Effect of simulated microgravity on mental transformations in a realistic perspective - taking task

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EFFECTS OF SIMULATED MICROGRAVITY ON MENTAL TRANSFORMATIONS IN A REALISTIC PERSPECTIVE-TAKING TASK

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ABSTRACT

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The study tested the specific impact of vestibular disruptions during parabolic flight on mental transformations involved in perspective-taking in a virtual reality environment enabling to test object- and self-centered mental transformations. The difference in mean response times and success rates between the control and test conditions observed on the Ground provide strong evidence that the task required subjects to engage in perspective-taking mental operations to solve the task. Similar results were observed in all conditions when comparing ground to 1g in-flight performance, suggesting that performance was not affected by in-flight conditions (e.g., stress, cabin vibrations, increased surrounding noise, etc.). When in-flight 0g responses were compared to in-flight 1g responses, reaction times tended to be faster in 0g compared to 1g. These preliminary results need to be confirmed with a larger sample size and complementary analyses in relation with other factors that may contribute to the observed results.

INTRODUCTION / SECTION TITLE

In space psychology, social interactions and good team collaboration are essential human factors for the success of long duration space flights. They largely depend on social understanding and social skills, including empathy and perspective taking, i.e. the ability to take another person's viewpoint.

Spacecraft crew are uniquely free to float in any relative orientation within the cabin, experience no vestibular or haptic cues, and learn to use visual landmarks or frame of reference to orient in the cabin. An illustration of this phenomenon were provided by 3-dimensional orientation training experiments performed in virtual reality (Oman, 2007). When participants were confronted with module interiors comprised of objects that had an upright and specific orientation, they managed the orientation training rapidly. According to the author, participants' short reaction times to orient indicate that the internal mental coordinate was anchored according to cabin landmarks or objects that acted as local reference frames while orienting. In contrast, when visual landmarks were incongruently oriented, reaction times to orient were much longer, indicating that the perceived orientation depended on participants' own body orientation or reference.

These findings indicate that mental transformations are performed by relying on reference frames. A frame of reference is a perspective a speaker chooses to describe a location in space or to perform an action (Mintz & al., 2004). This can be done by using an allocentric or object-centered reference frame, when the object itself or its features orients a speaker in space, such as the cabin landmarks in Oman's study. Orientation in space can also be performed according to an egocentric frame of reference that exploits the speaker's' own perspective, for instance when visual landmarks were incongruently oriented in Oman's virtual reality training task, and generally involves a body-axis rotation. Alternatively, spatial location and/or orientation may depend on an addressee-centered reference frame that requires a speaker to adopt another persons' perspective, or a third-person perspective.

Reference frames and thus orientations in space, either real or mental, result from multisensory integration of visual, proprioceptive and vestibular information (Friederici & Levelt, 1990). While these influences are difficult to dissociate on Earth in normal gravity conditions, in microgravity conditions, like parabolic flight conditions, vestibular inputs are disrupted. While absent or disturbed vestibular input (parabolic flights) can impair mental transformations (Grabherr et al., 2007), vestibular stimulation can facilitate spatial judgments (Deroualle et al., 2015; Falconer & Mast, 2012). It is important to point out that studies do not yet provide a fully coherent picture as to how vestibular processes are nested within spatial transformation abilities (for a review, Mast et al., 2014). Some studies suggesting a selective influence of vestibular stimulation on the rotation of whole-body reference frames. For instance, vestibular stimulation facilitated own body mental rotation as compared to sham stimulation, while no such effects were found for mental transformation of hand stimuli or during mental transformations of letters (Falconer & Mast, 2012). Congruent motion further facilitated mental rotation of one's own body:

participants were faster when their physical body rotated in the same direction as the mental rotation needed to take an avatar's viewpoint (Deroualle et al., 2015). Other studies show deficits in mental transformation of bodies and objects alike in vestibular patients, suggesting that spatial-cognitive abilities are more globally impaired in these patients, whereas there is also evidence for a more pronounced impairment in mental rotation of bodies (Grabherr et al., 2011). Still other studies provided evidence that disturbed vestibular input during weightlessness did not modify mental rotation performance of objects, hands or drawings of a person (Dalecki et al., 2013). Even a facilitation of mental rotation of 3-dimensional objects has been reported during prolonged exposure to weightlessness in astronauts. Thus, average rotation time per degree of rotation was shorter inflight than on the ground, particularly for stimuli calling for roll axis rotations (Matsakis et al., 1993). Elsewhere, in the Tumbling Room, only body stimuli (but not hand stimuli) were more accurately identified when room and body stimuli were aligned, indicating that static visual landmarks can affect performance in an egocentric mental transformation task (Preuss et al., 2013).

