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SHORT COMMUNICATION

Perceived Body Orientation in Microgravity: Effects of Prior Experience and Pressure Under the Feet

Jerome Carriot, Lionel Bringoux, Corinne Charles, Franck Mars, Vincent Nougier, and Corinne Cian

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Human activities often involve sensing body orientation using cues from gravity. Astronauts in microgravity are deprived of those cues and may have difficulty with certain tasks. We theorized that experience in microgravity combined with mechanically induced pressure under the feet (foot pressure) would improve the accuracy of a subject's perception of the body's z-axis as indicated by pointing to the subjective horizon (SH). ***Method:*** Experiments were conducted during parabolic flights using five experienced subjects and five novices. Subjects were required to raise their arm to point to their SH with eyes closed. Measurements were made on Earth and in microgravity, with or without foot pressure. Both pointing accuracy and the kinetics of the movement were analyzed. ***Results:*** Performance by experts was stable under all conditions. However, novices in microgravity pointed to a significantly lower SH (16.5°] below the 1-G SH) and slowed their movements (mean angular velocity of movement: $16.8° \cdot s^{-1}$ less than in 1 G). Foot pressure improved the performance of the novices so that it was closer to that observed at 1 G (8.9° below the 1-G SH). ***Discussion:*** These results suggest that pressure cues under the feet activated the internal model of gravity in the novices, and thus improved the accuracy of their perception of their z-axis. Subjects with prior experience in microgravity correctly perceived their z-axis without the supplementary input.

Keywords: arm movements, adaptation, frame of reference, expertise.

GRAVITY IS A CONSTANT, pervasive, and significant feature by which humans orient themselves to the environment; it affects practically every aspect of overt behavior. However, astronauts working in space must perform all kinds of tasks without gravity. They may lose their sense of body orientation or even develop a false sense of position relative to their environment.

A subject on Earth can point precisely to memorized targets without any visual information during the movement, even when the body's z-axis (head-to-foot) is tilted with respect to gravity. Such an egocentric task does not require knowledge of z-axis orientation relative to the environment, only the localization of the target and the position of the arm. However, when subjects are asked to use their arm to point to their subjective horizon (SH), tilting their z-axis systematically shifts the results (1). Because this geocentric task requires taking into account body orientation, it is a strong indicator of the perception of z-axis orientation with respect to the gravity vector (9).

This study was designed to investigate how perturbations of gravity influence perception of body orientation. We used a microgravity environment in which, without visual cues, the perceived z-axis remained the only available reference for body orientation. Lackner and DiZio found that free-floating subjects can feel disoriented (7). They hypothesized that perception of SH in microgravity was impaired due to misperception of the z-axis, but noted that a modification of the SH could also result from degradation of limb proprioception in microgravity (7). Otolith-spinal mechanisms normally regulate spindle sensitivity in the anti-gravity musculature; microgravity affects this system through modulation of excitatory control on the alpha and/or gamma motoneurons. The z-axis is then correctly perceived, but control of movement can be disrupted. This hypothesis implies modifications at the level of movement control, whereas misperception of the z-axis works at the level of central command.

In microgravity, somatosensory cues (touch and pressure) appear to be of great importance in spatial orientation (7). Applying pressure to the top of the head makes subjects feel upside down, confirming the increased weighting of localized somatosensory cues during spaceflight (11). The structural polarity of "up" or "down" cued by touch and pressure seems to be based on cognitive factors (7). Localized somatosensory cues may be centrally interpreted as reaction forces against gravity, leading subjects to perceive a virtual gravity vector and a specific body orientation with respect to that vector. We hypothesized that the mechanical application of pressure to the bottom of the feet (foot pressure) in microgravity would provide a virtual gravity vector and enable subjects to bring their SH closer to that measured in 1 G.

From the Département des facteurs humains, Centre de Recherches du Service de Santé des Armées, Grenoble, France (J. Carriot, L. Bringoux, C. Charles, C. Cian); 'Sport et Performance Motrice,' Université Joseph Fourier, Grenoble, France (J. Carriot, L. Bringoux, C. Charles, V. Nougier); and 'Mouvement et Perception,' Université de la Méditerranée, Faculté des Sciences du Sport, Marseille, France (F. Mars).

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Address reprint requests to: Corinne Cian, Département des facteurs humains, Centre de Recherches du Service de Santé des Armées, BP87, La Tronche Cedex 38702, France; corinnecian@crssa.net.

