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Visual Effects on the Subjective Visual Vertical and Subjective Postural Head Vertical During Static Roll-Tilt

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Objectives: Tilt perception is part of the perception of spatial orientation. It is determined not only by the allocentric gravity axis, but also by a second allocentric axis induced by visual information as well as by the egocentric body (head) axis induced by somatosensory information. The aim of this study was to quantify roll-tilt perception using the subjective visual vertical (SVV) and the newly developed subjective postural head vertical (SPHV) and to investigate the visual effects on both during static roll-tilt.

Study Design: Basic science

Methods: Nine male volunteers participated in this study. A flight simulator was used to create several roll-tilt environments that were then combined with visual information. SVV and SPHV were evaluated in healthy participants during static roll-tilt.

Results: The SVV evaluation revealed significant differences between the dark condition (control) and other visual conditions with respect to some of the body roll-tilt environments, and between a body roll-tilt of 0° and $\geq 20°$. The SPHV evaluation revealed a significant difference between the dark condition and the visual condition that was always roll-tilted 20° to the right of the body axis. However, there were no significant differences in SPHV error between a body roll-tilt of 0° and other tilt angles for every visual condition, unlike SVV error.

Conclusions: Our data indicate that human susceptibility to spatial disorientation is dependent on roll-tilt angle and visual information. They also suggest that the SPHV is not affected by roll-tilt angle, and thus differs from SVV.

Key Words: roll-tilt, subjective postural head vertical, subjective visual vertical, visual information, spatial disorientation.

Level of Evidence: NA

INTRODUCTION

In human perception, an image of the body and the space around it is subconsciously reproduced in the brain. This image maintains the inner spatial axes of direction, position, size, shape, distance, and motion both at rest and during motion in relation to space.[1,2] This function of reproducing the surrounding space in the brain, or the image of space, is called spatial orientation, and results from the integration of multiple sensory inputs from the visual, vestibular, and somatosensory systems in the brain.[3,4]

Tilt perception is the sensorimotor system's internal measure of how much the body (or head) is tilted from the vertical axis, which serves as a reference. On the ground, the gravity axis is absolutely vertical and constitutes an allocentric (earth-centric) axis.[5,6] Gravity and tilt are perceived by the otolith organs, including the saccule and utricle. However, tilt perception is determined not only by this vestibular-information-induced gravity axis but also by an allocentric axis induced by visual information, and by an egocentric (head-centric) body axis induced by somatosensory information.[5,6] Spatial orientation, including tilt perception, thus relies on the gravity axis, the visual environment axis, and the body (head) axis. These axes usually work complementarily and in collaboration. However, if any of the axes are absent or non-functional, spatial disorientation and balance disorders occur.

Tilt perception is evaluated using the subjective visual vertical (SVV), both in clinical practice and in neurotological research.[7–10] In SVV evaluation, a visible line is adjusted to align with the perceived direction of gravity.[3] The subject's roll-tilt perception can be assessed based on the error between the actual gravity axis and the value of the SVV. However, in space, where there is no gravity, it is difficult to evaluate tilt perception using the SVV, as it is based on the gravity axis.

To enable the assessment of roll-tilt perception in different gravitational environments, including zero gravity, we developed a novel method, the subjective postural head vertical (SPHV), that can be used to quantify roll-tilt perception by measuring the subjective head (body) axis.[11] In other words, while the SVV measures

