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Gravity and spatial orientation in virtual 3D-mazes

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Abstract. In order to bring new insights into the processing of 3D spatial information, we conducted experiments on the capacity of human subjects to memorize 3D-structured environments, such as buildings with several floors or the potentially complex 3D structure of an orbital space station. We had subjects move passively in one of two different exploration modes, through a visual virtual environment that consisted of a series of connected tunnels. In *upright* displacement, self-rotation when going around corners in the tunnels was limited to yaw rotations. For horizontal translations, subjects faced forward in the direction of motion. When moving up or down through vertical segments of the 3D tunnels, however, subjects facing the tunnel wall, remaining *upright* as if moving up and down in a glass elevator. In the *unconstrained* displacement mode, subjects would appear to climb or dive face-forward when moving vertically; thus, in this mode subjects could experience visual flow consistent with rotations about any of the 3 canonical axes. In a previous experiment, subjects were asked to determine whether a static, outside view of a test tunnel corresponded or not to the tunnel through which they had just passed. Results showed that performance was better on this task for the *upright* than for the *unconstrained* displacement mode; i.e. when subjects remained "upright" with respect to the virtual environment as defined by subject's posture in the first segment. This effect suggests that gravity may provide a key reference frame used in the shift between egocentric and allocentric representations of the 3D virtual world. To check whether it is the polarizing effects of gravity that leads to the favoring of the *upright* displacement mode, the experimental paradigm was adapted for orbital flight and performed by cosmonauts onboard the International Space Station. For these flight experiments the previous recognition task was replaced by a computerized reconstruction task, which proved to be more efficient in terms of the time required to achieve reliable results. Suppressing gravity did not immediately affect relative performance between the two modes, indicating that on-line graviceptor information is not directly responsible for this differential effect. Trends in the evolution of responses over the course of a 10-day mission, however, suggest that human subjects might adapt their ability to represent internally complex 3D displacements.

Keywords: Gravity, orbital flight, spatial memory, human, 3D-maze, virtual reality

1. Introduction

Human navigation involves an updating process of spatial information, accompanied by the development of spatial knowledge. Spatial updating is performed on the basis of both the integration of one's displacements and the recognition of environmental landmarks along the way. Although recent investigations have brought new insights into the mechanisms of spatial memory and cognitive strategies during navigation, most have concentrated on 2D navigation, this being the most common mode of navigation on Earth. These studies have therefore been largely restricted to planar spatial configurations with subjects performing displacements in an *upright* position with respect to gravity. In such conditions only yaw turns must be taken into account to solve spatial tasks.

Relatively little is known about 3D spatial memory,

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despite the fact that it is of importance in modern societies. Going from one point to another inside of a building is a typical situation requiring 3D spatial processing by the brain, and it occurs in everyday life. Only a few studies have addressed the issue of elevation during navigation and how the brain might process it. Gärling et al. [4] studied the encoding and recall of elevation information by asking subjects to estimate from memory the difference of elevation between famous landmarks within the same city. The results showed that the information on elevation that can be retrieved is not very precise. Furthermore, retrieval of this information is not achieved through a 'mental traveling process' between landmarks because decision times are not correlated with the distance separating them. This result suggests that altitude is processed independently of the horizontal dimensions. Montello and Pick [12] used a pointing task to compare the learning of spatial configurations of landmarks within or between layers of building's superimposed floors. They found that the pointing performance was slower and less accurate between layers than within layers. In fact, mental representations of the spatial configuration of landmarks for each layer were correct, and subjects could establish links between layers, although this was harder than retaining spatial information within one specific layer. These results support the idea that humans cannot easily construct 3D cognitive maps. Instead, navigation inside of buildings probably generates specific cognitive maps for each 2D layer. This suggests a clear difference between vertical and horizontal dimensions in processing and storage of spatial information for navigation.

Navigation in weightlessness inside of a space station provides another situation requiring the treatment of 3D spatial information. Although this situation is experienced much less frequently, it is thought to be useful for understanding the processes underlying spatial navigation as well as for testing hypotheses about the use of gravity as a reference frame. The suppression of the gravitational reference frame engenders many orientation problems often reported by cosmonauts in space [6], and in parabolic flights [8]. Spatial orientation problems in weightlessness include effects such as inversion illusions, visual reorientation illusions, extravehicular height vertigo and disturbed spatial memory [13]. The absence of gravity affects the way human subjects estimate the subjective vertical [11], which could explain some orientation illusions experienced in microgravity and the individual differences concerning them. The perception and storage of the orientation of a visual line combines both gravity and proprioceptive frames of reference: when both are present and aligned, or when gravity is absent, there is a preference for vertical and horizontal directions (a so called "oblique effect"). When gravitational and proprioceptive references are in conflict, however, there is no preferred direction [9]. Since gravity appears to be a crucial reference used for human spatial orientation and navigation on earth; once removed, perceptual strategies need to be altered.

The 2D versus 3D nature of spatial memory has been addressed in animal studies in which the directional organization of place cells and head-direction cells in hippocampal structures has been examined. Place cells appear to encode a rat's position in two-dimensional maps aligned with the horizontal plane. Head-direction cells of rats [15] appear to discharge preferentially according to the alignment of the head projected onto the gravitational horizontal plane (i.e. independent of the head's pitch orientation). In a recent study Knierim et al. [7] exploited the conditions of microgravity to test for a role of gravity in the neural activity of rats navigating in 3D. In weightlessness, one might guess that the horizontal plane associated with place cells and head direction cells would probably be projected onto the surface upon which the animal is walking. A modified Escher staircase was used in orbital flight in which 3 horizontal and 3 vertical turns separated by linear segments of equal length were sufficient to bring the rat back to its starting position. This special configuration is interesting because of the implications for the encoding of spatial information. If only yaw rotations are taken into account when updating internal spatial maps, integration of three 90° yaw rotations would not normally bring the animal back to the starting point. Recordings of hippocampal place cells revealed that no confusion was made by the representational system: after the six 90° turns place cells associated with the starting position in the maze were still firing, as if the rats "knew" they had come back to the starting point. The means by which 3D spatial information is encoded in what appear to be 2D maps therefore remains unclear.