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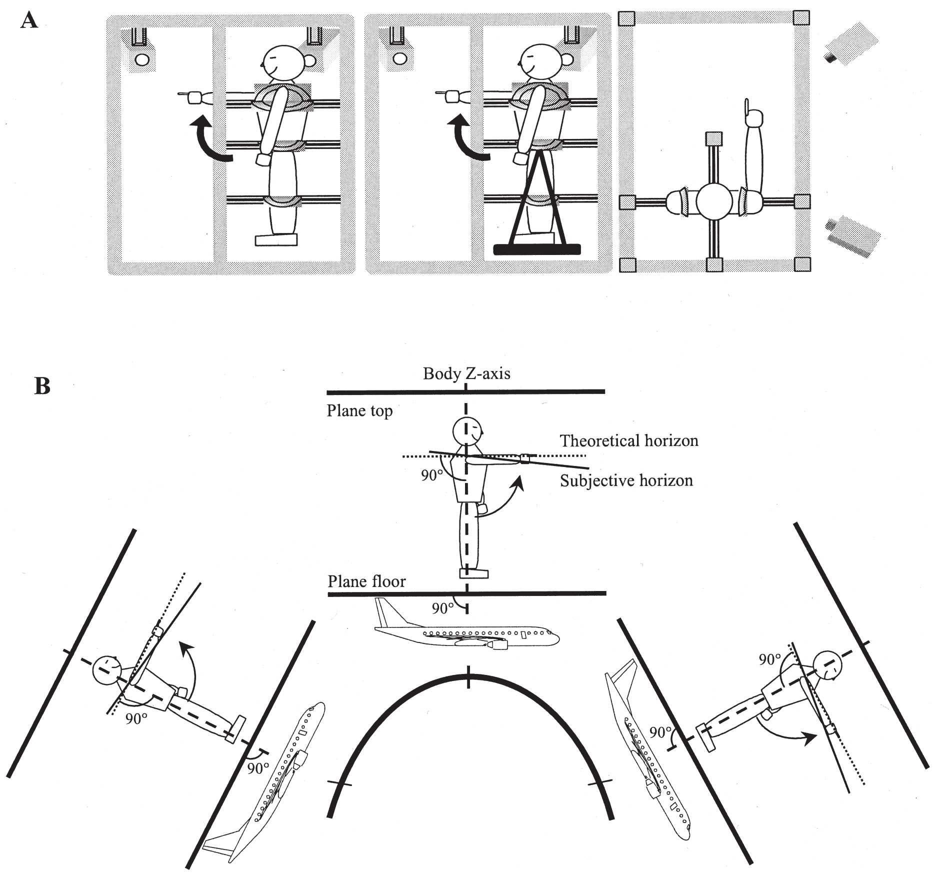

Fig. 1. A. Schematic representation of the experimental set-up. The left and center panels show side views of the set-up for microgravity without foot pressure and with, respectively. The right panel shows a top-view of the set-up including the cameras. B. Schematic representation of the movement used to indicate subjective horizon with respect to the body position inside the airplane at three different times during a parabola. The z-axis remained steady and perpendicular to the floor of the airplane. The arm position parallel to the floor of the airplane was the reference value.

An additional question concerned learning effects. It has been shown that in microgravity, when a repertoire of strategies used on the ground does not result in effective motor outputs, the central nervous system creates new strategies by means of a slow learning process (10). The dependence on non-inertial tactile and visual cues decreases after 1 wk in space, when the subjects manage to use their body frame of reference (11). Within this context, microgravity expertise through repeated experience of parabolic flights may induce an adaptive behavior that reduces or avoids the feeling of spatial disorientation. Therefore, we further hypothesized that z-axis perception would be less disrupted by microgravity in experts than in novices.

METHODS

The experiments were carried out during five parabolic flights aboard an Airbus A300 based in Bordeaux, France. Four conditions were studied: 1) 1 G on the ground 30 min before and 30 min after flight; 2) 1 G during level flight between parabolas; 3) microgravity without foot pressure (μG); and 4) microgravity with foot pressure (μG +FP). Each parabola started from level flight at 1 G and consisted of a 20-s pull-up at 1.8 G during which the aircraft climbed from 6000 to 8500 m, 20 s of microgravity obtained over the top of the trajectory, and then a symmetrical 20-s pull-out at 1.8 G to bring the aircraft back to horizontal flight at the original altitude. There was an interval of approximately 2 min between successive parabolas.