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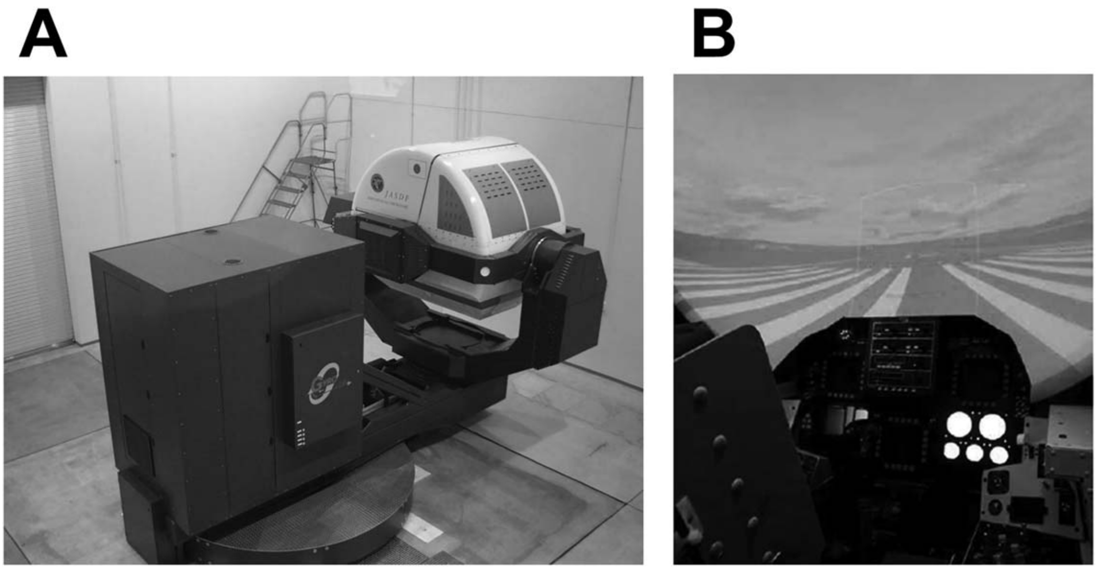

Fig. 1. Device used to produce a variety of tilt environments with visual stimulation. (A) GYROLAB GL-4000 flight simulator. (B) Inside the cockpit. The images were projected onto a screen in front of the participants.

the allocentric gravity axis via vestibular inputs, the SPHV measures the egocentric (head-centric) body axis via somatosensory inputs. Because the reference axes differ between the SVV and the SPHV, we hypothesized that they would differ with respect to the magnitude of the effect of visual information. Thus, the aim of this study was to quantify roll-tilt perception using the SVV and SPHV, then investigate both the effect of vision as well as the differences between these two methods in a static roll-tilt test.

METHODS

Participants

Nine healthy right-handed non-pilot male volunteers age 22–49 years (mean, 33.1 years) participated in this study after providing informed consent. None of the participants had any previous medical history relating to eye diseases, ear diseases, or equilibrium disorders. Before the experiment, all participants were interviewed about their physical and emotional condition. None were determined to have any abnormal health conditions and were not sleepy, hungry, or thirsty. The protocol was approved by the Nara Medical University's Committee for Ethics (notification no. 356). All experimental procedures were performed in accordance with the Declaration of Helsinki.

Device for Visual and Static Roll-Tilt Stimuli

The flight simulator GYROLAB GL-4000 (Environmental Tectonics Corporation, Southampton, PA), located at the Aeromedical Laboratory, Japan Air Self-Defense Force, was used in this study to produce a variety of tilt environments via visual stimulation. The cockpit of this flight training device has degrees of freedom on four axes: the planetary (3.05-m radius), pitch, roll, and yaw axes (Fig. 1A). In the cockpit, a projector is used to present both animated and still images on a screen (120° × 70° field of view) positioned 0.9 m in front of the participant (Fig. 1B). The head position of each participant was monitored in real time through a charge-coupled device (CCD) camera mounted in the cockpit. Communication with participants during the experiments was maintained via headsets.

Visual and Roll-Tilt Stimulation

The participants were shown four types of still images: 1) a dark image (control), 2) an image that was always roll-tilted 20° to the left of the body axis (vL20), 3) an image that was always parallel to the body axis (v0), and 4) an image that was always roll-tilted 20° to the right of the body axis (vR20). Additionally, the cockpit was inclined (angular velocity 1.00°/s) 1) 0°, 2) −10°, 3) −20°, and 4) −30°. Thus, 16 types of static stimuli, the products of four types of visual information and four types of roll-tilt, were presented to the nine study participants (Fig. 2). The rightward direction was defined as positive, and the leftward direction as negative.