2. Aims of the investigation

In a previous study [16], we tested different relationships between egocentric and allocentric frames of references for the memorization of complex 3D-structured environments. Subjects watched images of virtual environments displayed on a computer screen.

Images were updated continuously to simulate passive movements through 3D tunnels (tubular structures with stone-textured walls). These structures could represent buildings with several floors or the complex 3D structure of an orbital space station. Different displacement modes were compared, inspired by modes of navigation that might be observed in terrestrial and weightless conditions. In the most natural *upright* mode, corresponding to normal locomotion on Earth (Fig. 1 left), self-rotation when going around corners in the tunnels was limited to only yaw rotations. For horizontal translations, subjects faced forward in the direction of motion. When moving up or down through vertical segments of the 3D tunnels, however, subjects faced the tunnel wall, remaining *upright* as if moving up and down in a glass elevator. In the *unconstrained* displacement mode, which is analogous to what can be achieved in a weightless environment (Fig. 1 right), subjects would appear to climb or dive face-forward when moving vertically. Apparent rotations in curved sections were always around the single, most direct axis that would align the gaze with the axis of the tunnel. Thus, in this mode subjects could experience visual flow consistent with rotations about any of the 3 canonical axes, and the body orientation with respect to gravity (as defined by the initial *upright* posture) could vary. Following the passage through a tunnel using one such displacement mode, the cognitive task was to identify amongst four outside views presented successively, the 3D structure corresponding to the trajectory just experienced.

Tests performed on human subjects on the ground showed that the constrained *upright* mode, i.e. the mode that respects the constraints imposed by gravity, produced significantly higher recognition accuracy and lower reaction time, as compared to the *unconstrained* mode. For tunnels with 4 and 5 segments, data from 16 subjects revealed accuracy and reaction times (mean $\pm$ SE) of 82.8 $\pm$ 5.3% and 2360 $\pm$ 220 ms for the *upright* mode, and 68.0 $\pm$ 5.0% and 2750 $\pm$ 330 ms for the *unconstrained* mode. This difference between the two modes increased with the complexity of the tunnel, i.e. when the number of segments increased. The diminished performance for the *unconstrained* displacement mode may stem from the increased sensory conflict inherent in this condition. In both cases (*upright* and *unconstrained*) subjects had to dissociate information provided in the optic flow field indicating self-movement from semi-circular canal and proprioceptive information that corresponded to a fixed position in space. The *unconstrained* mode, however, added an additional conflict between otoliths and the visual flow field about the orientation of the body axis with respect to gravity. Alternatively, the differences may stem from the complexity of changing reference frames as subjects move through the tunnel. In order to construct a spatial representation of the tunnel, subjects must deduce from each apparent turn in an egocentric reference frame what will be the direction of the subsequent segment in an allocentric reference frame as seen from the outside. This transformation from egocentric to allocentric reference frames is easier in the *upright* mode because it involves only a rotation about the body vertical axis. Furthermore, in the *upright* displacement mode the up/down direction of the visual scene is locked to the up/down direction defined by gravity. This linkage to a stable reference might facilitate the task of integrating visual information from different viewpoints (internal and external).

In the current study we set out to test whether the improved performance for a natural, terrestrial mode of displacement stems from a direct influence of online graviceptor information or from a cognitive representation of the body's *upright* posture. We hypothesized that removing the effects of gravity on otolith organs would reduce the sensory conflict that subjects normally experience in the *unconstrained* displacement mode. This could conceivable lead to an increase in performance for this mode in the absence of gravity. Conversely, removing the stable reference provided by gravity increases uncertainty in the transfer of information between reference frames. From this one might expect a decrease in performance even in the *upright* displacement mode. Finally, practice with actual *unconstrained* movements in conditions of microgravity might allow subjects to improve their ability to integrate and store displacements that include both pitch and yaw body rotations. In this case, one could expect to see over the course of time spent in a weightless environment an improvement in performance for this 3D reconstruction task performed in the *unconstrained* mode. To test these hypotheses, three cosmonauts performed a modified version of the above-described experiment on the ground and in conditions of microgravity. These tests were performed as part of the scientific program of the Andromède mission to the International Space Station (ISS) in October – November 2001.

3. Materials and methods

3.1. Subjects

Five cosmonauts participated in this experiment, three from the main crew (denoted A, B and C) and two

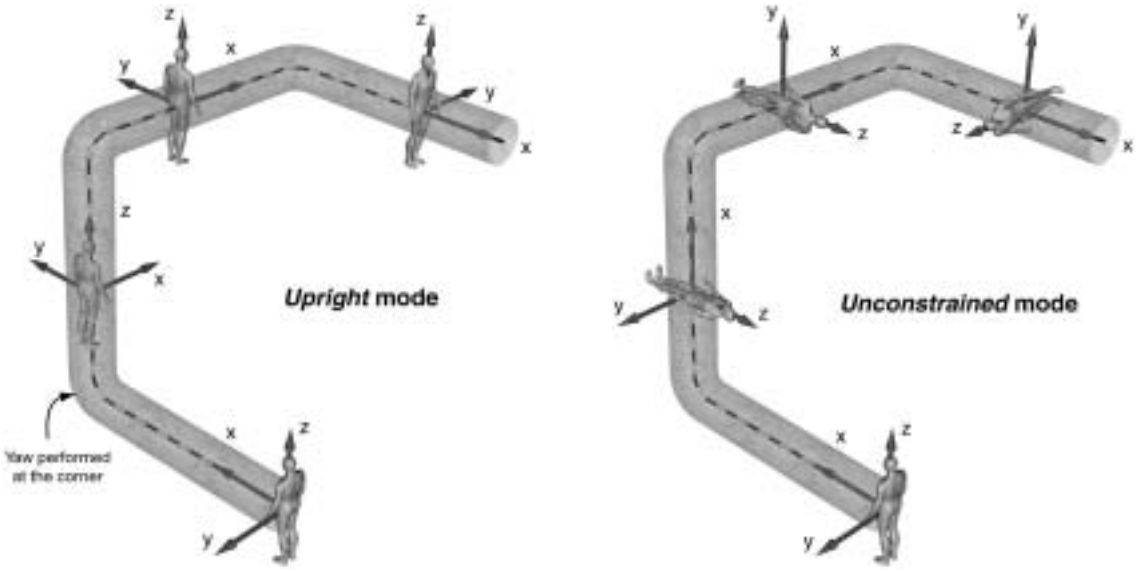

Fig. 1.

from the backup crew. Cosmonauts from the backup crew only performed the pre-flight sessions, therefore their results will not be reported here.

