NAVIGATING IN A VIRTUAL 3D-MAZE: TWO COMPETITIVE FRAMES OF REFERENCES FOR PERCEIVING AND MEMORISING

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Abstract

Although recent studies have brought new insights concerning the mechanisms of spatial memory and cognitive strategies during navigation, most of these studies have concerned 2D navigation and little is know concerning the problem of 3D spatial memory. In a previous experiment we have studied the influence of the relation between egocentric and allocentric frame of references on memorisation of complex 3D-structured environments in which one moved. These environments could represent buildings with several floors or a space station. In *terrestrial* navigation, self-motion includes yaw rotations and eventually vertical translations at vertical sections whereas in *weightless* navigation one can move along or turn about any axis. Results have shown that when only one mental rotation (the yaw) had to be performed to shift from egocentric to allocentric reference frame, memorisation of such corridors was improved. In a first experiment, we investigated if any single rotation axis is enough to facilitate this reference shift, and if not what in the *terrestrial* condition lead to better performances since three aligned axes could facilitate the reference shift (gravity, body and displacement's rotation axes). We compared in a computerised 3D-reproduction of the maze task the four conditions defined by dissociating these axes. Field dependent (FD) and independent (FI) subjects as determined by the rod and frame test showed distinct effects of the navigation conditions. FD group performances strongly degraded when gravity and body axis were conflicting, independently of the rotation axis whereas FI subjects performances only slightly decreased when the body was tilted and the rotation axis aligned with gravity. Besides tilting the body in the control condition only deteriorated performances for FD group. A third experiment was sent on board of the International Space Station and three cosmonauts were involved in this study. Since gravity could provide the reference frame for the *terrestrial* condition, we wanted to check if the suppression of sensed gravity would change the relative performances of *weightless* and *terrestrial* condition. Results apparently indicate that the suppression of sensed gravity doesn't affect at short term the performances of each condition, but could affect performances at long term in longer flights.

Keywords: spatial memory, reference frames, human, 3D-maze, virtual reality

I. Introduction

I.1. *Human navigation and 3D spatial problems*

Human spatial 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 which allows the retrieval of one's relative position, and then readjust the errors predicted by the integration of kinaesthetic cues. The visual and other sensory information processed are received according to an egocentric frame of reference. Their successive memorisation along a trajectory associated with landmarks is often qualified of "route knowledge". Once many distinct paths of a given environment are familiar, landmarks allows to connect these routes by transformation to allocentric frames of references, and "survey knowledge" of the environment emerges.

Although recent investigations have brought new insights concerning the mechanisms of spatial memory and cognitive strategies during navigation, most of them concerned 2D navigation. These studies were mostly restricted to planar spatial configurations and with the head standing upright with regard to the external reference provided by gravity. In such conditions only azimuth corresponding to yaw turns has to be integrated to solve spatial tasks. Little is know concerning the problem of 3D spatial memory, despite the fact that it takes a great 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. Navigation in weightless inside of a space station is another less frequent situation though useful to understand the underlying processes concerning both the use of a distinct displacement mode as well as the use gravity as a reference frame. Only a few studies have addressed the issue of elevation during navigation and how the brain might process it. Gärling et al. studied the encoding and recall of landmarks' elevation of a city (Gärling et al., 1990) by asking subjects to estimate from memory the difference of elevation between famous landmarks. The results have shown that low precision information of elevation can be retrieved, and that it is not through a 'mental travel process' between landmarks because decision times are not correlated with the distance separating them. It suggests that altitude is independent of the horizontal dimensions. Montello and Pick (Montello and Pick, 1993) used a pointing task to compare, either within or between layers, the learning of spatial configuration of landmarks along two distinct paths of a university's superimposed floors. They found that the pointing performance was slower and less accurate between than within layers. In fact mental representations of landmark's spatial configuration for each layer were correct, and subjects could establish links between layers, although it was harder than within one specific layer. These results supports the idea that the human brain cannot easily construct 3D cognitive maps, and probably navigating inside of buildings generates specific cognitive maps for each 2D layers. This suggests a clear difference in nature of processing and storage between information relative to vertical and horizontal dimensions.

Lets now introduce some findings about animal electrophysiology experiments that are of interest to this topic. The neural activity associated with 3D navigation in weightlessness was recently studied (Knierim et al., 2000). A modified Escher staircase was used in orbital flight (corresponding to a complex 3D path ending at the exact position of the starting point). Recordings of rats' hippocampal place cells revealed that no confusion was made by the representational system: after six 90°-turns, alternating leftward and upward, place cells associated with the maze beginning were still firing, as if they "knew" they had come back to the starting point. These results have to be carefully considered since they are inconsistent with recent findings on head direction cells of rats (Stackman et al., 2000): it discharges according to a preferred direction of the head alignment's projection in a gravitationally horizontal plane and independently of its pitch orientation. In weightlessness the horizontal plane associated with head direction cells is probably reoriented onto the surface the animal is walking on.

I.2. Considerations on reference frames

Describing the multiple representations of space in brain, Arbib (Arbib, 1991) introduced the problem saying "The representation of this quotidian space [of everyday action] in the brain is not one absolute space, but rather a patchwork of approximate spaces (partial representations) that link sensation to action”. It points out two important features of the brain: first that there is a lot of different spaces adapted to specific sensory input and motor output each one involving different reference frames, and second that these representations are not precise and finally it is the redundancy coming from the multiplicity of spaces concerning a particular problem that allows a rather good estimation and processing of the problem.

There are a lot of evidences provided by electrophysiological data recorded from rats that supports this idea of multiple reference frames handled by the brain. On one hand, we have the place cells from the hippocampus that discharge when the animal is around a certain place. It has been showed that the place associated to these cells can be defined according to a specific location but also according to a goal, landmark or starting position that can move relatively to the external reference frame (Gothard et al., 1996). With practice, place cells could also learn in a rotating platform to distinguish places from two reference frames: the rotating one relevant to the foraging task, and the static one relevant to the stable surrounding (Bures et al., 1997;Zinyuk et al., 2000). On the other hand, we have the head direction cells discharging when the head takes a specific direction. They can also be defined according to distinct reference frames mainly guided by vision (Zugaro et al., 2000): inside of a cylindrical arena, head direction cells are defined in the cylinder walls reference, but when removed they are defined in the room reference (Zugaro et al., 2001).

Studies about the contraversive pushing on neglect patients suggest that subjective body orientation is disturbed because of the cortical structures responsible for transforming sensory inputs into a cohesive reference frame for interpretation (Karnath, 1994), although gravity inputs seem not to interact with the orientation judgement, the bias being defined according to an egocentric reference frame (Karnath et al., 1998). It has been recently found that there is actually a second pathway for sensing the orientation of gravity used for control of posture (Karnath et al., 2000a;Karnath et al., 2000b) and visuo-motor control (Karnath, 1997) that is different than the one for orientation perception of the visual world. These studies support the idea that many distinct reference frames can be handled by the brain for specific processing, and sensory information is transformed for each specific use. This is often the case in motor control where the brain dispose of many reference frames according to the different motor task, for instance in a pointing task in 3D space it has been shown that a viewer-centred reference frame is used rather than an elbow centred (McIntyre et al., 1997).

In a previous investigation (Vidal et al., 2002), we have studied the influence of the relation between egocentric and allocentric frames of references on memorisation of complex 3D-structured environments in which one was passively driven. The environment's spatial structure could represent buildings with several floors or a space station. Different conditions were compared inspired of navigation in terrestrial, subaquatic and weightless elements. In *terrestrial* navigation, self-motion included yaw rotations and eventually vertical translations at vertical sections whereas in *weightless* navigation condition one could move along or turn about any axis. The task was to recognise among four successive outside views of corridors the correct travelled one. In order to perform this 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. Results have shown that in the terrestrial condition where only one mental rotation (in this case the yaw) had to be performed to shift from egocentric to allocentric reference frame, memorisation of such corridors was improved both in accuracy and in reaction time. This is consistent with an investigation concerning map reading for piloting in which it has been found that the simplest is the relation between the map reference frame and the environment to explore, the easiest will be spatial orientation (Péruch et al., 1995).

I.3. From mental rotations to cognitive maps

In order to understand the problematic of the investigations presented here, it is of interest to introduce findings on mental rotations. First of all, mental rotation of patterns involves rotation of a reference frame rather than rotation of a template-like representation (Robertson et al., 1987). In an experiment where subjects learned a 2D-structured array of objects, Easton et al. have demonstrated that the retrieval of relations between objects after imagined rotation or translation of the observer's point of view occurred by means of body-centred coordinate system, requiring therefore imagined body translation or rotation (Easton and Sholl, 1995). This is consistent with literature on mental rotation of displays: many studies have reported that performances in spatial updating of an object array where significantly better after imagined viewer rotation than after imagined object rotation (for a review (Wraga et al., 1999;Wraga et al., 2000)). Wraga et al. explain this discrepancy with the difficulty in the imagined array rotation that stem from inherent problems performing cohesive rotations of all components of the intrinsic representation, in contrast when the viewer moves the relative reference frame is automatically and naturally updated. An other explanation could be that mental transformation of images require at least partially motor processes in the brain: a motor dual-task by means of a joystick results in increasing performances of the image's mental rotation when the two rotations are compatible (Wexler et al., 1998), and the object imagined rotation reached nearly the viewer level when rotations included haptic information (Wraga et al., 2000).

Returning to our task described above, adding properly each segments to the mental representation while exploring the corridor also required the extraction of spatial relations after translation and rotations (which direction takes next turn). Therefore the mental construction was also done imagining ones rotation inside of the currently built representation. This mental rotation involved in the egocentric to allocentric shift was easier in the terrestrial condition because rotations were only about one axis corresponding to yaw rotations. But the rotation axis was aligned with two other axis defining two reference frames: the observer's main body axis and gravity's axis. In the current investigation we looked for the contribution of each of these alignments in the capacity to perform the mental rotation involved in the corridor's structure memorisation process. In a first experiment (called the ground experiment) we tilted these axes separating the alignment influences, and in a second experiment (called the space experiment) we simply suppressed the influence of the gravity reference frame.

II. 3D-Navigation, Ground Experiment

II.1. Problematic

Findings of a previous investigation revealed that in a natural terrestrial displacement condition that required mental rotations around only one axis (yaw) to update the environment's representation resulted in better performances than when rotations around the three canonical axes were required. In the first experiment we tried to answer to two questions. The first question rising is whether simply the fact of having to process a single rotation axis is enough to make the mental representation updating easier, or it has to be a particular axis. Since the single rotation axis of the terrestrial condition was aligned with both the main body and gravity axes, the second question rising is which reference frame contributed the most in improving the cognitive processes involved in memorizing a 3D-maze.