In this study, we sought to evaluate the specific impact of vestibular disruptions on mental transformations involved in perspective-taking in a virtual reality environment enabling to test object- and self-centered mental transformations. The virtual environment featured a 2-D display representing the interior of a spacecraft, a floating shelf (landmark) and an astronaut (avatar). The task required participants to mentally put themselves in the place of the character by performing an own body-axis rotation. In addition, in critical test conditions, either the character, or the landmark, or both items were tilted clockwise or counterclockwise by 45 degrees. The first aim of the study was to assess the effects of microgravity on object-centered mental rotations (visual landmark tilt) and on self-centered mental rotations (body-axis tilt) during perspective taking. The second aim was to test the influence of individual characteristics on these abilities. More especially empathy, e.g. the ability to understand and share the feelings, thoughts, and experience of another was thought to influence perspective-taking. Further, we tested whether subject's displayed a spontaneous tendency to be visually distracted by the surrounding environment (e.g. visual field dependency), by using a computerized version of the Rod-and-Frame test known to measure the influence of the visual frame of reference upon a subject's ability to determine the vertical or upright orientation.

MATERIALS AND METHOD

2.1 Subjects

We asked 11 human participants (all males, aged 35–49) to perform a perspective-taking task in a virtual reality (VR) environment, under both normal (1g) and microgravity (0g) conditions onboard a parabolic flight aircraft. All subjects had at least one prior experience of parabolic flights. In addition to the main task, each subject completed the classic rod-and-frame test (RFT; Witkin, 1948), an empathy test (Baron-Cohen & Wheelwright, 2004) and NASA-TLX questionnaires (Hart & Staveland, 1988). Both the main perspective-taking task and the RFT test were implemented in Matlab and ran on a personal computer.

2.2 Material

Perspective-taking task. Subjects were seated in a comfortable armchair and secured by foot straps and a 2-point lap seat belt. Both the straps and the seatbelt were kept slightly loose over the course of the experiment to reduce tactile and proprioceptive feedback during 0g periods. Subjects were equipped with a VR headset (Oculus DK2), over-the-ear headphones, and a wireless mouse that they manipulated over a solid cardboard directly attached to their thigh (Figure 1a). Every trial of the experiment was initiated with a fixation cross displayed at the center of the VR screen. After a short delay, a scene depicting the interior of a spacecraft with a 4x4 rectangular shelf floating in the middle appeared on the screen (Figure 1b). The scene covered the entire visual field of the subject to allow maximum VR immersion. On every trial, three identical objects (e.g., three bottles) were placed in individual compartments of the shelf. The location and nature of the objects varied on a trial-by-trial basis. Following another short delay, an avatar representing a colleague astronaut popped up either behind or in front of the shelf, in either an upright or tilted (45°) orientation. The gender of the astronaut was randomly chosen to be male or female on every trial. The avatar was shown for 1s before disappearing, after which a verbal instruction given by the astronaut was played in the headphones, instructing the participant to move an object from one shelf compartment to another. The instruction was always given from the astronaut's perspective. The goal of the subject was to correctly interpret the movement instructed by the astronaut and to drag-and-drop the identified object in the desired unit using the mouse. In the main experiment, subjects received no feedback about the movements they performed. For each trial, we recorded both the response time (measured from the end of the verbal instruction to the mouse click release in the target compartment) and the validity of the movement performed.

The task included 6 experimental conditions (Figure 1b) in which we systematically manipulated the position/orientation of the astronaut, as well as the orientation of the shelf:

- Condition no-perspective: the avatar is in front of the shelf, upright, the shelf is also upright.

- Condition no-tilt: the avatar is behind the shelf, upright, the shelf is also upright.
- Condition avatar-tilt: the avatar is behind the shelf, tilted at 45°, the shelf is upright.
- Condition shelf-tilt: the avatar is behind the shelf, upright, the shelf is tilted at 45°.
- Condition same-tilt: the avatar is behind the shelf, tilted at 45°, the shelf is tilted at 45° in the same direction.
- Condition opposite-tilt: the avatar is behind the shelf, tilted at 45°, the shelf is tilted at 45° in the opposite direction.