3.2. Experimental set-up

A laptop computer was used to generate visual flow corresponding to virtual motion inside of tunnels (Fig. 2). The vertical and horizontal field of view was 40° for a fixed viewing distance from the laptop screen of 32 cm. A cylinder with a mask was used to remove any visual disturbance from the outside and to maintain the subject's head in the right position with respect to the screen. In ground sessions, subjects were always seated with the laptop set on a table. In flight, subjects were restrained by straps to recreate the same posture as on the ground with regard to the apparatus. Using this apparatus, subjects observed virtual motions through the tunnels, reconstructed the 3D structure of the virtual tunnels and performed a verbal memory task (to be described below). Responses to the visual stimuli were recorded via a small keypad attached to the thigh of the subject or via the principal keyboard of the laptop computer. The stimuli for the verbal task were played through headphones, and the vocal responses recorded with a microphone.

3.3. Procedure

3.3.1. Trials

Each trial of the experiment included viewing of a virtual displacement followed by a reconstruction task. During the exploration phase subjects were driven passively at constant speed through a cylindrical 3D tunnel made of stones (see Fig. 3). Tunnels were comprised of linear, cylindrical segments placed at right angles and connected by curved sections (90° segments of a torus). The linear segments all had the same length and were aligned with one of the canonical axes (see Fig. 1). Each tunnel could be composed from 4, 5 or 6 such linear segments. Subjects were not informed in advance of either the complexity of the tunnel or the displacement mode to be used in each trial.

During the reconstruction task, subjects were asked to recreate via the keypad an external image of the remembered 3D-shape of the tunnel (see Fig. 4). They were first shown an external view of the first segment with four arrows labeled from 1 to 4 indicating the four possible directions of the next segment. Each segment was reconstructed by pressing the key corresponding to the label of the chosen red arrow. Once the correct number of segments was entered, a message appeared asking the subject to confirm the drawing by pressing the *validate* key. At any time, subjects could correct their last choice by pressing the *cancel* key.

Trials were self paced – subjects triggered each trial by pressing a specified key when ready. After each block of eight trials, a score calculated as the average accuracy for the 8 responses was displayed, followed by a suggestion to take a brief pause. Feedback on average accuracy was given in order to keep subjects motivated during the whole experimental session. Through this score, subjects were made aware of overall performance

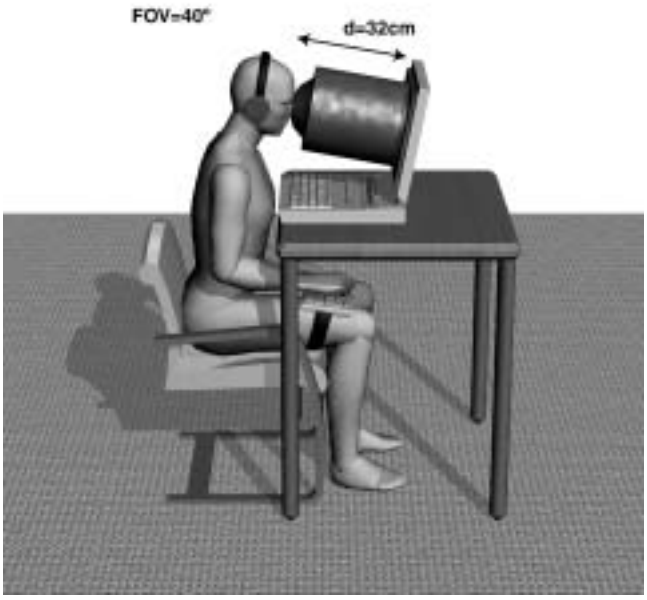

Fig. 2.

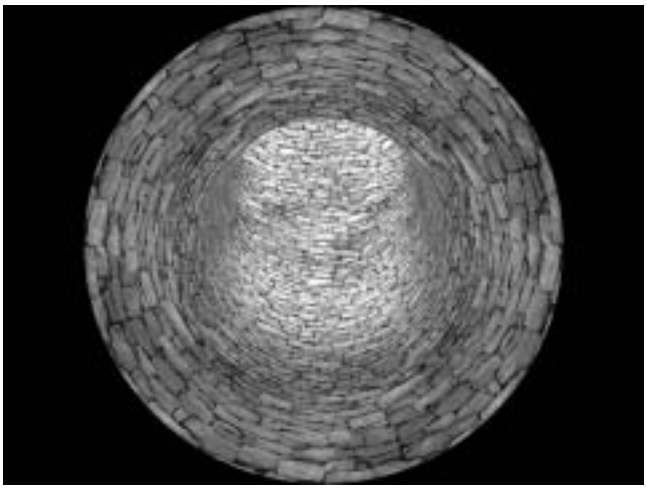

Fig. 3.

but received no information about what specific errors were committed.

3.3.2. Displacement modes

Two displacement modes, *upright* and *unconstrained* were tested, as described in the introduction. In the *unconstrained* mode a single yaw- or pitch-rotation was performed at each junction to reorient the line of sight with the next segment. Through successive pitch and yaw rotations, the implicit body position could be aligned at a given moment with any of the three canonical axes of the 3D space. In the *upright* mode, the head was always kept *upright*; in vertical segments the walls scrolled up or down in front of the subject as if inside a transparent elevator. In all displacement modes gaze-orientation rotated in anticipation of each turn as it would be done in natural conditions [5,17]. Tangential velocity was kept constant during the entire movement both in the linear and circular sections of the tunnel.