On one hand, we know that once body and gravity references will be conflicting by simply lying down subjects on their sides, some subject's performances will be affected by this conflict. For that reason, subject's field dependency was previously determined with the classical rod and frame test, and we expected to find correlations between this factor and subject's performances at the main task when lying down. On the other hand, we wondered whether the rotation axis of the displacement aligned with the body or with gravity would lead to better results. In the first case, rotations around the body axis (yaw turns) are from an ecological point of view the most natural and frequent situations; therefore although gravity is conflicting they could be properly interpreted. In turn, the second situation really occurs in real life: imagine watching somebody walking on TV lying down on a coach. Even if this situation is less frequent, the consistency of the displacements with regard to gravity could be enough to make such situation interpreted without ambiguity by the brain.

Considering mental rotations, Shiffrar and Shepard (Shiffrar and Shepard, 1991) have shown that performances were improved when the axes of the object, rotation, and gravitational vertical are aligned. Tilting one of them resulted in deteriorating both speed and accuracy of the mental rotation. According to these results, we formulated the following hypothesis for the first question above: while staying upright, tilting the rotation axis will deteriorate the mental updating process. Imagining rotations in the transverse plane (yaw rotation) independently of the body orientation with regard to gravity was always better for viewer rather than array imagined rotations (Creem et al., 2001). The viewer advantage was lost only when the rotation was in the coronal plane (roll rotation). In another research, a clear independence of body vs. gravity orientation was also found for imagining roll rotation of a cubical 3D-array (Oman et al., 2002). Therefore efficient transformations of the egocentric reference frame rely mostly on the possibility to imagine environment rotations around the observer's body axis. This suggested for our experiment this hypothesis for the second question above: conditions where rotations are consistent with the body reference frame would lead to the best performances independently of the gravity reference frame. This hypothesis implies that the rotation axis aligned with the body axis would provide better results than aligned with gravity.

II.2. Materials and Methods

Subjects

Sixteen naïve subjects (six women and ten men) aged from 19 to 34 have participated in this investigation, most of them were studying at the university in various fields and levels. All of them except two were right handed. They all gave written consent before starting and were paid for this experiment.

Computerised Rod and Frame test

In order to look for a correlation between performances in our spatial task and the well known individual differences concerning the influence of a visual frame on the subjective vertical (Asch and Witkin, 1948), subjects were previously submitted to a computerised rod and frame test. They were shown a tilted rod centred inside of a tilted frame (see

Fig. 1).

The rod was randomly tilted from vertical leftward or rightward of an angle ranging from 4° to 8°, the frame was either tilted by –22°, –11°, +11° or +22°. They had to adjust the rod with the keyboard's left and right arrows until they felt it was perfectly vertical. A single key touch increased or decreased the rod's tilt-angle of 0.1°, and a continuous pressure increased or decreased the rod's tilt-angle of 3°/s. Two blocks 12 trials corresponding to three adjustments for each frame's tilt-angle were performed, with a pause between the two blocks. Before each trial, a fixation point appeared during 500ms in the centre of the screen followed by a dark screen in order to guide the direction of gaze of subjects. We have ensured that the border of the screen could not be used as a visual reference by taking two precautions: on the one hand the only source of light was the rod and the frame, and their luminosity was set to a low level; on the second hand the frame was in the peripheral vision, and subjects where asked to keep their gaze in the centre of the screen. The rod and frame test lasted about 5 minutes.

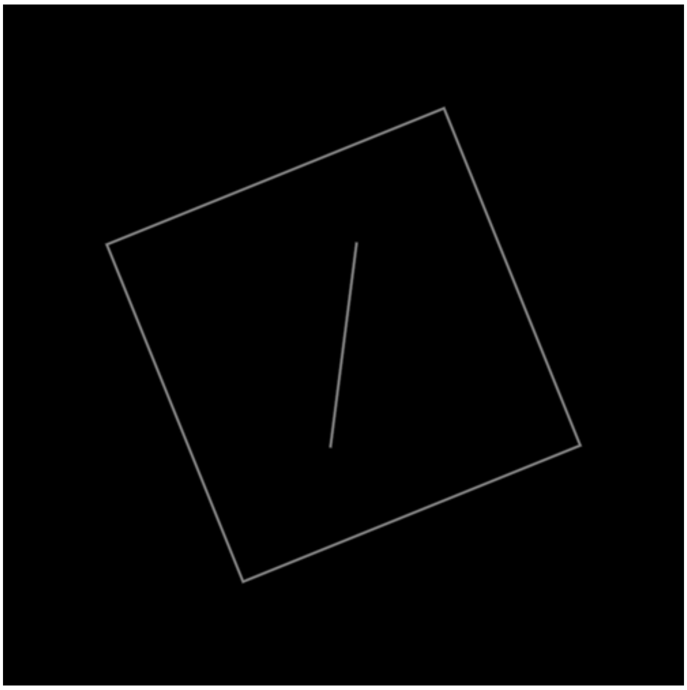

Fig. 1 – A view of the rod and frame test as experienced by subjects. The rod was randomly tilted from, the frame was either tilted by –22°, –11°, +11° or +22°. Subjects had to adjust the rod with the keyboard's left and right arrows until they felt it was perfectly vertical, the adjustment precision being of 0.1°.

Experimental set-up

Subjects were facing a large screen either seated on a chair whose height could be set, either lied on a bed on their sides in a 90°-roll position. In both situations, the line of sight was centred on the large screen on which the virtual displacements were projected (apparatus detailed in **Fig. 2**). The answers were given with a keyboard and the sounds played by a headphone worn by subjects. In order to avoid any influence of subject's body position on the keyboard handling, when subjects were seated it was laid over subject's knees, when lying down it was vertically fixed at the same distance from the arms.

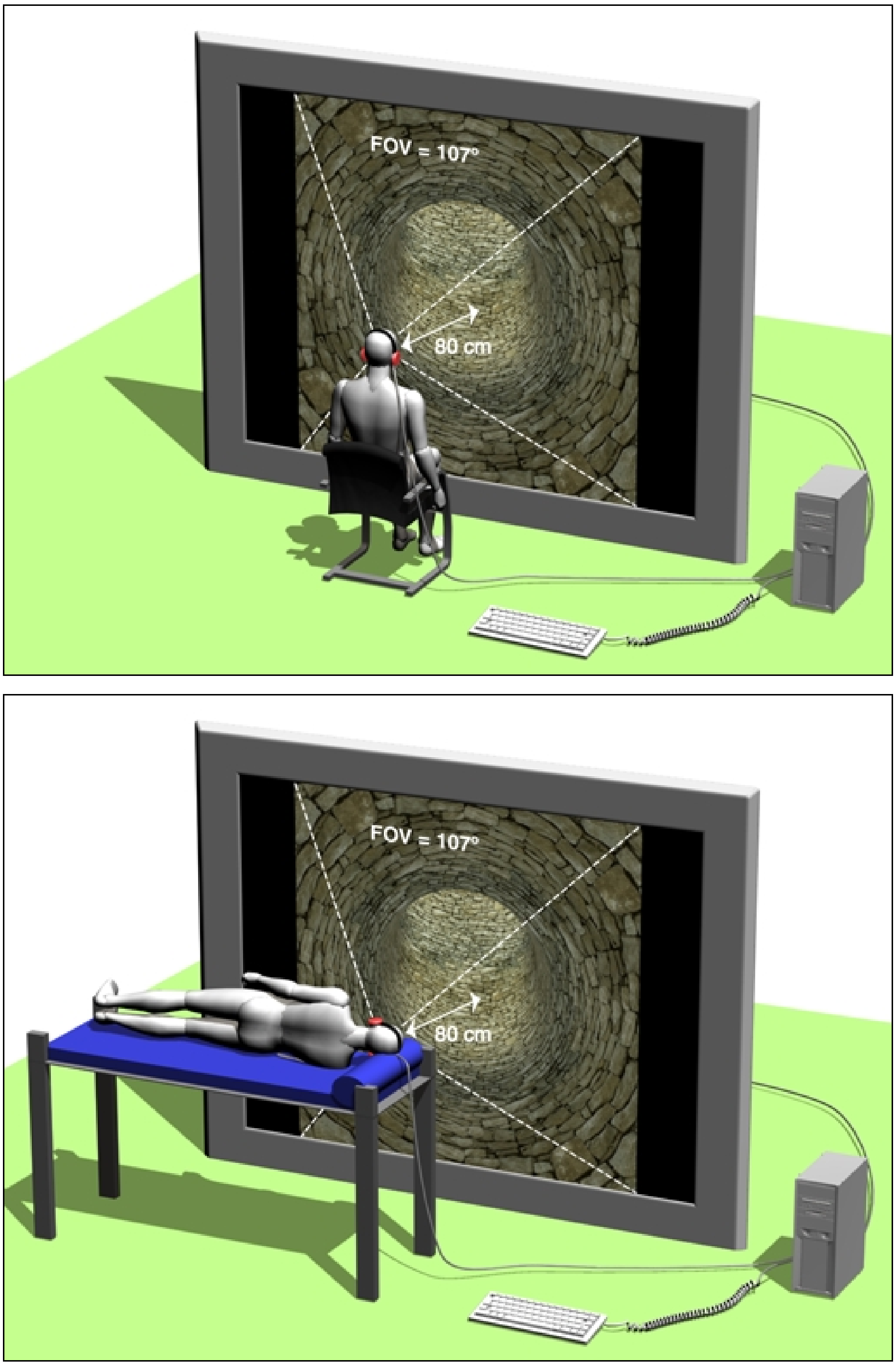

Fig. 2 – The experimental set-up for seating upright conditions (left) and lying down conditions (right). Subjects' line of sight was centred on a 107° of horizontal and vertical field of view translucent screen, they interacted using a keyboard and they worn a headphone. A PC computer with the GeForce2 video card generated the virtual displacements retro projected on the screen as well as the double task sounds. The squared resolution was of 1200x1200 pixels at a frame rate of 85Hz.

Procedure

Each trial of the experiment included a visual navigation phase followed by a reconstruction task. During the navigation phase, subjects were passively driven at constant speed through a virtual cylindrical 3D corridor made of stones. A static view showed an avatar at the beginning of the corridor for 1000ms before visual motion started (see **Fig. 3**). The segments constituting the corridors had the same length and were aligned with one of the canonical axes (see **Fig. 4**). Six different navigation conditions (detailed in the paragraph *Experimental conditions*) were compared in 10 different corridors, half being randomly selected in a 4-segments database and the other half in a 5-segments database.

Fig. 3 – The static inside view with the avatar displayed at the beginning of the exploration of the corridor. The avatar has the same body orientation as subjects, it gives an indication for the reconstruction referential. The perspective correction was adjusted to the real FOV experienced by subjects.