The common tilt direction was balanced across subjects (i.e., +45° clockwise for half of the subjects, -45° counter-clockwise for the other half).

Rod-and-frame test. Subjects were seated in a complete dark room in front of a 17-cm computer display. A black cylinder placed between the subject and the screen formed an optical tunnel. One opening of the cylinder directly abutted the screen and the other opening allowed the subject to rest their chin inside the tube. A black cloth covered the subject's head to remove any peripheral visual cues of verticality. The test itself consisted of a pre-programmed sequence of 10 rod-only trials followed by 10 rod-and-frame trials. On rod-only trials, the rod (luminescent bar, 2 cm long) was positioned randomly at an angle of either +40° or -40° from the vertical. The subject's goal was to rotate the rod (by moving the computer mouse) until it aligned with the perceived vertical and click to confirm their choice. On rod-and-frame trials, the frame was tilted 18° in a clockwise (+18°) or counter-clockwise (−18°) direction from the vertical. The rod was positioned at an angle of either +20° or −20° from the vertical. To eliminate possible biases and learning effects, the order of rod/frame orientation combinations was randomized. The subject's task was again to rotate the rod until its orientation matched the perceived vertical. The entire test lasted about three minutes and was preceded by 1 familiarization trial.

Empathy. Subjects filled out a 60-item multiple-choice questionnaire to determine their empathy quotient (EQ; Baron-Cohen & Wheelwright, 2004). The questionnaire consists of 40 empathy-related items and 20 control items scored 0, 1 or 2.

Workload. Subjects completed the NASA-Task Load Index questionnaire (NASA-TLX; Hart & Staveland, 1988) immediately after each session of the main task to assess mental and physical workload. Participants rated six subscales: mental demand, physical demand, temporal demand, performance, effort and frustration on a 20-point Likert scale. Raw data were converted into percentages for the statistical analyses.

2.3 Procedure

The parabolic flight campaign organized by Novespace (Mérignac, France) consisted of three flights operated on three successive days. Four participants and two experimenters boarded on each flight. Every subject took part in three experimental sessions:

- *Preflight* session: all subjects completed the EQ test and the rod-and-frame test on the first day of the campaign. After familiarization with the test material, participants performed the perspective-taking task onboard the aircraft (engine off) followed by workload ratings (NASA-TLX).

-*Inflight* session: on each flight, the aircraft performed a total of 30 parabolas separated by at least a 2-min period of steady flight (Figure 1c). Each parabola consisted of a