Evaluation of the SVV

All nine participants were tested as follows: The participant was fastened into their seat with a five-point seatbelt. The participant's head and neck were also fixed to the seat with a custom-made head fixation device and a neck collar (Laerdal Medical Japan, Tokyo, Japan; Fig. 3A). During the experiment, the lights in the cockpit were turned off. In addition, the participant wore goggles that limited the binocular field of view 36° to the left and right and 28° up and down, so that they could not see the frame of the screen.

In addition to still images for visual stimulation (Fig. 2), during SVV evaluation the participant was shown a bar on the screen and then asked to make it parallel with the direction of the gravity axis using a keyboard. During all experiments, communication with the participant was maintained via headsets, with real-time monitoring carried out using a CCD camera, as described above.

Except during the SVV evaluation, the participant was instructed to keep their eyes closed. One minute after the cockpit was roll-tilted to the designated angle then held motionless, the disappearance of the subjective rotation sense of the participant was confirmed. The SVV bar was then set at a random

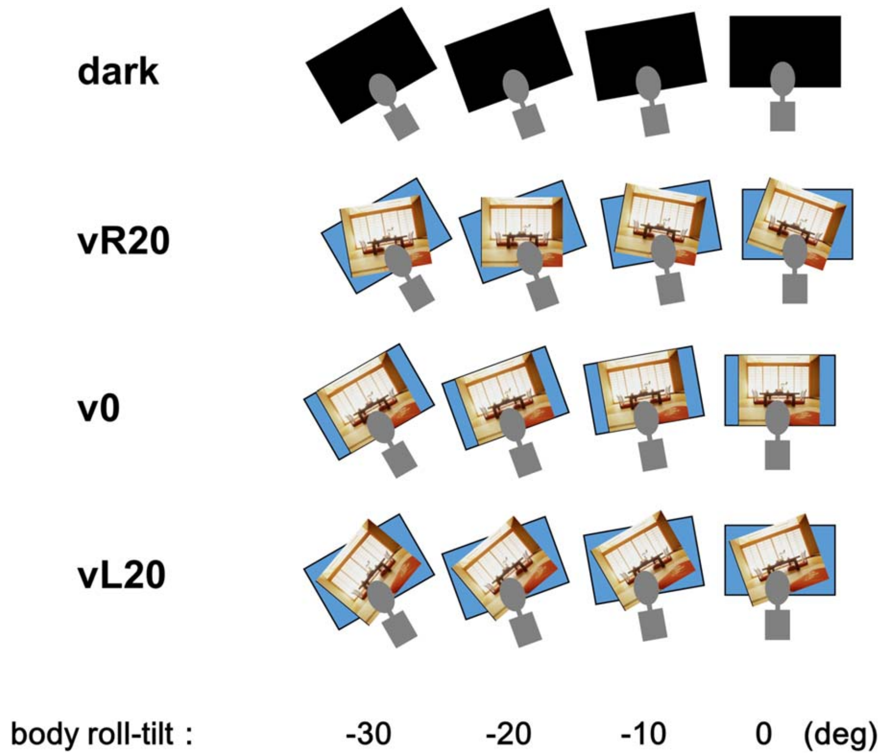

Fig. 2. Visual and roll-tilt stimulation. Participants were presented with 16 types of static stimuli, resulting from a combination of four types of visual information and four types of roll-tilt.

angle, after which the participant was asked to open their eyes and operate the SVV bar to perform the SVV evaluation The SVV error, defined as the difference between the correct gravity axis and the gravity axis reported by the participant, was then evaluated. The error in the SVV was measured three times for each stimulation and the mean value was calculated. The stimulations were separated by 30-second intervals, during which time the participant was instructed to close their eyes. The SVV bar was then set to a random angle as described above (Fig. 4A).

Evaluation of the SPHV

All nine participants were tested as follows: The participant was fastened into the seat with a five-point seatbelt. However, the head was not fixed in place but was instead aligned with the headrest of the seat.[11] SPHV was then evaluated under the same visual and roll-tilt conditions used in the SVV evaluation (Fig. 2). To evaluate head tilt, the participant wore a cap with a linear accelerometer (CXL04GP3; Crossbow Japan, Amagasaki, Japan; Fig. 3B). The head tilt angle was monitored and measured from the control room.