During the reconstruction task, subjects were asked to redraw with the computer the remembered 3D-shape of the corridor. They were first shown an external view of the first segment with an avatar at the entrance point indicating the orientation relative to which the reconstruction has to be made. This avatar as the one showed at the beginning of the navigation phase represented the observer. It was aligned with subject's body position, therefore when they were in the upright position the avatar was vertical, and when they were in the lying down position the avatar was horizontal (see **Fig. 4**). Four arrows labelled from 1 to 4 indicated the four possible directions of the next segment. Each segment was reconstructed by pressing the key corresponding to the label of the red arrow chosen. Once the correct number of segments was entered, a message appeared asking to validate the drawing by pressing the spacebar key. At any time, subjects could cancel their last choice by pressing the backspace key.

Appuyer sur [Space] pour valider.

Fig. 4 – The outside view during the reconstruction task, segment-by-segment subjects had to choose between the four possible directions, each segment direction being parallel to one of the canonical axes. Once the correct number of segments was entered, a message in French appeared asking to validate the drawing by pressing the spacebar key. Subjects could cancel their last choice at any moment by pressing the backspace key.

The full experiment for a subject was composed of two sessions of 30 trials each, divided in blocks of 10 trials. One of the sessions was performed seating upright including the three corresponding navigation conditions (see paragraph below), the other was performed lying down in a 90º-roll position including the three other navigation condition. The order of the sessions was counterbalanced between subjects. Each session started with six practice trials, two for each of the three navigation condition defined in the corresponding body position. Subjects could then learn how to use the computer interface. The task being cognitively very demanding, the two sessions of one subject were done on different days in order to avoid saturation. After each block of 10 trials, a score calculated with the average accuracy in the reproduction was displayed before a 5 minutes pause. This feedback was given in order to keep subjects motivated during the whole experiment. Subjects triggered each trial by pressing a specific key when ready.

The full experiment lasted approximately two hours.

Verbal dual-task

According to the model of working memory proposed by Baddeley in 1986 and validated since (Baddeley, 1998b), short-term memory is composed of two “slave” systems for storing and maintaining visuospatial and verbal information, piloted by the central executive system that processes the stored information, allocating attentional and cognitive resources. The first system, called the visuospatial sketchpad (VSSP) used for mental imagery manipulations (Pearson et al., 1996;Bruyer and Scailquin, 1998), is also involved in high-level comprehension and reasoning tasks that involve spatial representations like motion simulation (Salway and Logie, 1995) and mental simulations of mechanisms (Sims and Hegarty, 1997). All these investigations have shown a large independence of the VSSP with the verbal system consisting in the phonological and articulatory loop, and recent studies have shown with functional imagery techniques that they were processed in different regions of the brain (Baddeley, 1998a). In order to avoid memorisation of a verbal sequence of the directions taken in corridors, subjects performed a dual-task consisting of a verbal working memory load. Our task involves high-level manipulations of spatial representations; it is therefore processed by the VSSP, which is largely independent of the verbal working memory. Loading the verbal memory would result in preventing its use as an alternate encoding strategy for the corridor’s shapes. At the very beginning of each trial, three random numbers in the range of 20 to 59 were played on the headphones and subjects had to memorise them in the correct order. Just after the reconstruction task, subjects had to recall this sequence of numbers, and an immediate sound feedback was played if more than one number were not correct or not in the correct order.

Although the verbal capacity of working memory is usually larger than 3 items storage capacity, we though it would be enough to prompt the spatial storage strategy. An audio presentation of the numbers was used rather than a visual presentation in order to avoid visual memorisation in the VSSP.

Experimental conditions

Six navigation conditions were studied, four derived from a natural terrestrial condition where there is a single rotation axis is used in the displacement and two control conditions where the rotations about the three canonical axes are used. In all conditions, there are two different reference frames engaged: gravity's reference frame noted **(G)** and body's reference frame noted **(B)**. The four terrestrial-derived condition provided another particular reference characterised by the unique axis of rotation noted **(D)**, they were defined according to the alignment of this particular axis with the **(B)** and **(G)** reference frames. The following four navigation conditions were created this way (see **Fig. 5**):

(DBG)	Navigation condition where the rotation axis of the displacement is aligned with both the body axis and gravity, it is therefore vertical. Subjects are seated upright. This condition corresponds to the natural terrestrial navigation condition.
(D+BG)	Navigation condition where the rotation axis of the displacement is horizontal (90.0°-tilted) but the body axis is aligned with gravity. Subjects are seated upright.
(DB+G)	Navigation condition where the rotation axis of the displacement is horizontal and aligned with the body axis. Subjects are lying down in a 90°-roll position.
(DG+B)	Navigation condition where the rotation axis of the displacement is vertical thus aligned with gravity, but the body axis is horizontal. Subjects are lying down in a 90°-roll position.

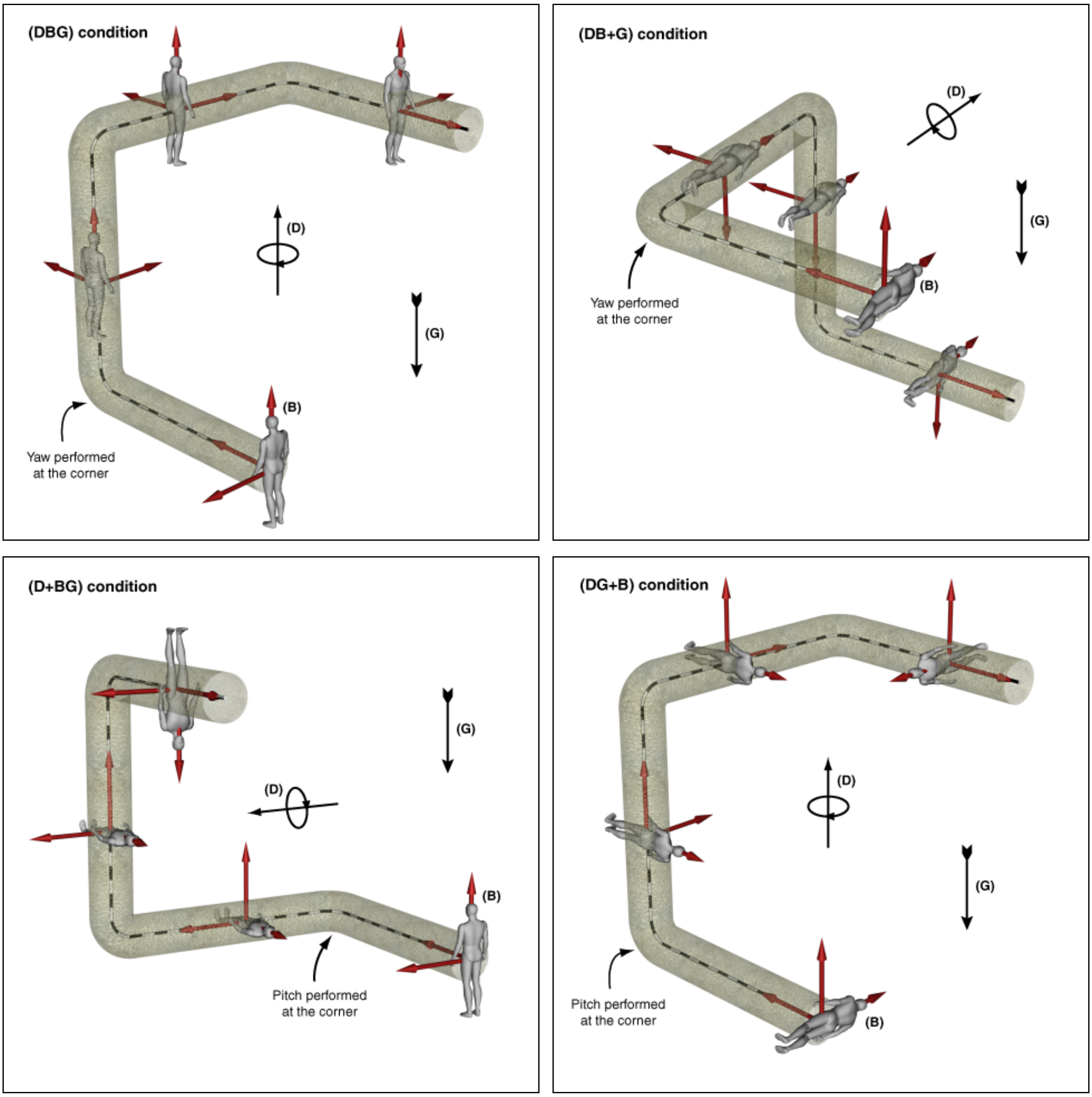

Fig. 5 – The four main conditions derived from natural terrestrial navigation: **(DBG)**, **(D+BG)**, **(DB+G)** and **(DG+B)** conditions named according to the alignment of some of the three axes defining the body, gravity and displacement reference frames (respectively noted **(B)**, **(G)** and **(D)**). Since the initial position in the corridors matches the subject's body position, it provides the body reference frame. Illustrations use the same corridor definition, eventually tilted leftward or rightward of 90º according to the condition. On the left sides are the conditions where subjects were seated upright and on the right side the conditions where subjects were lying down.

In **(DBG)** and **(DB+G)** conditions, the head was always kept upright and in vertical segments the walls scrolled up or down in front of the subject as if inside a transparent elevator. Before entering a vertical segment a yaw-rotation was done (indicated in the **Fig. 5**) in order to orient the sight to the direction taken after going up or down, this way subjects knew which direction was coming next. In the **V-** and **H-Control** conditions, the viewing direction pointed towards the end of the current segment and at each junction a single yaw- or pitch-rotation was performed to reorient the line of sight with the next segment, therefore allowing the three rotations of the 3D space. In all conditions gaze-orientation rotated in anticipation of each turn as it would be done in natural conditions (Grasso et al., 1996;Wann and Swapp, 2000;Wann and Swapp, 2000). Linear speed was kept constant during the whole displacement.

The two control conditions used as a performance reference. Since they involve no displacement reference frame, they are defined only according to the alignment of the body axis and gravity (see **Fig. 6**):

V-Control	Control navigation condition where subjects are seating upright.
H-Control	Control navigation condition where subjects are lying down.