The viewing conditions in the *unconstrained* mode

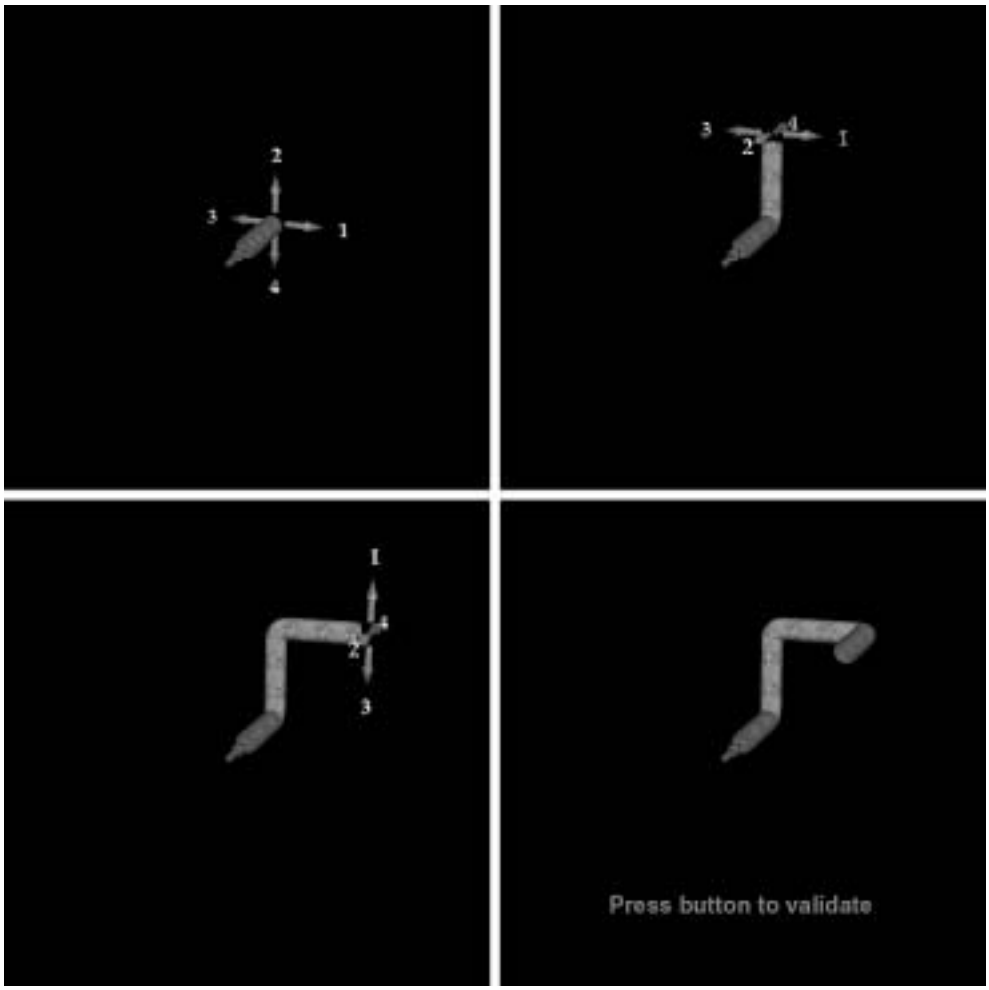

Fig. 4.

gave subjects advance information about the orientation of the upcoming segment in the 3D structure. In this mode, the viewing direction always pointed towards the end of the current segment where the next turn could be seen. Therefore, subjects always knew which direction was coming up next. In the *upright* mode, this advance warning about the direction of an upcoming turn would not normally be available in vertical segments in which subjects viewed the wall of the tunnel. To provide the same advance notice of the upcoming turn direction even in the *upright* mode, an additional yaw rotation was performed just before entering a vertical segment (see left panel of Fig. 1) so as to orient gaze to the direction to be taken after going up or down.

3.3.3. Dual-task and verbal span test

In order to avoid memorization of a verbal sequence of the directions taken in corridors (e.g. "left", "up", "left", "right"...), subjects were required to perform a dual-task to occupy verbal working memory. The primary task of reconstructing the tunnel involved high-level manipulations of spatial representations; it is therefore processed by the visuo-spatial sketchpad (according to Baddeley's model of working memory [1]), which is largely independent of verbal working memory. Loading verbal memory in a dual-task would prevent its use as an alternate encoding strategy for the corridor's shapes. At the very beginning of each trial, a sequence of four random numbers in the range of 20 to 59 were played in the headphones and subjects had to memorize them in the correct order. Just after the reconstruction task, they were required to recall and orally repeat this sequence of numbers, their answers being recorded by a microphone.

Due to the high level of competition for the elite position of cosmonaut, capacity of memorization is proba-

bly a selection criterion, either implicit or explicit, used to select among candidates for this job. Moreover, during their training cosmonauts often have to memorize numbers and lists of items. In order to calibrate the dual-task of the experiment, we measured the verbal memory span of our subjects for lists of numbers. Cosmonauts were submitted to a classical span test [10], as follows:

While an instruction to memorize the numbers was presented in the screen, subjects were successively given through the headphones N random numbers in the range from 20 to 59. As for the dual-task, an audio presentation of the numbers was used rather than a visual presentation in order to avoid recall through visual processes. After a black screen was presented for 6 seconds, subjects were asked to recall in the correct order the memorized numbers. The recalled sequence was recorded with the keyboard, corrections being allowed with the backspace key. The initial number of numbers to be memorized on the first trial was set to $N = 2$. If the recall was correct, the same test was done with $N = N + 1$, otherwise the test was repeated once. After two successive failures, the test ended and subject's verbal span was determined to be N–1.

Verbal span for all cosmonauts measured by this test was above or equal to 5. We set the number of numbers to be memorized in the dual-task to four in order to stay below saturation, while keeping a high level of verbal memory load.

3.3.4. Session plan

Cosmonauts spent 10 days in the weightless conditions of orbit, with 2 days onboard the Soyuz spacecraft and 8 days aboard the ISS. The experiment was scheduled to be performed 2 times on 2 separate days during the time aboard the ISS, with 3 days between sessions. To facilitate comparisons between ground and inflight data which might be affected by the time period between sessions, three one-week test periods were scheduled on the ground, two before the flight (denoted L-60 BDC and L-30 BDC, corresponding to periods $\sim$60 and $\sim$30 days prior to launch) and one after the flight (during the week immediately after return to Earth). Subjects performed the experiment twice on two separate days during each of these ground periods, with 2 days in between. Subjects also performed two sets of 2 training sessions, once in the period prior to the L-60 test sessions and once between the L-60 and L-30 test sessions.