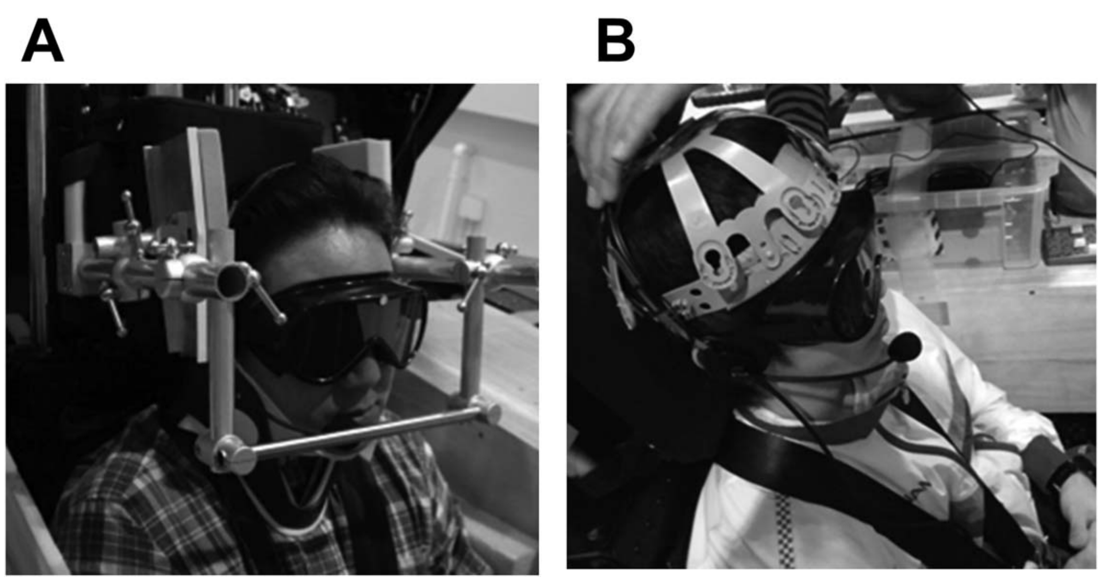

Fig. 3. Position of the participant in the cockpit. (A) During subjective visual vertical (SVV) evaluation. (B) During subjective postural head vertical (SPHV) evaluation