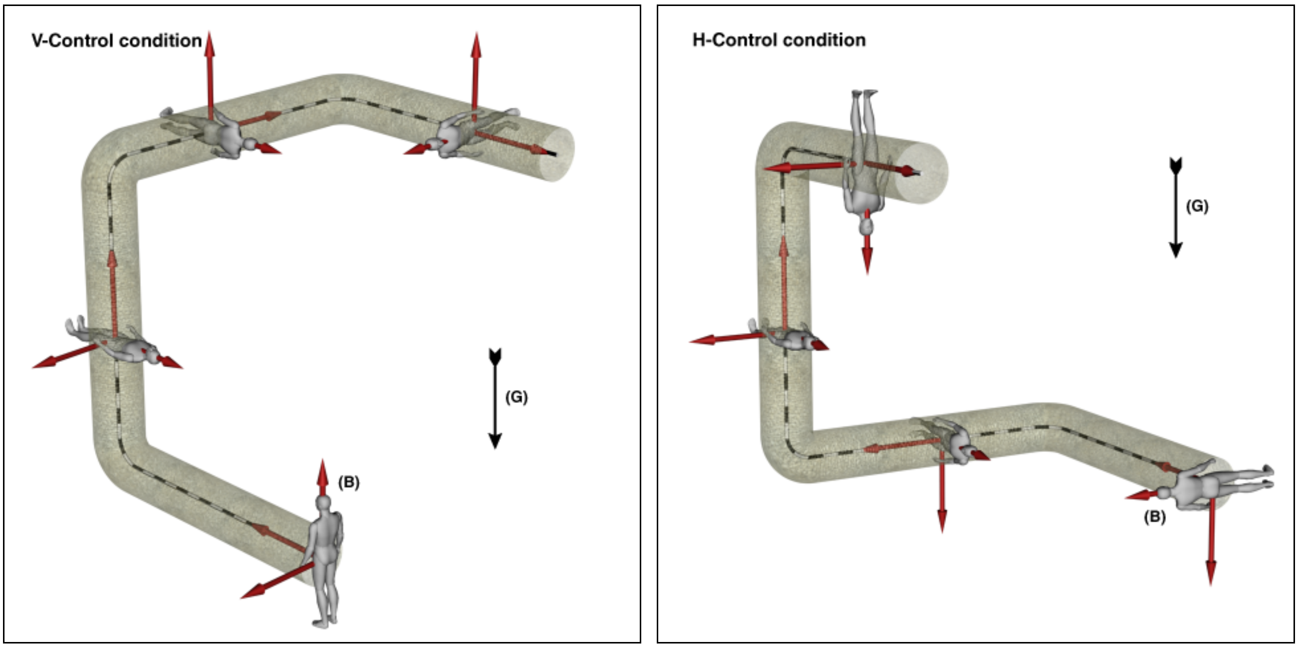

Fig. 6 – The vertical (left) and horizontal (right) control navigation conditions corresponding to the condition where subjects were seated upright and lying down. Illustrations use the same corridor as before.

Data analysis

For each trial, the total *reconstruction latency* and definition of the corridor and the answers to the dual-task were recorded. For every trial, an *accuracy score* for the drawn corridor was calculated corresponding 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 accuracy score would be (3-1)/(5-1) = 50%. The chance level of the accuracy score for a random reconstruction is at 13.9% and 10.9% for respectively 4- and 5-segments corridor, making an average chance level of 12.4% for balanced groups of trials containing the same number of 4- and 5-segments corridors. A score for the dual-task was also calculated called the *DT score*, corresponding to the number of correct numbers in the correct order divided by 3. For instance, if the given sequence was 23-57-31, both the answered sequences 23-56-31 or 57-23-31 would get the score 66.6%.

A 2 (field dependency group) × 2 (number of segments) × 6 (navigation condition) ANOVA design table was used. The *field dependency group* (field dependent (FD) and field independent (FI)) being considered as a between-subject factor, while *number of segments* (4 and 5), *navigation condition* (**(DBG)**, **(D+BG)**, **(DB+G)**, **(DG+B)**, **V-Control** and **H-Control**) were the within-subjects experimental factors. The dependent variables were the reconstruction accuracy score and latency, and the dual-task score. Post-hoc analyses were performed with Scheffé test when possible, and with a planned comparison when there was an interaction with the *field dependency group* between subject factor.

II.3. Results

Rod and Frame results

The average deviation from vertical reproduced for the four frame orientations were calculated for each subject ($\varepsilon_{\pm 11^\circ}$ and $\varepsilon_{\pm 22^\circ}$). The 11°-tilted frame and 22°-tilted frame effects were calculated for each subject, it corresponded to the deviation from the middle of leftward and rightward errors for each frame-tilt angle:

$$E_{11^\circ} = \frac{\left|\varepsilon_{+11^\circ} - \varepsilon_{-11^\circ}\right|}{2} \quad , \quad E_{22^\circ} = \frac{\left|\varepsilon_{+22^\circ} - \varepsilon_{-22^\circ}\right|}{2} \quad \text{and} \quad E_{\text{global}} = \frac{E_{11^\circ} + E_{22^\circ}}{2} .$$

The median values of the 11º- and 22º-effect obtained were respectively 2.17º and 2.04º. They were used to discriminate subjects: we had 8 subjects presenting a 22º- and 11º-effect below these criteria forming the field independent group (FI group, n=8, E_{global} = 1.06° ± 0.55°); and 8 subjects presenting a 22º- and 11º-effect above these criteria forming the field dependent group (FD group, n=8, E_{global} = 3.65° ± 0.83°). We managed to have well balanced groups with regard to the body position of the starting session: each group had 4 subjects that started upright and 4 subjects that started lying down.

Qualitative results

Subjects have reported that the task was very demanding and that they had to keep a high level of concentration in order to perform it properly. Despite the difficulty of the task, subjects' performances were rather good. As **Fig. 7** and **Fig. 8** show, accuracy in the reconstruction of the corridor was far above the chance level. In contrast, the dual-task was poorly executed (see **Fig. 10**): subjects said they often forgot the numbers or the order of the numbers. Some of the subjects who appeared to be field dependent according to the rod and frame test have said to have great difficulties in performing the task in the lying down conditions. They were strongly confused about what reference to use for both memorising and reconstructing: they knew the reconstruction was referred to their body but they had some conflicting interference with the gravity reference frame. These subjective remarks are correlated with the performances presented in the results and discussed later.

Accuracy on reconstruction

The reconstruction performances (accuracy score mean ± standard error) grouped by field independent subjects, field dependent subjects and altogether for different navigation conditions are given in **Table 1**. The effect of field dependency factor on each condition will be analysed, and the conditions performances will be compared. The control conditions are presented first, they will be used as a reference for the lying down effect on both field dependent and independent group. Then the four terrestrial derived conditions (**(DBG)**, **(D+BG)**, **(DB+G)**, and **(DG+B)**) will be analysed.

Group	*n*	*Upright navigation conditions*			*Lying down navigation conditions*		
		(DBG)	**(D+BG)**	**V-Control**	**(DB+G)**	**(DG+B)**	**H-Control**
Field independent	8	77.60 ± 5.59	67.92 ± 6.23	70.84 ± 6.58	83.03 ± 4.41	69.17 ± 5.70	76.88 ± 5.89
Field dependent	8	73.13 ± 5.51	53.76 ± 3.66	62.71 ± 4.04	44.80 ± 10.81	42.29 ± 5.87	34.27 ± 5.49
Altogether	16	75.36 ± 3.83	60.84 ± 3.94	66.77 ± 3.87	63.91 ± 7.49	55.73 ± 5.26	55.57 ± 6.74

Table 1 – Reconstruction accuracy score (mean ± SE) for different navigation conditions and grouped by field dependency factor. The control conditions are highlighted in grey.

V-Control an H-Control comparison

The interaction between FD group and navigation conditions **V-Control** and **H-Control** (see **Fig. 7**) showed significant differences (F(1,14)=11.11; p<0.005). In the upright position field dependent (FD) and field independent (FI) groups have the same average performance with respectively 62.7% and 70.8% (no statistical difference), whereas in the lying down position FD group have an average performance of 34.2% and FI group have an average performance of 76.8% (F(1,14)=28.01; p<0.0002). The degradation of performances of FD group when lying down as compared to upright was very significant (F(1,14)=15.1; p<0.0016). The number of segments of corridors had a significant effect on both **V-Control** condition (F(1,14)=22.69; p<0.0003) and **H-Control** condition (F(1,14)=8.91; p<0.01).

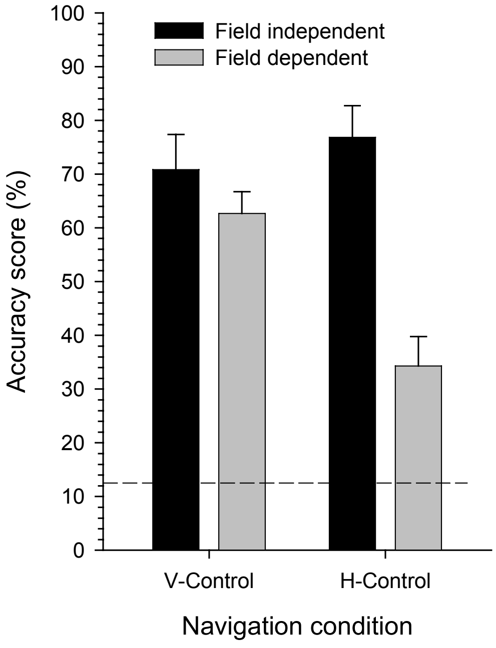

Fig. 7 – Average reconstruction accuracy score (means + SE) for both field dependent (n=8) and independent groups (n=8), as functions of the control navigation conditions. Dashed line represents the chance level.

Terrestrial-derived conditions comparison

The reconstruction accuracy score averaged by field independent and field dependent groups for the four terrestrial-derived conditions are plotted in **Fig. 8**. The same way as for the control conditions, only the conditions in the lying down position showed significant effects of the field dependency factor: 83.0% for the FI group against 44.8% for the FD group at the **(DB+G)** condition (F(1,14)=10.72; p<0.006) and 69.2% for the FI group against 42.3% for the FD group at the **(DG+B)** condition (F(1,14)=10.80; p<0.006). Field dependent group performances are strongly degraded when lying down which is not the case for field independent group performances. Aside from this body orientation effect, there was also a clear tendency separating the FI and FD group performances at the **(D+BG)** condition (F(1,14)=3.84; p<0.07).

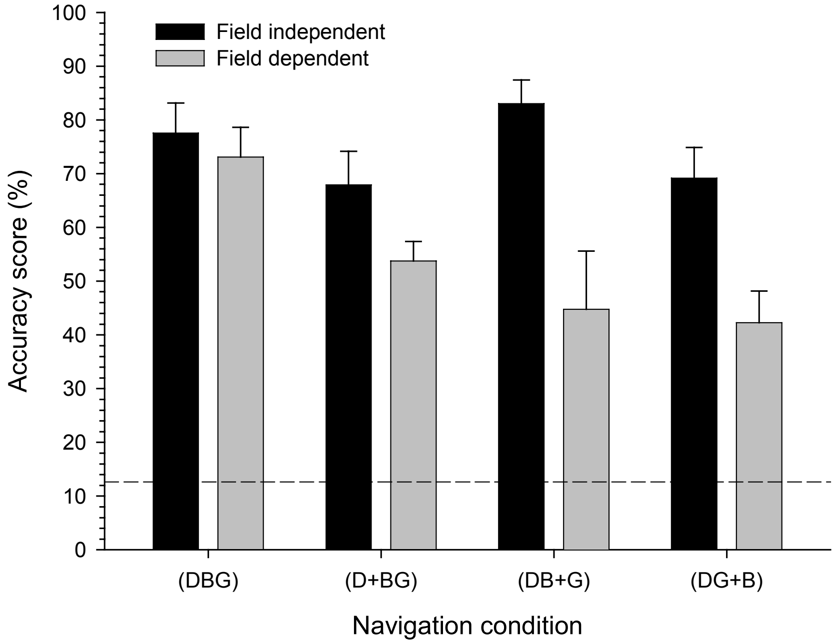

Fig. 8 – Average reconstruction accuracy score (means + SE) for both field dependent (n=8) and independent groups (n=8), as functions of the navigation conditions derived from the natural terrestrial navigation condition. Dashed line represents the chance level.