Each experimental session lasted approximately one hour. Subjects performed 32 trials in each session with stimuli drawn from predefined catalogues comprised of 2 displacement modes $\times 2$ tunnel lengths (number of segments) $\times 8$ segment configurations for each tunnel length (out of all the combinations of 90° turns possible for a tunnel of that length). Six such catalogues were used over the course of the experiment: two training catalogues Tr1 containing tunnels with 4 and 5 segments, used during the first training sessions; a second pair of training catalogues Tr2 containing tunnels with 5 and 6 segments, used in subsequent training sessions; and the true test catalogues TST, also containing tunnels with 5 and 6 segments.

Table 1 summarizes the testing and training schedule for this experiment. The rationale for the experiment design was as follows: First, it was expected that subjects might show a learning effect on the performance of this task. Cosmonaut subjects were therefore required to perform the task multiple times before the flight, with the hopes that they would reached a stable plateau in performance before the last pre-flight session. This allowed us to compare the pre-flight, in-flight and post-flight results in order to differentiate the influence of gravity from training effects in the cognitive processing of the task. Second, the specific stimuli with a set of 32 trials might affect performance. Thus, it was important to use the same catalogues of stimuli both on the ground and inflight. Different catalogues were used in training and testing periods, however, in order to avoid over-familiarity with the specific stimuli from a given catalogue. Finally, two different catalogues of similar complexity were used for the two sessions within a given period in order to avoid learning of the trial sequences. This design, rather than a truly random presentation of all possible stimuli, was driven by the small number of subjects available for this study. For a random presentation to a large number of subjects, effects of stimulus catalogue and presentation order are expected to cancel out in the average. For the small number of subjects here, however, there is a risk that inflight stimuli might be easier or harder than ground stimuli just by chance. In the design used here, we were susceptible to effects of stimulus complexity and sequence order, but because these effects were common across all gravitational conditions, these effects should cancel out in the comparison between 0 g and 1 g data.

3.4. Data analysis

For each trial, the total *reconstruction latency* and the *score* reflecting the accuracy of the response were computed. Reconstruction latency was computed as

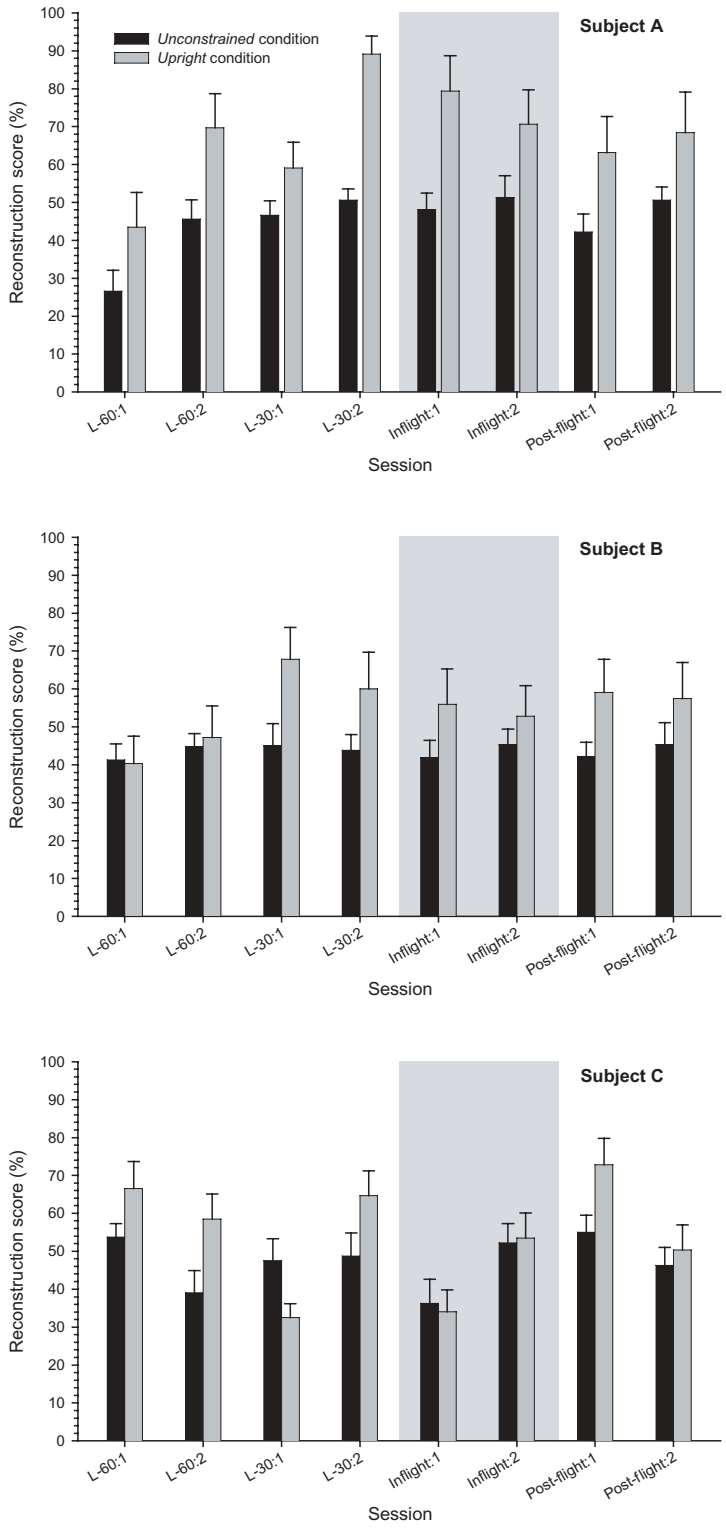
Subject A
Unconstrained condition
Upright condition
Reconstruction score (%)
Session
L-60:1
L-60:2
L-30:1
L-30:2
Inflight:1
Inflight:2
Post-flight:1
Post-flight:2
Subject B
Subject C

Fig. 5.