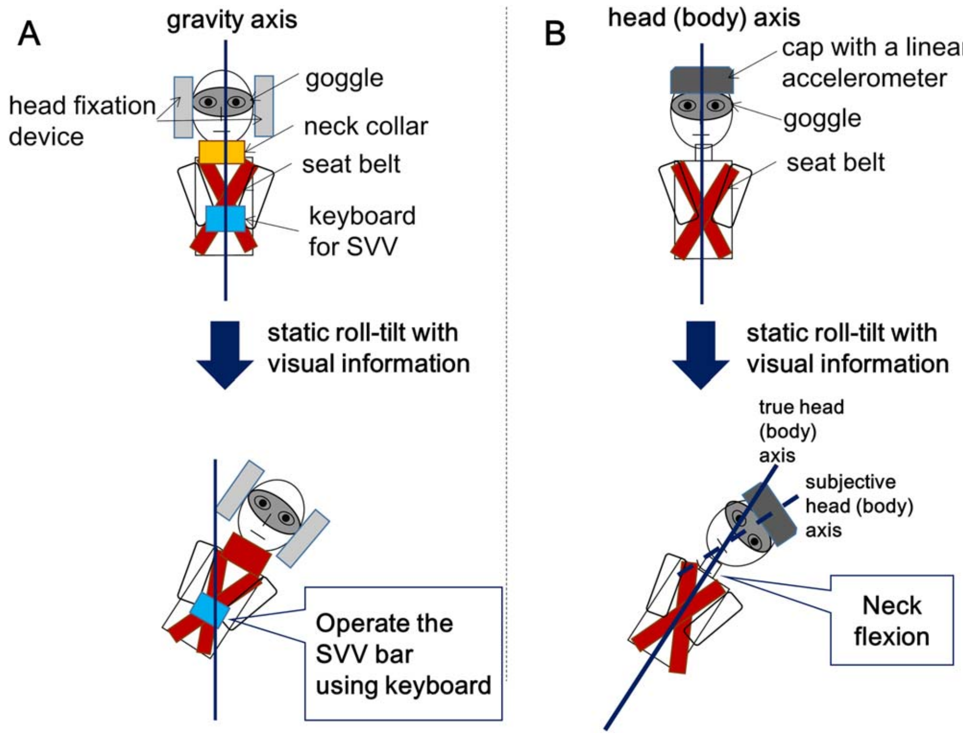

Fig. 4. Performance of the task in the cockpit. (A) During the subjective visual vertical (SVV) evaluation, the participant was fixed to the seat with a seatbelt, a head fixation device, and a neck collar. The participant also wore goggles that limited their binocular field of view. After the cockpit had been roll-tilted to the designated angle and was then motionless, the participant was asked to operate the SVV bar using the keyboard. (B) During the subjective postural head vertical (SPHV) evaluation, the participant was fixed to the seat with a seatbelt and wore a cap with a linear accelerometer. However, the head was aligned with the headrest and was not fixed in place. When the cockpit had been roll-tilted to the designated angle, the participant was directed to move the head to the position (head axis) that they thought was parallel with their body axis.

Except during the SPHV evaluation, the participant was instructed to keep their eyes closed. One minute after the cockpit was roll-tilted to the designated angle then held motionless, the disappearance of the subjective rotation sense of the participant was confirmed. The participant was then instructed to open their eyes and move their head to the position (head axis) they thought was parallel with their body axis. The error in the SPHV, defined as the difference between the correct head (body) axis and the head (body) axis reported by the participant, was then measured. The error in the SPHV was measured three times for each stimulation and the measurements used to calculate the mean value. The simulations were separated by 30-s intervals, during which time the participant was instructed to close their eyes and return to the original neck position (Fig. 4B).

Statistical Analysis

The effects of the roll-tilt angle and visual information in the SVV and SPHV were assessed with two-way analysis of variance (ANOVA). The SVV and SPHV error among roll-tilt and among visual information were compared using Dunnett's multiple comparison tests.

RESULTS

In our experiment, none of the participants reported complaints or irregularities, and none exhibited unexpected body or head movements.

Evaluation of the SVV

The SVV errors during the performance of a static roll-tilt of 0° (control), −10°, −20°, and −30° in the dark (control) were $-1.4 \pm 0.5°$, $-2.9 \pm 0.7°$, $-4.6 \pm 1.9°$, and $-3.5 \pm 2.4°$, respectively (mean ± standard error). The corresponding values during vL20 visual information were $-5.5 \pm 0.8°$, $-7.4 \pm 1.1°$, $-9.6 \pm 1.8°$, and $-9.8 \pm 3.7°$, respectively (Fig. 5).

Two-way ANOVA revealed a significant effect on visual information ($F_{(3,\ 128)} = 14.530$, $p < .0001$) and roll-tilt angle ($F_{(3,\ 128)} = 7.3531$, $p = .0001$); however, there was no interaction between the two ($p > .05$). For every roll-tilt, Dunnett's multiple comparison tests showed a significant difference between the values in the dark experiment and those during vL20 visual information ($p < .01$). Under dark conditions and during vR20, v0, and vL20 visual information, Dunnett's multiple comparison tests showed that SVV errors differed significantly between static roll-tilts at 0 and −20° (*$p < .01$), and between static roll-tilts at 0 and −30° (*$p < .01$; Fig. 5).

Evaluation of the SPHV

The SPHV standard was defined as the value obtained with the body vertical under the dark (control) condition.