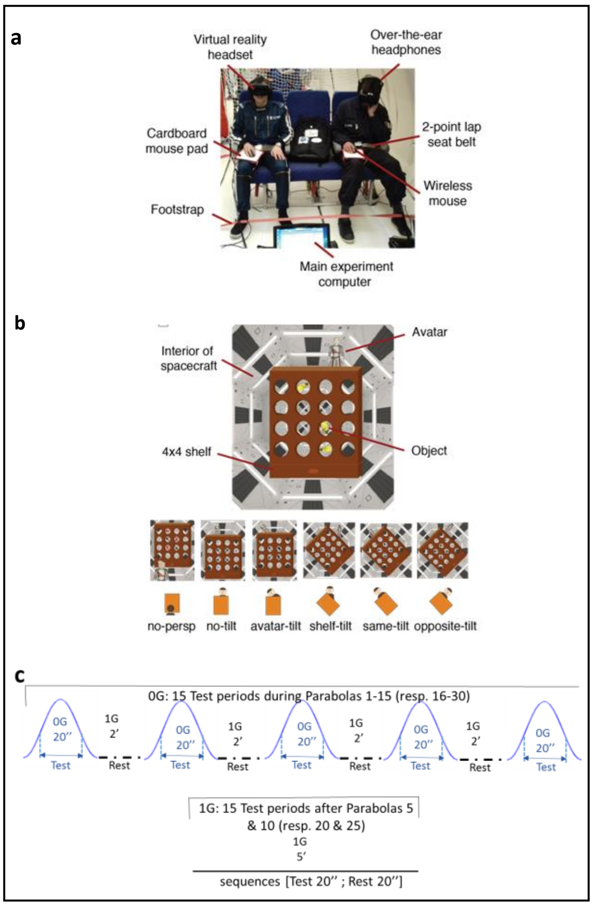

Fig. 1. Task design and protocol. a) Typical experimental session onboard the aircraft. Subjects seated and secured in a regular airplane seat were equipped with headphones, a VR headset, and a wireless mouse they manipulated over a solid cardboard directly attached to their thigh. b) Scene shown on every trial on the VR display. Following a brief (1s) appearance, the avatar (representing a colleague astronaut) instructs the subject to move an object from one shelf compartment to another. After interpreting the desired object and the movement to be performed, the subject used the mouse to select the object and place it in the target compartment. Bottom row: in each of the 6 experimental

conditions, the position/orientation of the avatar and/or the orientation of the shelf was manipulated to elicit distinct mental transformations. c) Sequence of parabolas during a flight. Subjects completed 0g trials (typically 3 or 4) during every 20-s parabola, each separated by ~2-min breaks. Every 5 parabolas was followed by a longer break (>5 min) during which subjects completed 1g trials during alternating 20-s test/rest periods.

sequence of 1.8g–0g–1.8g episodes, each lasting ~20 seconds. Every five parabolas were followed by a 5-min break (steady flight), extended to 8 min at mid-flight. During each half of the flight, 2 participants performed the perspective-taking task. For every subject, half the trials were done in microgravity conditions over 20-s periods, the other half was done in normal gravity conditions over 20-s test periods alternating with 20-s rest periods during the 5-min breaks. This strategy was used to match overall testing periods between 1g and 0g, as well as to mimic the interruptions between parabolas. After completing all trials, subjects filled the NASA-TLX questionnaire.

-*Postflight* session: immediately upon landing, participants performed again the perspective-taking task onboard the aircraft (engine off), followed by workload ratings (NASA-TLX).

The present report details the results observed in the perspective-taking task.

RESULTS

Validation of the experimental protocol. To verify the validity of our protocol and confirm that participants engaged in perspective-taking during the task, we analyzed subjects' performance across experimental conditions using data collected on the ground in normal gravity conditions (i.e., combining pre- and post-flight datasets). We first focused on response times (RTs, mean of correct and incorrect responses), defined as the time elapsed between the end of instruction and the participant's response (click release). We found that RTs varied systematically across the 6 conditions (Friedman's test performed on within-subject mean RTs, $p=1.2x10^{-5}$). Follow-up pairwise comparisons revealed that RTs were significantly slower in all 4 test conditions compared to the no-tilt control condition (Wilcoxon sign-rank tests, $p<0.01$ for all test conditions; Figure 2a). In addition, we found that RTs were significantly slower in the avatar-tilt condition compared to the other 3 test conditions (sign-rank tests, $p<0.01$). Next, we analyzed success rates (SRs), defined as the percentage of correct responses per condition. We found that SRs varied systematically across the 6 conditions (Friedman's test performed on within-subject mean SRs, $p=1.4x10^{-8}$).

Follow-up pairwise comparisons revealed that SRs were significantly lower in all 4 test conditions compared to the no-tilt control condition (Wilcoxon sign-rank tests, $p<2x10^{-3}$ for all test conditions; Figure 2a). In addition, we found that SRs were significantly higher in the shelf-tilt condition compared to the other 3 test conditions (sign-rank tests, $p<0.02$; Figure 2b). The difference in response times and success rates between the control and test conditions provide strong evidence that the task did require subjects to engage in perspective-taking mental operations to solve the task. Moreover, success rates for all conditions were well above chance level (which was between 12.5–33% depending on which shelf compartment the target object was placed in), indicating that subjects understood the task and the various experimental conditions.

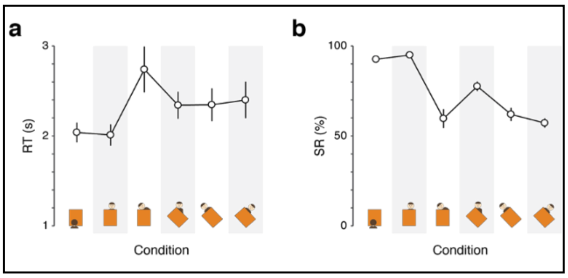

Fig. 2. Performance on the ground. a) Mean response time (RT) in the 6 experimental conditions. RTs are first averaged within subject, then combined across subjects to obtain a mean RT (open circle) and the associated standard error (error bar). b) Same as a) for success rate (SR). In both plots, pre- and post-flight datasets have been combined.