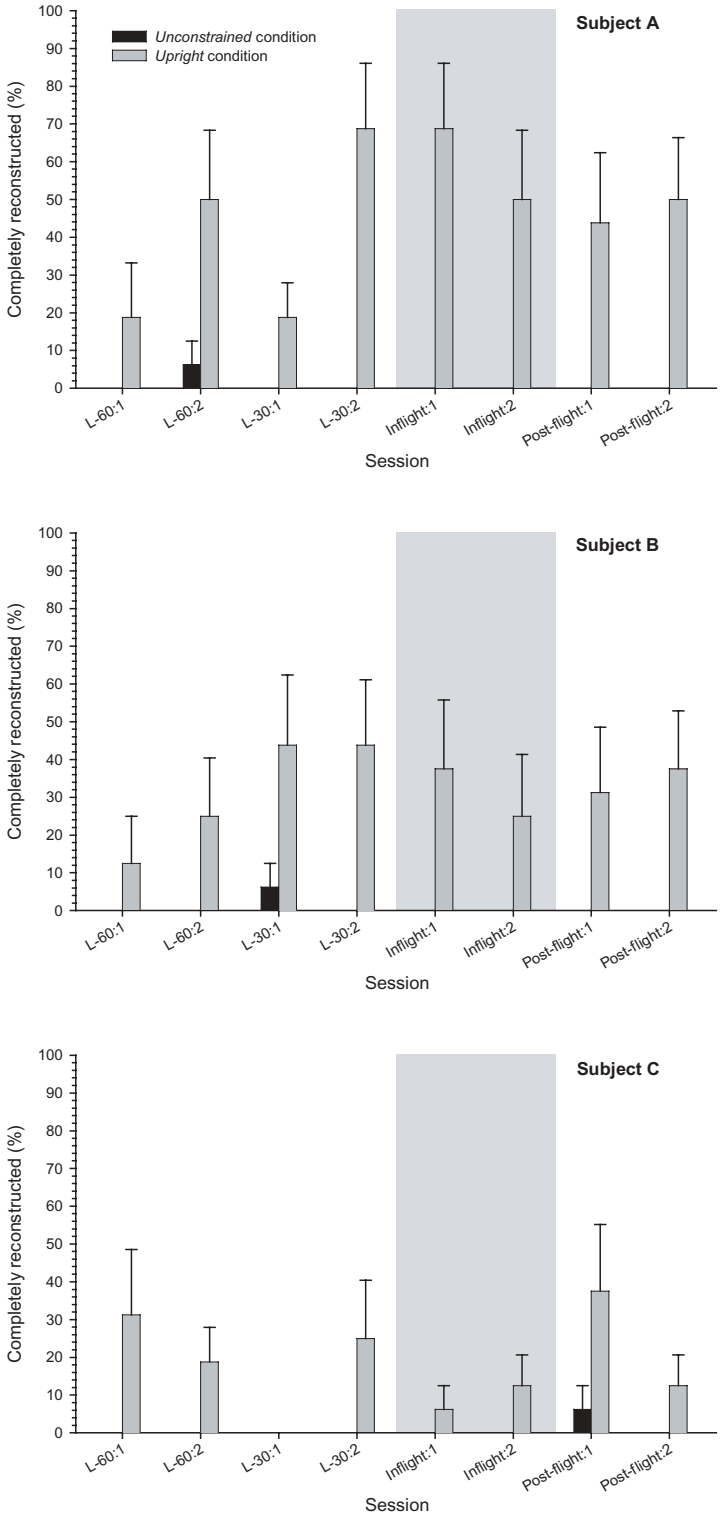
Subject A
Unconstrained condition
Upright condition
Completely reconstructed (%)
Session
L-60:1
L-60:2
L-30:1
L-30:2
Inflight:1
Inflight:2
Post-flight:1
Post-flight:2
Subject B
Completely reconstructed (%)
Session
Subject C
Completely reconstructed (%)
Session

Fig. 6.

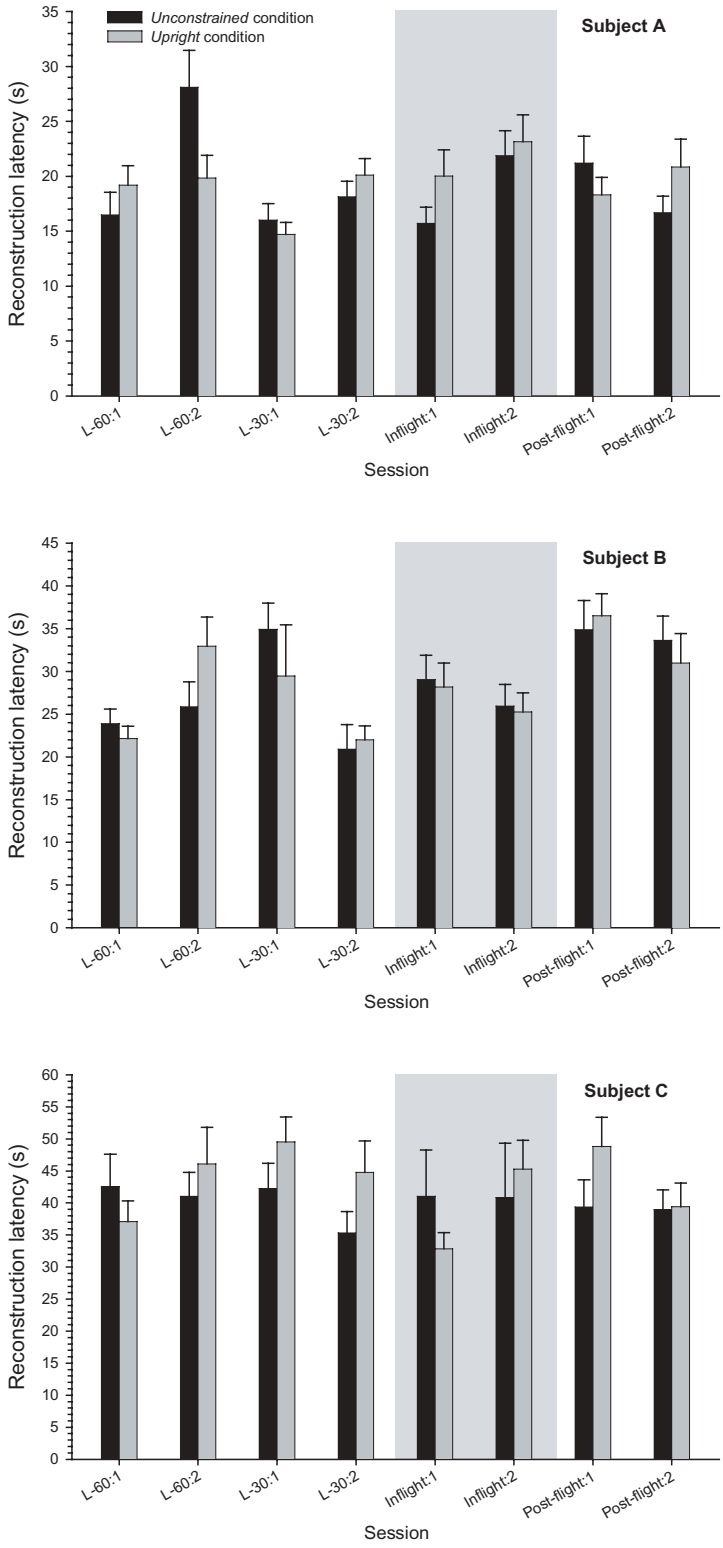
Unconstrained condition
Upright condition
Subject A
Subject B
Subject C
Reconstruction latency (s)
Session
L-60:1
L-60:2
L-30:1
L-30:2
Inflight:1
Inflight:2
Post-flight:1
Post-flight:2