The SPHV errors observed when participants performed a static roll-tilt of 0°, −10°, −20°, and −30° in the dark (control) were $0.0 \pm 0.0°$, $-1.7 \pm 1.1°$, $-2.2 \pm 2.5°$, and $-0.4 \pm 1.4°$, respectively (mean ± SE; Fig. 6). With vR20 visual information, the corresponding values were $-0.2 \pm 0.9°$, $2.8 \pm 0.9°$, $3.0 \pm 0.8°$, and $1.1 \pm 1.8°$, respectively (mean ± SE).

Two-way ANOVA revealed a significant effect on visual information ($F_{(3,\ 128)} = 2.9858$, $p = .034$); however, there was no significant effect on roll-tilt angle ($p > 0.05$) and no interaction between the two ($p > .05$). Dunnett's multiple comparison tests showed that SPHV errors

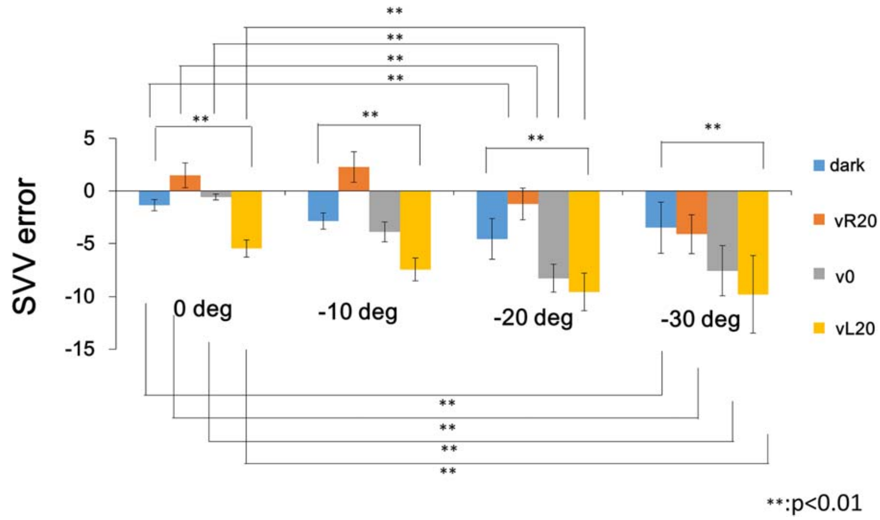

Fig. 5. The results of the SVV evaluation. Two-way ANOVA revealed a significant effect on visual information ($p < .0001$) and roll-tilt angle ($p = .0001$); however, there was no interaction between the two ($p > .05$). For every roll-tilt, Dunnett's multiple comparison test revealed significant differences between the dark and vL20 conditions for each body roll-tilt angle (*$p < .01$). For body roll-tilts of $-10°$ and $-20°$, the differences compared with 0° were also significant (*$p < .01$). Values represent the mean ± SE. ANOVA = analysis of variance; SE = standard error; SVV = subjective visual vertical.

differed significantly between the values in the dark experiment and those during vR20 visual information (*$p < .01$) (Fig. 6).

DISCUSSION

The perceived direction of gravity is influenced by the visual environment, the true direction of gravity, and the body reference. Previous studies have used SVV to investigate the relative contributions of these cue types.[12–15] In the present study, we used not only the SVV but also the SPHV to quantitatively evaluate roll-tilt perception. Other investigators have used the subjective postural vertical method to evaluate the perception of body verticality using a joystick maneuver such as the SVV.[16,17] However, the proposed SPHV method allows evaluation of the body axis easily using the participant's own head.[11] In the present study, we used this measure to investigate the correlation between the gravity axis and the visual environment axis, and between the gravity axis and the body (head) axis. To our knowledge, this is the first report of the effects of visual information on the SVV and SPHV during static roll-tilt, performed using a flight simulator.

Measuring the SVV in the dark evaluates only the gravity axis, and measuring the SPHV only evaluates the head (body) vertical axis. In the presence of a motionless image, the SVV represents the interaction of the vertical axis of the visual information with the gravity axis, and the SPHV represents the interaction of the vertical axis of visual information and the head (body) axis.

The significant differences we observed in SVV error between a body roll-tilt of 0° and ≥20° suggests that recognizing a roll-tilt of 20° or more is difficult, regardless of visual information.