Effect of training on pre- and post-flight performance. A second important verification we performed was to test for any effects of training on subjects' performance. Indeed, it is conceivable that over the course of the 3 sessions completed by each participant, performance may have improved due to repeated exposure to the task. We therefore compared performance across conditions pre- and post-flight. We

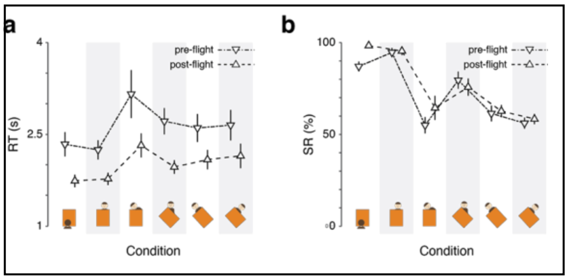

Fig. 3. Performance pre- and post-flight. a) Mean response time (RT) in the 6 experimental conditions for pre- (dashdotted line) and post-flight (dashed line). RTs are first averaged within subject, then combined across subjects to obtain a mean RT (open triangle; pointing down for pre-flight, pointing up for post-flight) and the

associated standard error (error bar). b) Same as a) for success rate (SR).

found that response times were much faster post-flight compared to pre-flight, irrespective of the condition (Wilcoxon sign-rank tests, $p<0.05$ for all conditions except opposite-tilt, $p=0.08$; Figure 3a). By contrast, we did not find any systematic improvement in performance in terms of success rates (Figure 3b). Except for a slight decrease in SRs post-flight in the no-persp control condition (sign-rank test, p=2x10-3), SRs associated with all the other conditions were similar pre- and post-flight. The drop in RTs between pre- and post-flight could be due to two main factors. One possibility is that subjects got better at performing the mental transformations required by the task. However, the fact that RTs decreased of the same amount (~0.6 s) irrespective of the condition type (i.e., including in the control condition where no perspective-taking was required) makes this explanation unlikely. This interpretation is also not consistent with the fact that success rates were virtually unchanged between pre- and post-flight. A more likely explanation for this improved performance is an increased familiarity with the response apparatus. Anecdotal reports from subjects indeed indicated that it took them some time to get accustomed to the wireless mouse and the cardboard attached to their thigh. We therefore attributed the improved performance post-flight to this effect.

Effect of in-flight factors on performance. As a final preliminary analysis, we sought to determine whether subjects' performance was influenced by stress or any other factors that could have manifested during the flight, even in normal gravity conditions. We therefore compared 1g in-flight performance to performance on the ground. We used only post-flight data as a baseline based on our previous analysis showing a learning effect between pre- and post-flight. We found that both RTs and SRs were similar in all conditions when comparing ground to in-flight performance (Figure 4). These results indicate that performance was not affected by in-flight conditions (e.g., stress, cabin vibrations, increased surrounding noise, etc.).

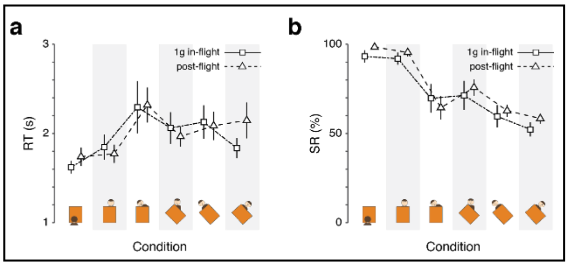

Figure 4. Performance in-flight (1g) and post-flight. a) Mean response time (RT) in the 6 experimental conditions for 1g in-flight (solid line) and post-flight (dashed line). RTs are first averaged within subject, then combined across subjects to obtain a mean RT (open square for 1g in-flight, open triangle pointing up for post-flight) and the associated standard error (error bar). b) Same as a) for success rate (SR).