The global performances for the **(DBG)** condition (with in average 77.6%) was higher than for the **(D+BG)** condition (with in average 60.8%, F(1,14)=9.54; p<0.008), as well as for the **(DB+G)** condition (with in average 63.9%, F(1,14)=5.11; p<0.04), and the **(DG+B)** condition (with in average 55.7%, F(1,14)=12.36; p<0.004). A planned comparison revealed that these differences result only from the FD group performances, the FI group showing no significant difference between the **(DBG)** condition and the others. There was no other significant difference between conditions globally or by group. The only tendency that should be highlighted (F(1,14=3.45; p<0.085) is the performance degradation of the FI group between the **(DB+G)** condition (with 83.0%) and **(DG+B)** conditions (with 69.1%). In turn, for the FD group there was no difference between these conditions.

To summarise, for the FI group the **(DBG)** and **(DB+G)** conditions obtained approximately the same level of performances, slightly higher than the **(D+BG)** and **(DG+B)** conditions level. In turn, for the FD group the level of performance of **(DB+G)** and **(DG+B)** conditions is the same but apparently slightly below the **(D+BG)** condition and significantly below the **(DBG)** condition.

Terrestrial-derived compared to control conditions

Performances at the **V-Control** condition were significantly below the **(DBG)** condition (F(1,14)=6.48; p<0.024) with respectively 66.8% and 75.36%. This observation is consistent with the results of a previous study of 3D navigation condition (Vidal et al., 2002). A planned comparison revealed again that this difference results only from the FD group performances, the FI group showing no statistical difference. This is probably due to the small difference for a small number of subjects in each group (n=8). Apart from that, there was no difference between the terrestrial-derived conditions and the corresponding control conditions neither for the FD group, neither for the FI group. Therefore removing the coherence of one the reference frames of the terrestrial condition is enough to degrade the results as compared to a navigation condition where there is no particular axis for the rotations.

Total latency for reconstruction

Reconstruction latencies of subjects grouped by field dependency factor for different navigation condition are given in **Fig. 9**. Latencies were statistically shorter for upright conditions (19.7 ± 1.0s for the **(DBG)**, **(D+BG)** and **V-Control** conditions grouped) than for lying down conditions (26.6 ± 3.9s for the **(DB+G)**, **(DG+B)** and **H-Control** conditions grouped) (F(1,14)=14.64; p<0.002). A planned comparison shows that this difference is only significant for the field dependent group (F(1,14)=11.97; p<0.004) and not for the field independent group. Post-hoc revealed that the only significant mean differences between conditions are: the **(DB+G)** condition latency average is longer than the **(DBG)** (p<0.002), the **(D+BG)** (p<0.012), and the **V-Control** (p<0.0015) condition latency's averages.

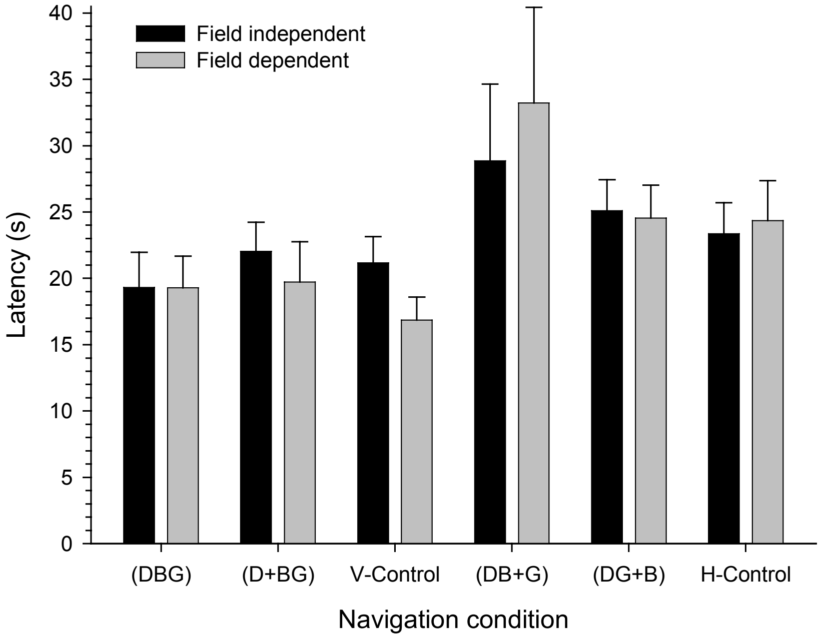

Fig. 9 – Reconstruction latency (means + SE) for both field dependent (n=8) and independent groups (n=8), as functions of the control navigation conditions.

Dual-task performances

The performances at the dual-task were rather high with in average 73.9% ± 3.3% (see **Fig. 10**), subjects have properly memorised and recalled the numbers. It means that they had at least partially the verbal working memory loaded, and that their strategy at the main task could not entirely rely on the verbal memorisation of the directions taken in the corridor. Interestingly, there was no statistical difference in the dual-task results neither across field dependency groups neither across conditions, and for that reason they could not be used in the analysis as an indicator of difficulty of the main task. In fact, this observation confirms the independence of the visuospatial sketchpad and the phonological loop as mentioned before: although conditions had a noticeable influence on the spatial task, it didn't necessarily make the verbal memorisation of the numbers any harder. Besides, the differences obtained in the accuracy of the reconstruction according to the different conditions must then come from the spatial processing of the navigation information.

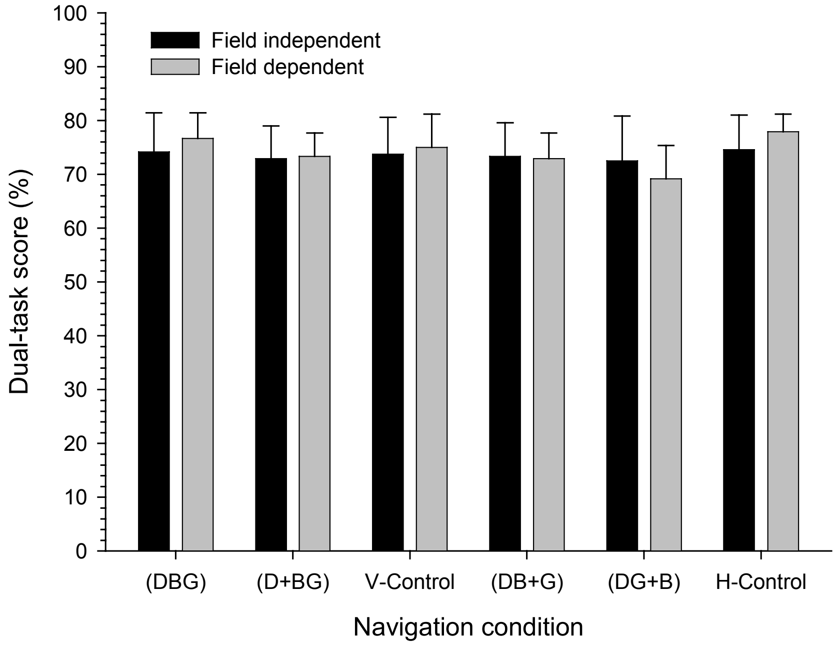

Fig. 10 – Dual-task score (means + SE) for both field dependent (n=8) and independent groups (n=8), as functions of the control navigation conditions.

II.4. Discussion

In the control conditions, we observed that in the memorising and recalling process of 3D corridors, there is a strong effect of lying down subjects for field dependent (FD) subjects whereas there is none for field independent subjects (FI). The horizontal control condition corresponded to a condition where body and gravity frames of reference are tilted as compared to natural conditions where they share the same vertical axis. Field dependent subjects are affected by this tilt and though there is no particular axis for this displacement condition, their performances are very degraded. In turn field independent subjects remain unaffected. This difference was also observed in the terrestrial-derived conditions: the field dependent factor had a significant effect only on conditions where subjects were lying down, and again with a strong deterioration of the field dependent group performance. As we expected, the introduction of an unnatural orientation of gravity by lying down disturb some subjects. Interestingly, the field dependency factor was correlated with it and allows predicting if lying one on the side will have an effect on subject's performances. For this reason, we will most of the time discuss the results considering separately FI and FD groups.

The accuracy in the reconstruction task indicates that regardless of gravity orientation, field independent (FI) subjects have the same performance level in the terrestrial-derived conditions where the displacements axis **(D)** is consistent with their body reference frame **(B)**, whereas it is slightly lower in conditions where **(D)** is tilted relatively to **(B)**. Besides, vertical and horizontal control conditions for FI subjects showed no difference, which also supports the idea that for this category of subjects there is a strong independence of the spatial memorisation process from gravity orientation with regard to body orientation. Although not significantly, only the processing time for reconstruction could be a little higher when FI subjects where lying down, resulting from the handling of two conflicting reference frames: gravity and body. This is coherent with the well-known characteristics of field independent subjects. In the rod and frame test they can adjust rather precisely the rod to the vertical while the visual field reference frame is conflicting with both gravity and body reference frames. Therefore field independent subjects can select the most appropriate reference frame to use for a specific task and ignore any other conflicting reference frame, which explains why they are more capable of handling two conflicting reference frames.

In contrast, the accuracy in the reconstruction task of field dependent (FD) subjects was significantly lower the two terrestrial-derived conditions where gravity is tilted with regard to the body reference frame (lying down position) as compared to the natural condition **(DBG)**, and this independently of the orientation of the displacement axis. Performances when the displacement axis was tilted but standing upright were also significantly lower than for the natural condition, but seemed slightly higher than for the lying down terrestrial-derived conditions. This observation was also reported for the vertical and horizontal control conditions. As regards the reconstruction processing time for FD subjects, latencies were significantly longer for all lying down conditions. Therefore the spatial memorisation process of a 3D-maze for field dependent subjects is very degraded when body and gravity reference frames are not consistent; moreover the misalignment of the displacement axis in the upright condition also leads to poorer performances. Again this is coherent with field dependent subjects characteristics. Despite the fact that in the rod and frame test they know the frame is tilted, their adjustments are not precise because the visual reference frame influences them. They cannot ignore the conflicting reference frame in order to rely only on the appropriate ones provided in this case either by gravity or by the body posture.