Fig. 7.

Table 1

Period	Dates	Catalogue	Notes
Training 1	08/01 – 08/20	Tr1	
L-60 BDC	08/21 – 08/24	TST	2 days between tests
Training 2	8/24 – 9/17	Tr2	
L-30 BDC	09/17 – 09/21	TST	2 days between tests
Inflight	10/26 – 10/28	TST	Flight Days 6 and 8
Post-flight	11/02 – 11/06	TST	Days 2 and 4 after touchdown

the time between the presentation of the initial segment in the response phase and the press of the validate button to confirm the response. The *score* at the task corresponded to the number of segments reconstructed correctly from the beginning excluding the first segment, divided by the total number of segments of the corridor minus one. For instance, if the corridor had 5 segments, and the first three segments only were correct the score would be $(3-1)/(5-1) = 50\%$.

The chance level for a random reconstruction of corridors with n segments is given by the following formula:

$$\prod_n = \left(\frac{1}{4}\right)^{n-1} \cdot 1 + \sum_{k=n-2}^{1} \frac{3}{4}\left(\frac{1}{4}\right)^{k} \cdot \frac{k}{n-1}$$

The chance level is at 10.9%, 8.3% and 6.7% for respectively 4-, 5- and 6-segments corridor, which makes an average chance level of 7.5% for balanced groups of trials containing the same number of 5- and 6-segments corridors.

Because of the small number of participants in this experiment, meaningful statistical analyses cannot be performed that would reflect general tendencies in the human population (or even the cosmonaut population) as a whole. In order to compare *intra*-individual performance for *these subjects* across displacement modes we performed analyses of variance (ANOVA) separately for the latencies and scores of each subject. We contrasted test period (4 levels: L-60, L-30, flight and post-flight) $\times$ session repetition within the period (2 levels: 1 and 2) $\times$ number of segments (2 levels: 5 or 6) $\times$ displacement mode (2 levels: *upright* and *unconstrained*).

4. Results

4.1. Reconstruction score

Subjects' individual scores at the reconstruction task averaged by displacement mode, test period and experimental session are presented in Fig. 5. Starting from the first acquisition session, all subjects had average scores well above chance level (i.e. $> 7.5\%$). Qualitatively, subjects A and B produced regular patterns during pre-flight test periods – performance was better for the *upright* mode than for the *unconstrained* mode, consistent with normative data from our previous ground experiments. Subject C responses were slightly less consistent across preflight sessions – performance of this subject for the *upright* mode was lower than for the *unconstrained* mode in ground session L-30(1).

Global performance of each subject was significantly lower for 6 segments than for 5 segments, with a significant mean decrease of 12.7% (F(1,7)=8.90 ; $p < 0.02$) and 12.2% (F(1,7)=15.01 ; $p < 0.01$) for subjects A and B, respectively. No interaction was found with any of the other experimental factors, in particular with the displacement mode. Subjects A and B seem to have reached their learning saturation after the first L-60 session in that post-flight performances was not higher than L-30 pre-flight levels. We can thus compare performances between the L-30 period, the in-flight period and the post-flight period. From the L-30 sessions onward, performance for the *upright* mode were significantly higher than for the *unconstrained* mode (with an average difference of 23.4% for subject A (F(1,7)=17.19 ; $p < 0.005$) and 14.9% for subject B (F(1,7)=7.18 ; $p < 0.04$)). This difference was also significant for each session in-flight except for flight session (2) of subject B. Curiously, subject C showed no difference between the two displacement modes in-flight.

For subject A, performances for the second session within each test period on the ground were significantly higher than for first session (with respectively 10.5% and 20.5% of difference in average for the *unconstrained* mode (F(1,7)=11.02 ; $p < 0.02$) and *upright* mode (F(1,7)=10.89 ; $p < 0.02$)), this was not the case for the flight period. The lapse of time separating the two sessions within the same period being much shorter than the one between periods, short-term practice effects were probably responsible for this observation. The interaction between test period (L-30 vs. flight) $\pm$ session (first vs. second) $\pm$ displacement mode (*upright* vs. *unconstrained*) was signifi-

cant (F(1,7)=11.00 ; $p < 0.013$) indicating that there was a difference in the short-term practice effect for ground versus inflight sessions. None of these properties could be demonstrated statistically for subjects B and C, although subject B shows a similar trend.

Considering each displacement mode separately across and within test periods, not only was performance for subjects A and B in the *upright* mode slightly lower inflight compared to the second session of the L-30 preflight tests, but performance also decreased between the first and the second inflight sessions (dropping from 79.4% to 70.6% for A and from 56.0% to 52.8% for B). In contrast, inflight performance observed for the *unconstrained* mode was equivalent to that of the ground sessions, and still slightly increased between the two sessions (rising from 48.1% to 51.3% for A and from 41.9% to 45.3% for B). The difference between displacement modes for subject B was greater in the post-flight period, as compared to the inflight period, with a difference of 7.5% in-flight (2) and 16.9% in post-flight (1), whereas for subject A this differential was approximately the same for the second in-flight session and the first post-flight session.