Subjects

There were 10 healthy right-handed volunteers (mean age 33 yr) who participated in the experiment. The novice group (4 men and 1 woman) had experienced a maximum of 62 parabolas (20 min maximum of microgravity) before this experiment. The expert group (also 4 men and 1 woman) had experienced about 3000 parabolas (mean 3087, range from 2697 to 3627), more than 1000 min of microgravity, during the past 5 yr. All subjects were naive about the purpose of the experiment and gave signed informed consent in compliance with the Huriet Law (i.e., Helsinki Convention) which governs and regulates human experimentation in France.

Apparatus

Subjects without shoes stood in a box approximately 140 cm long x 80 cm wide x 190 cm high. They were held in place by means of bungee cords attached to wide belts wrapped around the body at the level of the chest, hips and knees. The cords exerted a distributed tension so that the subjects were held steady in the box during microgravity with their Z-axis perpendicular to the floor of the airplane without contacting any surface (**Fig. 1A**, left panel). Foot pressure was generated by pulling a rigid plate up under the subject's feet by means of bungee cords adjusted to the subject's leg length and attached to the hip belt (Fig. 1A, middle panel). F1

To record kinematics, reflective markers were placed on the right side of the body at the hand (first phalanx of the index finger), shoulder (acromion), hip (iliac crest), and head (zygomatic process). Two digital cam- AQ: 1 eras (DCR-TRV900E, Sony,), separated by an angle of 60° (Fig. 1A, right panel), recorded the pointing movements with a sampling frequency of 25 Hz. The recorded sequences were then digitized by means of a AQ: 2 conversion card (Pinnacle DV500,) and the software Adobe Première (Version 6.1). The video sequences were analyzed with the Ariel Performance Analysis System (APAS 2000, v1.1, Ariel Dynamics Inc., San AQ: 3 Diego, CA) to process the kinematics data associated with the markers. Data were filtered with a Butterworth filter (10 Hz cutoff frequency).

Procedure

Each trial consisted of five consecutive pointing movements performed with eyes closed during a 20-s period. The subject began with the right arm hanging down along the body, then raised the extended arm to point to the SH as quickly and as accurately as possible. Subjects were instructed to indicate the horizon defined on Earth as "where the sun rises in the sea at the level of the shoulder." They were further told to adjust the arm's level to coincide with the plane they perceived as perpendicular to gravity passing throughout their shoulder. In flight, this geocentric task was referenced to the interior of the aircraft so that the "horizontal plane" was parallel to the floor of the aircraft (**Fig. 1B**). Subjects indicated that they had reached their final arm position by pushing a button held in the left hand that activated a red light; further corrections were not allowed. The arm was then returned to the starting position for the next trial. Subjects performed the task on three 1-G phases (before, during, and after flight) and on eight successive parabolas, four each for μG and μG+FP in mixed order.

Data Collection

The stability of the body and of head position with respect to the body were confirmed by calculating the mean positions of the markers at the hip, shoulder, and head for each subject in each condition. Analysis of variance (ANOVA) was applied to these data for the x-, y-, and z-axes. Results showed no significant effect of condition ($p > 0.05$), indicating that body position was stable throughout all trials and conditions. We could, therefore, measure the angular movement between the axis of the trunk (markers of the hip and shoulder) and the axis of the arm (markers of the shoulder and index), where 90° represented the arm perpendicular to the body's z-axis and parallel to the floor. The final pointing position or SH for each condition was calculated in degrees averaged across all trials.

For technical reasons, movement kinematics were recorded for only six subjects (three experts and three novices). The analyzed variables were: 1) mean angular velocity of movement (VM), a better temporal indication than movement duration when amplitude varies, where slower movement is thought to be associated with more consistent control; 2) peak acceleration of the movement (PAM), representing the central command programmed before movement onset; and 3) time to peak acceleration of the movement (T-PAM) as a percentage of movement time, which indicates the extent to which the movement is controlled.

RESULTS

In order to verify that there was no systematic difference among the different 1-G phases, we analyzed all variables using ANOVA for Group (expert vs. novice) × the three 1-G phases (before, during, and after flight) with repeated measures for phase. Results showed no significant effect of phase; we, therefore, pooled the 1-G data to form a single reference value for each dependent variable. No effect of group was found at 1 G for SH [F (1,8) = 0.2; $p > 0.05$; **Fig. 2A**] or for the F2 PAM [F (1,8) = 2.5; $p > 0.05$; **Fig. 2C**]. However, compared with the novices, the experts showed a significantly higher VM [F (1,8) = 105.7; $p < 0.05$] and a longer T-PAM [F (1,8) = 25.5; $p < 0.05$; **Fig. 2B and 2D**, respectively].