Another interesting finding was provided by the **(D+BG)** condition in which the rotation axis of the displacement was 90°-roll tilted and subjects seated upright. Although body and gravity reference frames are consistent, the field dependency effect was almost significant on the measured accurate performances, FI group having better overall scores than FD group. On one side, FI subjects had almost the same performances (no significant differences) than when the rotation axis was aligned with the two other axes (corresponding to the **(DBG)** condition). On the other side, FD subjects had significantly poorer performances than at the **(DBG)** condition. It seems that even if body and gravity reference frames are consistent, FD subjects are less capable to imagine rotations about an axis distinct from the body axis, whereas FI subjects can do it rather properly.

If we consider subjects altogether, the answer to the first question of whether simply the fact of having to process a single rotation axis is enough to make the mental representation updating easier is no, it has to be a particular axis. This is consistent with findings on mental rotations previously described (Shiffrar and Shepard, 1991). This answer was clear for the FD group, but not so clear for the FI group which recorded performances were lower when the rotation axis was tilted but not significantly. Concerning the question of whether the rotation axis of the displacement consistent with the body reference frame or with the gravity reference frame when body is tilted with regard to gravity would lead to better performances, we have found some unexpected observations. Here again FD subjects reacted differently from FI subjects. There is actually a strong tendency for the FI group indicating that the alignment of the rotation axis with the body axis facilitates the brain processing of the condition, which is consistent with the fact that mental rotations are always better when there is the possibility to imagine rotation around the observer's body axis (Creem et al., 2001). On the contrary, FD didn't show any difference in accuracy between these conditions, both being equally degraded as compared to upright conditions. We argue that the problem of FD subjects in dealing with two conflicting reference frames took take over the expected preference for rotations around the body axis. Besides, processing time for the condition where rotations were aligned with the body were longer in particular for FD subjects, signifying that they needed more time in this condition to get the same performances as when rotations are around gravity axis. A possible explanation for these surprising remarks could be that in our experiment we displayed an avatar reminding the position of subject's body. This was done in order to orient the reconstruction task where the avatar was also displayed at the entrance of the corridor. If subjects had taken this as a support for imagining rotations, it would have given preferential treatment to the condition where subjects were lying down and the rotations were around their body axis. In spite of that, FD subjects processing latencies were great without improvement in accuracy. If we had shown an avatar aligned with the displacement axis instead, FD subjects would probably have better performances in the condition where gravity is aligned with the rotation axis than in the condition where the body is aligned with the rotation axis. We think that it would be of interest for Creem, Wraga & Proffitt researches about physically impossible mental rotation (Creem et al., 2001) to distinguish FD from FI subjects. They concluded that transformations of egocentric reference frames are better when they consist of rotations around the observer's body axis. Our findings suggest that these conclusions might be distinct according to the field dependency groups.

III. 3D-Navigation, Space Experiment

III.1. Problematic

The suppression of gravity reference frame engenders many orientation problems often reported by cosmonauts in space (Harm and Parker, 1993), and in parabolic flights. A detailed review of spatial orientation problems in weightlessness such as inversion illusion, visual reorientation illusion, EVA height vertigo, and disturbed spatial memory was written by Oman (Oman, 2001). Beside, the absence of this frame of reference possibly affects the way brain estimates the subjective vertical (Mittelstaedt and Glasauer, 1993), this would explain some of the orientation illusions and the individual differences concerning them. The perception and storage of a visual line direction combines both gravity and proprioceptive frames of reference: when both were present and aligned or in weightlessness conditions there was a preference for vertical and horizontal direction perception, in turn when these references were conflicting there was no preferred direction (Lipshits and McIntyre, 1999). Therefore gravity seems to be a crucial reference used for human spatial orientation and navigation on earth, and once removed, navigation strategies are susceptible to be altered.

The present experiment was part of the scientific program of the Andromède mission consisting in a taxi flight to the International Space Station (ISS) in October 2001. In this research, we wanted to check if suppressing gravity would change the relative performances of the weightless and terrestrial conditions as described in a previous investigation (Vidal et al., 2002) and corresponding respectively to the **(DBG)** and **V-Control** conditions of the prior experiment.

On one hand, we hypothesized that the fact of being in space with no gravity and implying different modes of navigating than the ones on earth would result in improving the performances of the weightless condition. On the other hand suppressing gravity removes, as we have seen in the ground experiment, one of the reference frames strongly used by humans to build mental representations of their environment. Therefore we also hypothesized that the terrestrial condition in space would get worse performances as compared to those on earth.

III.2. Materials and Methods

Subjects

Five cosmonauts participated in this experiment, three from the main crew (cosmonauts A, B and C) and two from the backup crew. Cosmonauts from the backup crew only performed the pre-flight sessions, therefore their results will not be reported.

Verbal Span test

The capacity of memorisation is used to select among the candidates for cosmonauts, moreover during their training they often have to memorise numbers and items. Therefore in order to calibrate the double task of the experiment, we wanted to check if they have a large verbal span for memorising numbers. Cosmonauts were submitted to a classical preliminary span test described below (Miller, 1956).

The initial number of numbers to memorise was set to N=2. While an instruction to memorise the numbers was presented in the screen, subjects were successively given through the headphone N random numbers going 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 visual memorisation. After a black screen presented during 6 seconds, subjects were asked to recall in the correct order the memorised numbers. The recall was done with the keyboard, corrections being allowed with the backspace key. 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 set to N–1. The span test lasted about 3 minutes.

All cosmonaut’s verbal span measured by this test was above or equal to 5. Since cosmonauts passed a great number of sessions during the whole experiment, we decided to set the number of numbers to memorise in the dual-task to 4 in order to stay below saturation but still keeping a high level of verbal memory load.

Experimental set-up

A laptop was used to generate the virtual motion inside of corridors (see **Fig. 11**). The experienced field of view was of 40º of vertical field of view corresponding to a distance from the laptop screen of 32cm. An optic tunnel with a rest mask was used to remove any visual disturbance from the outside and to set subjects head to the right position. The answers were given with a small keypad connected to the laptop. The sounds used for the double task were played with a headphone, and the vocal answers recorded with a microphone. In ground sessions, cosmonauts were always seated with the laptop lying on a table, and in flight sessions they were strapped with the same global posture with regard to the apparatus.

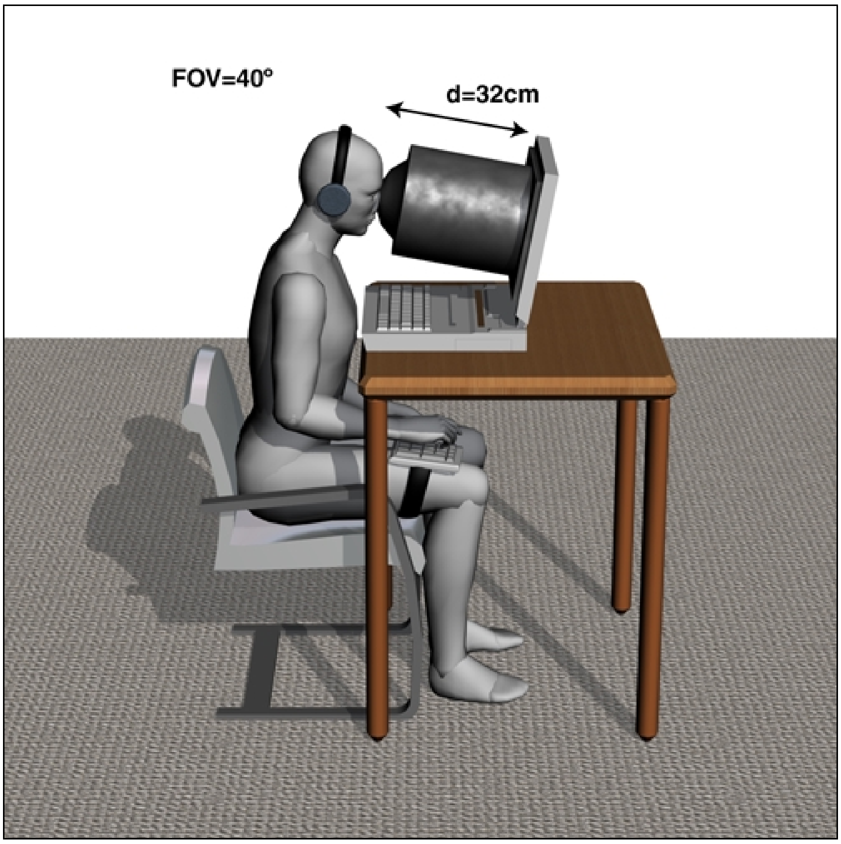

Fig. 11 – The experimental set-up used in both ground and in-flight sessions. Cosmonaut's line of sight was centred on a laptop screen covering 40° FOV. Answers were given with a keypad and a microphone, and a headphone played the sounds. The laptop was equipped with a ATI Rage mobility 128 graphic card, generating visual motion at a frame rate of 20Hz.

Procedure

Trials had exactly the same sequencing as before: first the numbers for the double task were played through the headphone, then the navigation phase with one of the conditions, then the reconstruction phase using the keypad and finally the recalling of the numbers for the double task. The only differences were that not of all the conditions were studied and the recall for the double task was vocal and recorded by a microphone. Since in space no use can be made of the gravity reference frame for memorising the shape of an environment, the lying down conditions make no sense in weightlessness. Therefore only the following two upright conditions were studied: the *terrestrial* condition and the *weightless* condition corresponding respectively to the **(DBG)** condition and the **V-Control** condition of the prior experiment.

Each session was composed of 32 predefined trials including 8 trials of each of the navigation condition for two successive corridor's number of segments. We disposed of six series of trials properly counterbalanced for the different sessions. The two series of trials used for the data acquisition sessions included corridors of 5 and 6 segments, and half of the four series used for the training sessions included corridors of 4 and 5 segments and the other half included corridors of 5 and 6 segments. The series were alternated across sessions in order to avoid any learning of the trial sequences. The acquisition sessions were grouped in 4 experimental periods scheduled as follow:

- Two sessions in the D-60 pre-flight period (from 08/21 to 08/24)
- Two sessions in the D-30 pre-flight period (from 09/17 to 09/21)
- Two sessions in-flight (from 10/26 to 10/28)
- Two sessions in the post-flight period (from 11/02 to 11/06)

An interval of three days separated the two sessions of each period for each cosmonaut. Two training periods including two sessions were carried out, one before the D-60 period and one between the D-60 and the D-30 periods. In the first training period, the difficulty of the trial series was only of 4- and 5-segments. Scheduling that many sessions were necessary so that the cosmonauts had reached their learning saturation before the last pre-flight session. This allowed us to compare the pre-flight, in-flight and post-flight results in order to extract the influence of gravity in the cognitive processing of the task.