Since performance of subject C observed inflight in both displacement modes increased from about 35% in the first session to 53% in the second session, it could be suggested that the anxiety resulting from a first experience of flying in space was responsible for the low performance level at the first session, and probably also for the difference with the results yielded by the two other cosmonauts. For this subject the first post-flight session showed a difference of 17.8% between the *unconstrained* and the *upright* modes, consistent with the other two subjects.

The percentage of trials in which subjects reconstructed the tunnel shape with 100% accuracy is presented in Fig. 6. The first striking result is that subjects could not completely reconstruct any of the tunnels in the *unconstrained* mode, whereas in the *upright* mode the mean percentage of trials in which the tunnel was accurately produced (including L-30, inflight and post-flight sessions) was of 50.0%, 36.5% and 15.6% for subject A, B, and C, respectively. The second result is that for the *upright* mode, the percentage of completely reconstructed tunnels and the reconstruction score have a very similar evolution across sessions. If we look at the flight period for subjects A and B, the performance drop between the first and the second session was more contrasted with this measure (percentage of completely reconstructed tunnels) than with the one observed for the reconstruction score. Indeed, by using this measure of reconstruction accuracy, the interaction between the periods (ground vs. flight) and session (first vs. second) was significant for subject A (F(1,7)=9.10; $p < 0.02$), and almost for subject B (F(1,7)=4.76; $p < 0.06$).

4.2. Reconstruction latency

Individual latencies for subjects on the reconstruction task averaged by displacement mode and grouped by successive experimental sessions are presented in Fig. 7. Subject A responded more slowly on orbit, taking on average 1.1 s more to execute the task in space than during the last pre-flight ground sessions, whereas subjects B and C responded more quickly, taking 1.9 s and 2.1 s less time to respond on orbit. Interestingly, subject A's latency for the *unconstrained* mode decreased by 0.6 s on average in space (from 19.4 s to 18.8 s) while for the *upright* mode it increased by 2.8 s (from 18.8 s to 21.6 s). Subject B's latency averages were approximately the same for both displacement modes, with respectively 29.0 s for ground sessions and 27.1 s for in-flight sessions. Subject C latency's averages were lower for the *upright* mode in space (by 5.2 s) while they were higher for *unconstrained* mode (by 1 s).

4.3. Dual-task performances

Table 2 presents the cosmonauts' performance at the dual-task for the two displacement modes and according to each mission period. The numbers recalled-score was rather independent of the displacement mode, thus the dual-task could not be responsible for the differences observed in the spatial reconstruction task. Performance slightly decreased inflight. Subjects A and B recalled the numbers of the dual-task with a high level of accuracy, suggesting that they had at least partially loaded the verbal working memory and that their strategy at the main task did not entirely rely on verbal memorization of the corridor's directions.

5. Discussion

The advantage of the *upright* mode over the *unconstrained* mode was observed individually in nearly every session. This leads us to the strongest conclusion that can be made from this study, given the limited number of subjects in this experiment: on-line sensation of body orientation provided by the sensation of gravitational acceleration through vestibular and proprio-

Table 2

	L-60		L-30		Inflight		Post-flight	
	Upright	Unconstrained	Upright	Unconstrained	Upright	Unconstrained	Upright	Unconstrained
Subject A	84.4%	87.5%	96.9%	95.8%	84.4%	84.4%	87.5%	75.0%
Subject B	84.4%	88.5%	82.3%	83.3%	69.8%	66.7%	70.8%	79.2%
Subject C	56.3%	66.7%	64.6%	62.5%	34.4%	32.3%	41.7%	52.1%

ceptive cues is not the direct source of the preference for the *upright* mode of self-motion for reconstructing the 3D structure of the tunnel. Were this the case, the suppression of gravity would have resulted in an immediate equilibration of performance between the two displacement modes. In order to perform the spatial reconstruction task, participants had to create a mental image or representation of the environment structure while moving inside it. Since perception was done in an egocentric reference frame and recognition task in an allocentric reference frame, a reference shift had to be performed while exploring to build the mental image segment by segment. This required different kinds of mental rotations: rotations about the three canonical axes for the *unconstrained* mode and only rotations about the body axis. In a parallel study [16] we tested whether on Earth the preference for the *upright* mode was due to the fact that only one type of rotation (i.e. yaw rotation) was needed in this mode. Trials in which self-rotation was limited to pitch rotations did not lead to the same improved performance with respect to the *unconstrained* displacement mode. Thus, one cannot attribute the differences in displacement mode to the 'simpler' stimuli observed in the *upright* mode. From the results obtained in microgravity we conclude that the sensory conflict between visual and otolithic information on the ground cannot explain the differences in performance for the different displacement modes. Nor does the stable reference frame provide by gravity account for the differences be sistent with the results in the literature on mental rotation. Evidence has been found supporting the idea that 1) hand rotations about the vertical axis are easier than about another axis [14], and 2) the alignment of the rotation axis with the body axis rather than with gravity is responsible for this improvement [2]. Other factors like the visual polarization of space that also contribute to the spatial orientation [13,18] appear to have a stronger influence. While care must be taken before extrapolating these results to human beings as a whole, these three subjects provide an existence proof for an effect of cognitive influences involving an internal representation of an *upright* position of the body.

Some more, albeit anecdotal, observations can be made concerning the adaptation of these effects to the conditions of microgravity. The overall results at the reconstruction task could indicate a different effect of weightlessness on the two different modes of displacement. First, we notice that performance for the *upright* mode in flight, although still better than for the *unconstrained* mode, was lower than that observed in the last ground session. Furthermore, there was an additional decrease in performance for this mode between the two inflight sessions. This is in contrast to the typical increase in performance achieved in the second session of each test period on the ground. Second, although performance on the *unconstrained* mode was essentially the same as on the ground at the beginning of the flight, performance for this mode did not decrease as it did for the *upright* mode between the first and second inflight sessions. Both of these observations would be consistent with a slow process of adaptation to the *unconstrained* microgravity environment. For instance, the adaptation to navigation in weightlessness could modify the weighting that is normally given to gravity when defining a stable reference for the cognitive processing of motion, which was the case for eye-movements [3]. Alternate strategies relying more on visual information and less on gravity would emerge. If one were to test the long-term evolution of performance on this task, one might in time observe a significant decrease in the advantage of the *upright* over the *unconstrained* modes of displacement, as suggested by these short term tendencies in microgravity.

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