To find out whether microgravity and foot pressure affected perception of the z-axis, all variables were analyzed using ANOVA for group × condition with repeated measures on the latter. A post hoc (Newman-Keuls) analysis was performed for variables where $p < 0.05$. SH showed no main effect for group [F (1,8) = 2.08; $p > 0.05$], but did show a significant effect of condition [F (2,16) = 6.78; $p < 0.05$] as well as a significant interaction of group × condition [F(2,16) = 7.05; $p < 0.05$]. As shown in Fig. 2A, novices indicated a lower SH in both microgravity conditions but were closer to their 1-G baseline with foot pressure, whereas experts indicated the same SH for both 1 G, μG, and μG+FP.

The VM for both groups was slower in microgravity compared with 1 G [F(2,8) = 73.69; $p < 0.05$], but was always faster for experts than for novices [F(1,4) = 7.85; $p < 0.05$; Fig. 2B]. Foot pressure increased VM for novices but did not influence experts (Fig. 2B). Novices showed a lower PAM than did experts [F(1,4) = 7.41; $p < 0.05$; Fig. 2C], and an effect of condition was observed [F(2,8) = 18.34; $p < 0.05$] as well as an interaction for group × condition [F (2,8) = 18.91; $p < 0.05$]. For novices, PAM was significantly smaller for μG and was closer to the 1-G value for μG+FP, whereas experts showed no change with condition. Finally, T-PAM was longer in microgravity than at 1 G [F(2,8) = 6.95; $p < 0.05$] with no difference between μG and μG+FP (Fig. 2D). No difference was observed for group [F(1,4) = 4.70; $p > 0.05$]. The interaction of the two factors [F(2,8) = 7.24; $p < 0.05$] showed that T-PAM for the experts remained stable throughout all conditions. For the novices, it was shorter in 1 G than in the other two conditions ($p < 0.05$) which remained similar ($p > 0.05$, Fig. 2D).

DISCUSSION

One aim of this study was to investigate how prior experience with microgravity might influence percep-