Data analysis

For each trial, the total *reconstruction latency*, the *accuracy score* for the drawn corridor and the recalled numbers of the double task were recorded. These were calculated the same way as previously for the ground experiment. Because of the small number of participants in this experiment, at this stage we only give a descriptive presentation of the results, and no statistical analysis was done to compare means. The conclusions taken from this experiment just follow the impressions we have of these results and should be carefully considered. We expect in the future to have more cosmonauts participating in order to be able to make real statistical analysis and to confirm the tendencies we have extracted from the present results.

III.3. Results

Accuracy on reconstruction

Cosmonauts' individual accuracy at the reconstruction task averaged by navigation condition and grouped by successive experimental sessions are presented in **Fig. 12**. The chance level of the accuracy score of the reconstruction was below 10%, therefore all cosmonauts were responding highly above chance since the first acquisition session. Cosmonauts A and B had performance profiles well organised whereas cosmonaut C performances showed some irregularities across sessions. This could be due to the very demanding activities of cosmonauts before spatial flights, and since cosmonaut C was flying for the first time, he could have given less attention to our experiment, his results will be discussed apart.

Cosmonauts A and B seem to have reached their learning saturation at this task after the first D-60 session (post-flights level of performances being not higher than D-30 period's), we can thus compare performances between the D-30 period, the in-flight period and the post-flight period. From the D-30 sessions onward, performances for the *terrestrial* condition were noticeably higher than for the *weightless* (with an average difference of 23.4% for A and 14.9% for B). For cosmonaut A, performances for the second sessions of each ground period were higher than for the first sessions (with respectively 10.5% and 20.5% in average for the *weightless* and *terrestrial* condition). The interval separating two sessions within the same period being much shorter than the one between periods, this observation was due to short-term practising effects. For both A and B cosmonauts, performances at the *terrestrial* condition for the in-flight sessions was bellow the previous ground session and slowly decreased between the first and the second session (dropping from 79.4% to 70.6% for A and from 56.0% to 52.8% for B). In contrast performances at the *weightless* condition slowly increased (rising from 48.1% to 51.3% for A and from 41.9% to 45.3% for B). The accuracy difference between navigation conditions for cosmonaut B increases back in the post-flight sessions (with a difference of 7.5%

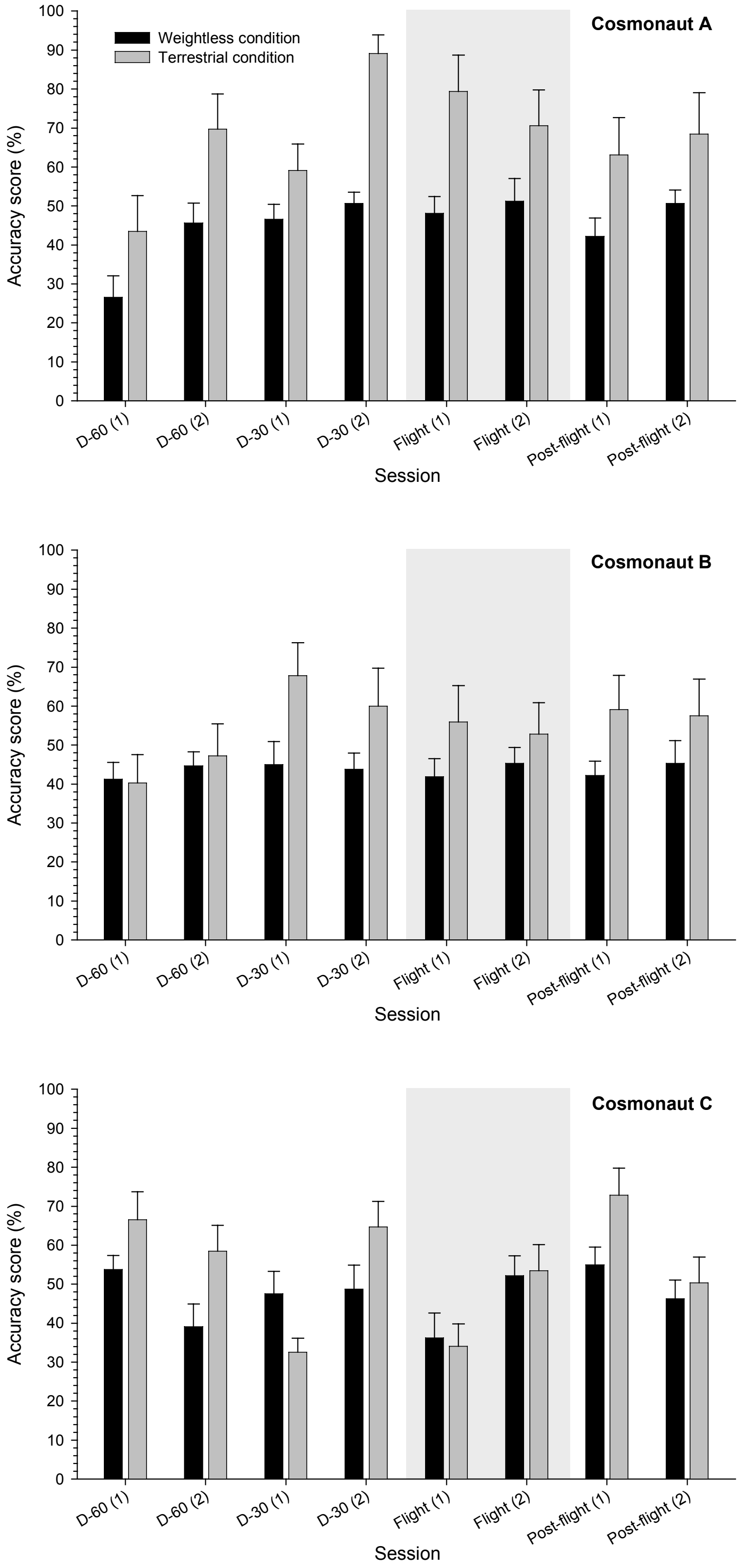

Fig. 12 – Reconstruction accuracy scores of the three cosmonauts averaged by navigation condition (mean + SE, n=16) and grouped by successive experimental sessions. The two in-flight sessions are highlighted in grey.

in-flight (2) and 16.9% in post-flight (1)) whereas for cosmonaut A it stays approximately as low as in the second in-flight session.

Performances of cosmonaut C for the *terrestrial* condition were noticeably higher than for the *weightless* only in ground sessions excepted for D-30 first session (with an average difference of 14.0%). Curiously the in-flight results showed no difference between the two conditions, the performances increasing approximately from 35% in the first session to 53% in the second session. Here again, the low performances at the first session could be due the anxiety resulting from first-time flying in space. Finally, in the first post-flight session a difference of 17.8% separated the *weightless* and the *terrestrial* conditions.

Total latency for reconstruction

Individual latencies of cosmonauts at the reconstruction task averaged by navigation condition and grouped by successive experimental sessions are presented in **Fig. 13**. Cosmonaut A took in average 1100ms more to execute the task in space than in ground sessions whereas cosmonauts B and C took respectively 1900ms and 2100ms less. Interestingly, cosmonaut A latency's averages for the *weightless* condition decreased of 600ms in space (from 19.4s to 18.8s) while for the *terrestrial* condition they increased of 2800ms (from 18.8s to 21.6s). Cosmonaut B latency's averages were approximately the same for both navigation conditions, with respectively 29.0s for ground sessions and 27.1s for in-flight sessions. Cosmonaut C latency's averages were lower for terrestrial condition in space (of 5200ms) while they were higher for weightless condition (of 1000ms). This last observation can be explained by the fact that cosmonaut C haven't kept in space a higher level of accuracy at the reconstruction for the *terrestrial* as compared to the *weightless* condition, whereas cosmonauts A and B have maintained the advantage but increasing globally the latencies for the *terrestrial* condition.

Double task performances

Cosmonauts recalled the numbers of the dual-task with a high level of accuracy, therefore they had at least partially the verbal working memory loaded, and again their strategy at the main task was not entirely relying on the verbal memorisation of the corridor's directions.

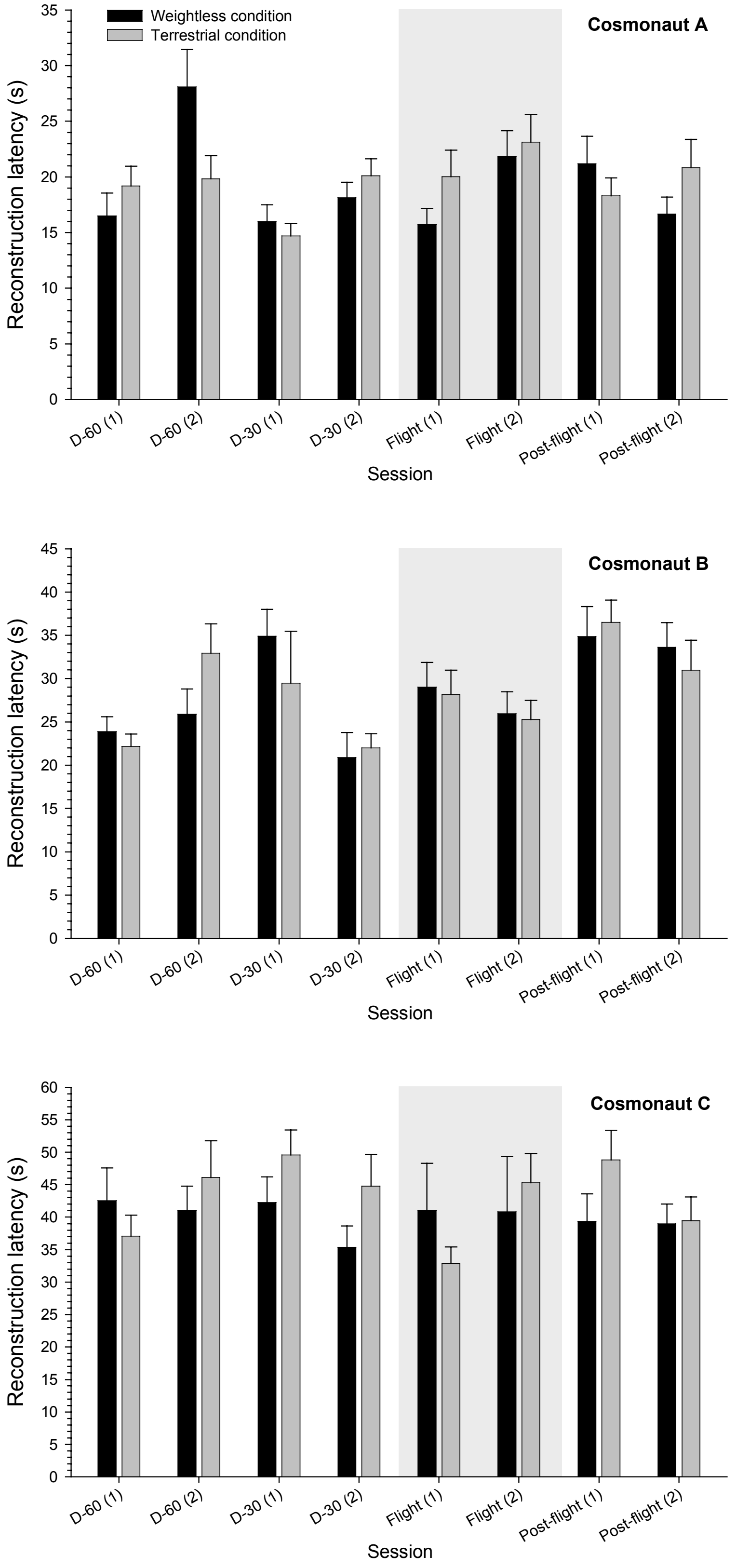

Fig. 13 – Reconstruction latencies of the three cosmonauts averaged by navigation condition (mean + SE, n=16) and grouped by successive experimental sessions. The two in-flight sessions are highlighted in grey.