Effect of microgravity on perspective-taking abilities. The main hypothesis we sought to test in this study was an influence of microgravity on mental operations involved in perspective-taking. Accordingly, we compared in-flight 0g performance to in-flight 1g performance. We found that RTs in the 2 control conditions were similar in 1g and 0g. By contrast, in the test conditions, we observed a trend of faster RTs in 0g compared to 1g (Figure 5a). However, most likely due to the relatively low sample size, only one condition reached statistical significance (same-tilt condition, sign-rank test, $p=0.04$) and another condition showed a marginal effect (shelf-tilt, sign-rank test, $p=0.07$). Based on our previous observation that 1g in-flight performance was statistically undistinguishable from post-flight performance, we reiterated the analysis of RTs after combining 1g in-flight and post-flight datasets to increase our statistical power. Results confirmed that RTs in both the shelf-tilt and same-tilt conditions were significantly faster in 0g compared to 1g (sign-rank tests, $p=0.04$ and $p=0.02$, respectively). In terms of SRs, we found no change between 1g and 0g, even when 1g in-flight data were combined with post-flight data (Figure 5b). Subjects were therefore as accurate, but faster in 0g

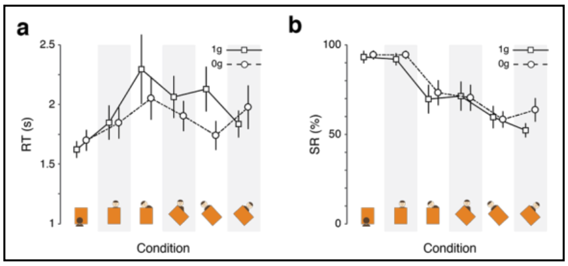

Figure 5. Performance in-flight in 1g and 0g. a) Mean response time (RT) in the 6 experimental conditions for in-flight 1g (solid line) and 0g (dashdotted line). RTs are first averaged within subject, then combined across subjects to obtain a mean RT (open square for 1g in-flight, open circle for in-flight 0g) and the associated standard error (error bar). b) Same as a) for success rate.

compared to 1g in at least 2 test conditions (shelf-tilt and same-tilt). Importantly, this performance improvement was not observed in control conditions, ruling out a trivial explanation of an overall movement facilitation in 0g, which would have also manifested in the control. Together, these results seem to suggest a specific facilitation of mental rotation operations during perspective-taking under microgravity conditions, which will need to be confirmed by further analyses and/or increased sample size.

DISCUSSION

The purpose of this study was to evaluate the effect of microgravity on perspective-taking abilities, which constitute a crucial collaborative and social skill during short and long-term space missions. Previous studies have argued that gravity may play a direct role in an individual's ability to perform mental transformations (Mast et al., 2003). In particular, mental operations have been shown to depend on both visual (Preuss, et al., 2013) as well as vestibular cues (Grabherr et al. 2007, 2011), which may therefore be impacted in weightlessness conditions. However, results regarding the effects of microgravity on mental rotations have been mixed (Matsakis et al., 1992; Leone et al., 1995). Here, we specifically designed our paradigm to assess mental rotation performance in a realistic operational context of space missions, employing a collaborative task similar to what astronauts may have to perform while onboard a spacecraft. In spite the ecological nature of the paradigm, the design still allowed us to maintain tight experimental control of relevant parameters, and several additional conditions were included to control for various nuisance effects (e.g., training effect, stress during the flight, etc.).

We analyzed the data from 11 subjects collected over one parabolic flight campaign. Analysis of ground performance confirmed the validity of our protocol (drop in performance, both in terms of response times and success rates, in the test conditions requiring perspective-taking compared to control conditions). Comparison of pre- and post-flight data revealed a significant improvement in performance (only in terms of RTs), which we attributed to an increase in familiarity with the response apparatus across subjects. Next, comparison of post-flight and in-flight data collected in 1g indicated that there was no nuisance factors during the flight (e.g., stress) that affected performance. Regarding testing for an effect of microgravity on perspective-taking abilities, results suggested a selective facilitation in 0g which remains to be confirmed with a higher sample size. Moreover, this putative facilitation appeared to be more pronounced in subjects who had been identified as non visual field-dependent via a classic rod-and-frame test. These conclusions are still preliminary, and will require additional analyses. It will be useful to analyze for instance RT of correct and incorrect responses separately, as they may reflect different response strategies. Further, it may be relevant to determine whether subjective workload data confirm, or even further extend the behavioral data in the perspective-taking task. Though findings of short-term experiments from parabolic flight involving naïve subjects may not be generalized with long-term experiments involving highly trained astronauts, the present results taken together strongly suggest that our paradigm constitutes a powerful platform to evaluate perspective-taking abilities in a microgravity environment.

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