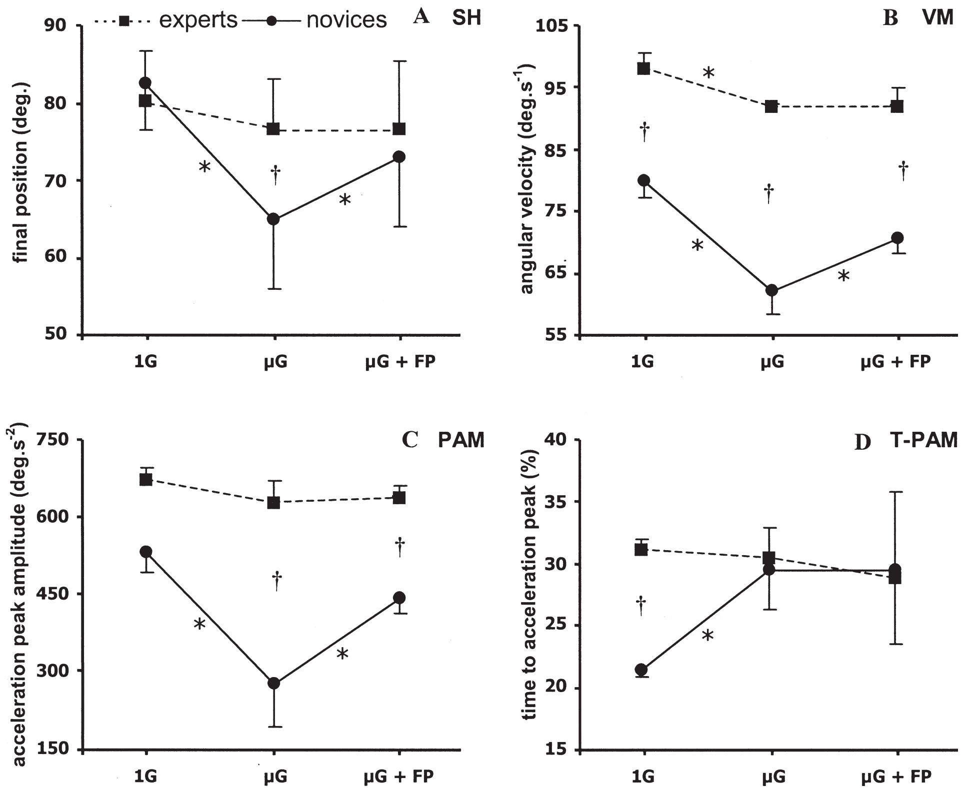

Fig. 2. Mean values and standard deviations for measured variables under three experimental conditions [1 G, microgravity (μG), and microgravity with foot pressure (μG+FP)]: A.) Final pointing position, indicating the subjective horizon (SH); B.) velocity of movement (VM); C.) peak acceleration of the movement (PAM); and D.) time to peak acceleration of the movement (T-PAM). The novices are shown by circles with solid lines and the experts by squares with dashed lines. Statistical significance ($p < 0.05$) is shown by † for differences between groups and * for differences among conditions.

tion of the z-axis during perturbations of gravity (absent or virtual). Results showed a lower SH in microgravity for novices, whereas experts retained stable perceptions. This difference cannot be related to ability to point to the horizon per se, as pointing accuracy in 1 G was similar for both groups. Moreover, it cannot be explained by an effect of frequent, rapid changes of condition (i.e., the parabola's succession of 1 G, 1.8 G, and microgravity) as the movements executed at 1 G in flight were similar to those executed on the ground before and after the flight.

Moving the arm toward the "horizontal," that is perpendicular to the body, requires the subject to take into account their z-axis. The presence of normal gravity allows an accurate perception of this axis. However, in microgravity the novice subjects were disoriented (7) and unable to use their z-axis as a frame of reference (5,11). As a result, their SH was less accurate and their movement kinematics differed. Adding pressure under the feet allowed novices to improve their performance. These pressure cues may have been interpreted as a force reaction against "virtual gravity" (6), perhaps by allowing central activation of a model of gravity that improved perception of the z-axis (9). This central hypothesis was supported by the observed modification of movement kinematics. The decrease of PAM and the increase of T-PAM in microgravity suggested that the central nervous system initialized the body frame of reference on the basis of available sensory information before starting the movement. For novices, this initial sensory state, modified by the exposure to microgravity, may have induced an incorrect prediction of the effect of microgravity on their motor behavior; by relying on both modified proprioceptive feedback and a misperception of their z-axis with respect to the floor of the airplane, novices may have overestimated the "muscle unloading effect" of microgravity (13). Such an overestimation would induce a movement of smaller amplitude and thus a lower SH, as shown by our data. A complementary hypothesis is suggested by studies of adaptation of postural control to microgravity (3,8), where subjects leaned forward with respect to the "vertical" even though they felt their posture to be normal. Adaptation to the absence of gravity was suggested to involve two mechanisms: a short-term operative process and a long-term conservative one. In our experiment, only the former could have been activated. Since subjects were held perpendicular to the floor of the airplane, they may have perceived themselves as leaning backward with respect to the reference position, causing them to undershoot their pointing movement.

Providing pressure under the feet would not improve proprioceptive feedback, but probably did allow the novices to make a more precise identification of their z-axis with respect to the airplane, resulting in a more accurate SH. In contrast, the experts showed no change in movement kinematics whatever the gravity condition. Although one might expect that producing the same movement in the absence of gravity would induce greater movement amplitude and speed, it is consistent with previous data showing stability of movement kinematics in 1 G (12). The only observed differences in 1 G were localized at the level of the muscles with an increase of the co-contraction when the movement was performed in the direction of gravity (12). A similar EMG pattern may also be observed in microgravity to reach the same movement accuracy with rather constant movement kinematics. Furthermore, the experts'

AQ: 4 movement was more ballistic, exhibiting higher SM and higher PAM, suggesting that the movement was preprogrammed and less dependent on the presence or absence of gravity. The experts, who were used to working without the frame of reference provided by gravity, may have developed an adaptive behavior that takes altered gravity into account. They would, then, be better at extracting and associating those relevant cues from the sensory systems that are still useful (2) in order to create a frame of reference for their body which remains stable, despite changes in external conditions, AQ: 5 with respect to the airplane (5,11). This would explain why their performance did not change with our three conditions.

In conclusion, the removal of gravity as a frame of reference prevented novices from developing an accurate perception of the exocentric space, probably because they misperceived the orientation of their z-axis. As already shown in the literature (7), the central activation of an internal model of gravity, by means of pressure cues under the feet, improved the perception of the z-axis. Moreover, people with more prior experience of parabolic flight may have learned to use their z-axis as a strong frame of reference to avoid spatial disorientation.

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