III.4. Discussion

The advantage of terrestrial condition on weightless condition was observed individually in nearly every session. Cosmonauts had reached saturation level in the reconstruction accuracy from the D-30 and onward. It was then possible to compare performances in-flight with pre- and post-flight.

The overall results at the reconstruction task (accuracy for all cosmonauts and only for cosmonaut A latency) indicate a different effect on both navigation conditions. On one hand, we noticed first that performances at the terrestrial condition were lower in-flight and second that unlike in ground sessions, terrestrial condition performances decreased between the first and the second in-flight session. On the other hand, the weightless condition had globally the same level of performance and was still improved in the second flight session like in the other ground periods. It is important to dissociate long-term from short-term effects of cosmonaut's exposure to weightlessness. Actually these findings can be interpreted and explained by means of a long-term effect as well as a minor short-term effect.

The suppression of gravity as an input reference directly processed for spatial orientation purpose would result in affecting immediately navigation performances, it represents this way a possible short-term effect. This could have been responsible for the lower terrestrial performances in-flight since this conditions probably used gravity as a reference frame. In contrast, the adaptation of navigating in weightlessness could modify the weighting of gravity providing usually one stable reference in the cognitive processing of motion. **(reference Dai 1994)**. Alternate strategies relying more on visual information and less on this external reference would emerge, representing this time a long-term effect. This in turn could explain the slow decrease of the terrestrial condition performances in the second flight session instead of the usual second session improves.

IV. Conclusion

In conclusion, reference frames involved in navigation have very distinct influences of the on the capacity to build a mental representation of the environment structure according to field dependency factor. We know that the updating of such representation requires the capacity of imagining the observer's rotations inside of it. First we found that field dependent subject's performances were strongly degraded when body and gravity were misaligned whereas field independent subject's were not. Second apparently field independent subjects when body is tilted with regard to gravity seem to have a preference for displacements where rotations are performed around the body axis, and this was not the case for field dependent subjects. Third, even when body and gravity reference frames are consistent, tilting the rotation axis induced poorer performances for field dependent subjects, but not for field independent subjects. To summarise, field dependent cannot handle any kind of conflicting reference frame, the worse being a tilted body with regard to gravity, in turn field independent will have a rather high level of performances for any reference frame's conflicting situation. The field dependency as determined by the classical rod and frame test is a good indicator for performances whenever subjects are exposed to inconsistent frames of reference, field independents showing higher resistance to conflicts.

Globally, the fact of having the displacement consistent with the body reference frame was probably the most important in the natural terrestrial navigation condition. Although gravity seems contribute, since the space experiment indicates that removing it tended to decrease in time the performances of the terrestrial condition. As regard to the space experiment, in order to have clearer and more general results we need to add participants, and since the experimental set-up stayed on board of the ISS, it might be possible. Besides, to properly identify the long-term effect described above, it would be of interest to test cosmonauts with the same protocol in a long-duration flight.

V. Acknowledgement

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VI. References

1. Arbib MA (1991) Interaction of multiple representations of space in brain. In: Brain and space (Paillard J, ed), Oxford: Oxford University Press.
2. Asch SE, Witkin HA (1948) Studies in space orientation. II. Perception of the upright with displaced visual fields and with body tilted. Jo Exp Psychol 38: 455-477.
3. Baddeley A (1998a) Recent developments in working memory. Curr Opin Neurobiol 8: 234-238.
4. Baddeley A (1998b) Working memory. C R Acad Sci III 321: 167-173.
5. Bruyer R, Scailquin JC (1998) The visuospatial sketchpad for mental images: testing the multicomponent model of working memory. Acta Psychol (Amst) 98: 17-36.
6. Bures J, Fenton AA, Kaminsky Y, Zinyuk L (1997) Place cells and place navigation. Proc Natl Acad Sci U S A 94: 343-350.
7. Creem SH, Wraga M, Proffitt DR (2001) Imagining physically impossible self-rotations: geometry is more important than gravity. Cognition 81: 41-64.
8. Easton RD, Sholl MJ (1995) Object-array structure, frames of reference, and retrieval of spatial knowledge. J Exp Psychol Learn Mem Cogn 21: 483-500.
9. Gärling T, Böök A, Lindberg E, Arce C (1990) Is elevation encoded in cognitive maps? J Envir Psychol 10: 341-351.
10. Gothard KM, Skaggs WE, Moore KM, McNaughton BL (1996) Binding of hippocampal CA1 neural activity to multiple reference frames in a landmark-based navigation task. J Neurosci 16: 823-835.
11. Grasso R, Glasauer S, Takei Y, Berthoz A (1996) The predictive brain: anticipatory control of head direction for the steering of locomotion. Neuroreport 7: 1170-1174.

12. Harm DL, Parker DE (1993) Perceived self-orientation and self-motion in microgravity, after landing and during preflight adaptation training. J Vestib Res 3: 297-305.
13. Karnath HO (1994) Subjective body orientation in neglect and the interactive contribution of neck muscle proprioception and vestibular stimulation. Brain 117 (Pt 5): 1001-1012.
14. Karnath HO (1997) Spatial orientation and the representation of space with parietal lobe lesions. Philos Trans R Soc Lond B Biol Sci 352: 1411-1419.
15. Karnath HO, Ferber S, Dichgans J (2000a) The neural representation of postural control in humans. Proc Natl Acad Sci U S A 97: 13931-13936.
16. Karnath HO, Ferber S, Dichgans J (2000b) The origin of contraversive pushing: evidence for a second graviceptive system in humans. Neurology 55: 1298-1304.
17. Karnath HO, Fetter M, Niemeier M (1998) Disentangling gravitational, environmental, and egocentric reference frames in spatial neglect. J Cogn Neurosci 10: 680-690.
18. Knierim JJ, McNaughton BL, Poe GR (2000) Three-dimensional spatial selectivity of hippocampal neurons during space flight. Nat Neurosci 3: 209-210.
19. Lipshits M, McIntyre J (1999) Gravity affects the preferred vertical and horizontal in visual perception of orientation. Neuroreport 10: 1085-1089.
20. McIntyre J, Stratta F, Lacquaniti F (1997) Viewer-centered frame of reference for pointing to memorized targets in three-dimensional space. J Neurophysiol 78: 1601-1618.
21. Miller GA (1956) The magical number seven, plus or minus two: some limits on our capacity for processing information. Psychol Rev 63: 81-97.
22. Mittelstaedt H, Glasauer S (1993) Crucial effects of weightlessness on human orientation. J Vestib Res 3: 307-314.
23. Montello DR, Pick HLJ (1993) Integrating knowledge of vertically aligned large-scale spaces. Environment and Behaviour 25: 457-483.
24. Oman CM (2001) Human visual orientation in weightlessness. In: York Conference 2001: Levels of Perception (Harris L, Jenkin M, eds), Springer Verlag.
25. Oman CM, Shebilske WL, Richards JT, Tubré TC, Beall AC, Natapoff A (2002) Three dimensional spatial memory and learning in real and virtual environments. Spatial Cognition and Computation 2: 355-372.
26. Pearson DG, Logie RH, Green C (1996) Mental manipulation, visual working memory, and executive processes. Psychologische Beiträge 38: 324-342.
27. Péruch P, Vercher J-L, Gauthier GM (1995) Acquisition of spatial knowledge through visual exploration of simulated environments. Ecological Psychology 7: 1-20.

28. Robertson LC, Palmer SE, Gomez LM (1987) Reference frames in mental rotation. J Exp Psychol Learn Mem Cogn 13: 368-379.

29. Salway AF, Logie RH (1995) Visuospatial working memory, movement control and executive demands. Br J Psychol 86 (Pt 2): 253-269.

30. Shiffrar MM, Shepard RN (1991) Comparison of cube rotations around axes inclined relative to the environment or to the cube. J Exp Psychol Hum Percept Perform 17: 44-54.

31. Sims VK, Hegarty M (1997) Mental animation in the visuospatial sketchpad: evidence from dual-task studies. Mem Cognit 25: 321-332.

32. Stackman RW, Tullman ML, Taube JS (2000) Maintenance of rat head direction cell firing during locomotion in the vertical plane. J Neurophysiol 83: 393-405.

33. Vidal, M., Amorim, M. A., and Berthoz, A. Navigating in a virtual 3D-maze: How do egocentric and allocentric reference frames interact? (submitted). 2002.
Ref Type: Unpublished Work

34. Wann JP, Swapp DK (2000) Why you should look where you are going. Nat Neurosci 3: 647-648.

35. Wexler M, Kosslyn SM, Berthoz A (1998) Motor processes in mental rotation. Cognition 68: 77-94.

36. Wraga M, Creem SH, Proffitt DR (1999) The influence of spatial reference frames on imagined object- and viewer rotations. Acta Psychol (Amst) 102: 247-264.

37. Wraga M, Creem SH, Proffitt DR (2000) Updating displays after imagined object and viewer rotations. J Exp Psychol Learn Mem Cogn 26: 151-168.

38. Zinyuk L, Kubik S, Kaminsky Y, Fenton AA, Bures J (2000) Understanding hippocampal activity by using purposeful behavior: place navigation induces place cell discharge in both task-relevant and task- irrelevant spatial reference frames. Proc Natl Acad Sci U S A 97: 3771-3776.

39. Zugaro MB, Berthoz A, Wiener SI (2001) Background, but not foreground, spatial cues are taken as references for head direction responses by rat anterodorsal thalamus neurons. J Neurosci 21: RC154.

40. Zugaro MB, Tabuchi E, Wiener SI (2000) Influence of conflicting visual, inertial and substratal cues on head direction cell activity. Exp Brain Res 133: 198-208.