During presentation of the vL20, SVV error tended to lean to the left, with significant differences between the dark and vL20 conditions for every roll-tilt angle. In addition, the error tended to increase as the roll-tilt angle increased. These results suggest that vL20 information strongly affects the SVV, resulting in a larger error.

During presentation of the vR20, the SVV error tended to lean to the right at $< -10°$ of body roll-tilt; however, at $\geq -10°$, the SVV error tended to lean to the left (= body roll-tilt), suggesting that at $> -10°$ of body roll-tilt, otolith-induced vestibular information is used to correctly recognize the gravity axis. Previous studies reported that information from the otolith organs is ambiguous during posture recognition.[18–20] Our experimental results support these previous findings.

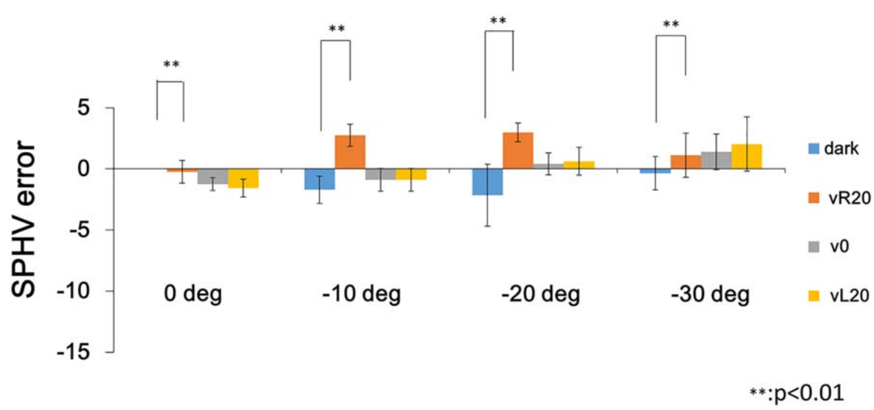

Fig. 6. The results of the SPHV evaluation. Two-way ANOVA revealed a significant effect on visual information ($p = .034$); however, there was no significant effect on roll-tilt angle ($p > .05$) and no interaction between the two ($p > .05$). Dunnett's multiple comparison test revealed significant differences between the dark and vR20 visual information conditions for each body roll-tilt angle (*$p < .01$). Values represent the mean ± SE. ANOVA = analysis of variance; SE = standard error; SPHV = subjective postural head vertical.

In the SPHV evaluation, there was a significant difference between the dark and vR20 conditions for every roll-tilt angle. However, there were no significant differences in the SPHV error between a body roll-tilt of 0° and other tilt angles in every visual condition, unlike SVV error. These results suggest that, in contrast to the SVV, the SPHV is not affected by the roll-tilt angle.

While the SVV is primarily an evaluation of the allocentric gravity axis via vestibular information, the SPHV is primarily an evaluation of the egocentric body (head) axis via cervical somatosensory information. However, if a patient has been treated for head and neck cancer by radical neck dissection and therefore does not have a sternocleidomastoid, the SPHV results would be likely to differ from those measured in a healthy person.

In addition, if our SVV results are applied to a flight situation, pilots may not be able to recognize their own posture, depending on the combination of visual information and the roll-tilt angle, and thus may easily experience spatial disorientation.

The current study contained several limitations that should be considered. Testing a larger number of participants and the inclusion of roll-tilt to the right would extend the current findings. In particular, a larger sample size would be useful for confirming whether the variation in the current results followed a normal distribution, or whether participants could be distinguished into several groups. However, the training device used in the experiment was originally designed for the training of air force pilots and its use is severely restricted. Thus, only nine participants could be recruited and only roll-tilt to the left was tested. Additional visual and tilt conditions should be examined in future studies.

CONCLUSION

In conclusion, a quantitative evaluation of roll-tilt perception using the SVV and SPHV revealed that the latter method is not affected by the roll-tilt angle, unlike the SVV. Despite differences in the features of the SVV and SPHV, the current data demonstrate that human susceptibility to spatial disorientation depends on roll-tilt angle and visual information.

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The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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