the large roll maneuver, this value was ±3 mA. Because the driving function of the GVS signal was based on the physiological (high-pass filter) characteristics of the semicircular canals,[12] the signal decayed with a time constant of 5 s. The small initial magnitude of the post-roll GVS signal, together with the decay, may have diminished the intended perceptual effect of GVS. A contributing factor to this may be that the manually flown roll maneuvers made the stimulus less controllable and resulted in inconsistent roll rates. Because of the large inaccuracy in stimulus maneuver, it would have been better to replay a recorded maneuver or a computer-generated profile. There was a technical reason why we did not do this: although the simulator offers a mode to replay preprogrammed flight maneuvers, that mode does not allow for control handover to the subject in the simulator cabin. In manual control mode, flight control can be easily transferred from the instructor to the subject.

The motion-perception phase of this study also had several limitations. First, there may be a confounding factor of vection induced by the visual stimulus. Although subjects were asked to focus on the GVS-evoked motion sensation, it may be difficult to separate this from any visually evoked sensations of motion. This explains why there was a nonzero report of motion sensation intensity in the no GVS ($K_i = 0$) condition (see Fig. 2). Furthermore, subjects also indicated a match between the GVS-evoked and visually evoked motion directions in the non-GVS condition. This may again be because the immersive visual environment induced vection and thus some sense of real motion. Second, GVS evokes ocular torsion that could influence visual cues,[2,28,44] which may differ in phase from the GVS-induced motion sensation, for which we did not account. Third, subjects had to compare GVS trials with a reference motion. Prior to the GVS conditions, a reference condition without GVS stimulation but with simulator motion was presented. Although this was only to help the subjects understand the task of comparing their motion sensation with the roll motion observed in the outside visual, it is not unlikely that subjects were able to remember this trial by the end of all GVS trials. Finally, another aspect that should be considered when using GVS in pilot training is the potential discomfort induced by the electrical stimulus behind the ears. Despite applying anesthetizing skin cream, two of our subjects had to withdraw from the study due to experienced discomfort. The use of a stronger anesthetic may prevent this.

Two previous simulator studies showed that GVS stimuli of similar magnitude (3 mA and 5 mA), but longer duration, consistently disturbed pilots' control behavior.[29,31] The GVS signals lasted 30 s[29] and 100 s,[31] and they affected control inputs in a general, nondirectional way. This nondirectional approach may be educational in demonstrating the general effects of artificial sensations of motion (sometimes referred to as "vertigo"), but it is by design incapable of demonstrating specific vestibular SD illusions, such as the post-roll effect. A study by Kim et al.[23] provides evidence that GVS, with a current of 2 mA for 2 s, including slow ramp-up and slow down time, can be used to overcome (rather than induce) a vestibular illusion. Our aim was not to use GVS to cancel the sensation induced by a vestibular illusion, but to induce the illusion itself. The findings of the current study highlight the many challenges in using GVS to induce specific (post-roll) illusions, which make it difficult to achieve the level of control required to induce them within a free-flight simulator environment.

ACKNOWLEDGMENTS

This research was funded by the Dutch Ministry of Defense, under Research Program V1917 "5thGenStressors".

Financial Disclosure Statement: The authors have no competing interests to declare.

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