Brain Computer Interface Vs Walking Interface in VR: The Impact of Motor Activity on Spatial Transfer

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ABSTRACT

The goal of this study is to explore new navigation methods in Virtual Reality (VR) and to understand the impact of motor activity on spatial cognition, and more precisely the question of the spatial learning transfer. We present a user study comparing two interfaces with different motor activities: the first one, a walking interface (a treadmill with rotation) gives the user a high level of sensorimotor activity (especially body-based and vestibular information). The second one, a brain computer interface (BCI), enables the user to navigate in a virtual environment (VE) without any motor activity, by using brain activity only. The task consisted in learning a path in a virtual city built from a 3D model of a real city with either one of these two interfaces (named treadmill condition and BCI condition), or in the real city directly (the real condition). Then, participants had to recall spatial knowledge, according to six different tasks assessing spatial memory and transfer. We also evaluated the ergonomics of these two interfaces and the presence felt by participants. Surprisingly, contrary to expectations, our results showed similar performances whatever the spatial restitution tasks or the interfaces used, very close to that of the real condition, which tends to indicate that motor activity is not essential to learn and transfer spatial knowledge. Even if BCI seems to be less natural to use than the treadmill, our study suggests that BCI is a promising interface for studying spatial cognition.

Categories and Subject Descriptors

H.1.2 [**Information Systems**]: Models and Principles, User/Machine Systems - *Human factors, Human information processing*, *Software psychology*; H.5.2 [**Information Systems**]: User interfaces – *Ergonomics, Evaluation/methodology, Theory and method, User-centered design*.

General Terms

Human Factors, Measurement, Performance, Experimentation.

Keywords

Interfaces, Navigation, Virtual Reality, Spatial Cognition, Treadmill, Brain Computer Interface, User Study.

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1. INTRODUCTION

One future goal of the Virtual Reality (VR) technologies for neuropsychologists is to place patients in virtual situations that are similar to real-life situations, in order to improve the diagnostic or the effects of virtual learning on daily living activities [18]. VR is also important for example, to train people in airplane simulators, and to increase their performances, where real training is difficult, due to the cost and the availability of equipments. So, one question is to identify the variables that promote the knowledge transfer from a virtual to a real environment. In this paper, we focused more precisely on the role of motor activity and the interfaces on spatial cognition. Indeed, the impact and the amount of motor activity in VR that is necessary to successfully learn and recall spatial knowledge learning are still undefined. Spatial cognition involves cognitive processes which are necessary for many daily life situations, such as shopping in supermarkets (e.g., finding a product in a section) or driving. These cognitive processes are often affected by neurological diseases, brain trauma, etc. [18]. According to Montello [13], spatial cognition refers to two components: the first one, the cognitive component named wayfinding, corresponds to the processes necessary to plan an itinerary, to take a direction, to store and restitute spatial knowledge. The second component is a sensorimotor one which concerns all the displacements, and visual, vestibular and kinesthetic information, informing on the position and direction of our own body/head in an environment [19]. In real environments, it has been shown that body-based and vestibular information are important to learn and restore spatial knowledge. However, motor and cognitive component are often studied at the same time, and little research focused only on the cognitive component, due to the difficulty to isolate it. With VR technology, we proposed to isolate the motor component with the use of a Brain Computer Interface (BCI). BCI are communication devices that enable users to send command to a computer application by using brain activity only. This activity is generally measured using ElectroEncephaloGraphy (EEG) [14]. While initial BCI research was mostly targeted at severely paralyzed users, e.g., to design brain-controlled prostheses or wheelchairs [3], more recent works have also identified promising applications for healthy users, in areas such as video games or VR, among many others [9, 23]. In this work, we focus on the impact of the (sensori) motor component on the cognitive component of spatial transfer using two interfaces in VR. More precisely, we used for a spatial transfer task, 1) a treadmill with rotation, which provides vestibular, full–body based information and a motor activity near to real walking, and 2) a BCI, which permits to navigate in a Virtual Environment (VE) without motor activity, by brain activity only. These two learning conditions in VR were compared to a real condition where participants performed the same learning task in a comparable real environment. We used different spatial restitution tests to evaluate spatial acquisition levels and transfer. To our knowledge, this is the first user study which proposed a method to distinguish the motor from the cognitive component for spatial cognition. This is also the first study which compares a BCI to a walking interface, more particularly addressing the transfer question.

2. RELATED WORK

2.1 Spatial Cognition and cognitive processes

Several models of spatial knowledge acquisition exist. One of the most cited is the Landmark Route Survey (L-R-S) model of Siegel and White [22] which advances that spatial knowledge is acquired by steps: first, landmarks are stored, then the route survey (fixed sequences of landmarks and action). The last stage concerns survey knowledge, comparable to a map view of the environment. The two first levels are egocentric (i.e. involves the person's point of view) while the last stage is allocentric (i.e. spatial information are integrated independently from the personal point of view). The survey knowledge is more difficult to achieve and requires the repetition of spatial information. But currently, this model is questioned in particular the fact that spatial information may not be acquired only by steps but also in parallel [6].

2.2 Spatial Cognition and motor processes

One theory of spatial knowledge acquisition concerns path integration [12]. This theory admits that it is possible to acquire spatial knowledge without optic flow, only based on body-based information generated by our motor activity, updating away information of position and translation of the body. In real environments, the impact of body based-information, and more precisely vestibular information on spatial knowledge, have been deeply studied. For example, Loomis et al. [10] showed that when only optic flow is involved, performances on directional responses were much poorer than when walking. Mittelstaedt and Mittelstaedt [12] also found that vestibular information is essential, specifically when visual information is not present. Vestibular information would be necessary for the perception of distances, angles, and for route knowledge (i.e. egocentric spatial updating [2]), while allocentric knowledge would use position and orientation of visual cues.

2.3 Spatial Cognition and VR studies

Our real question is: do interactions in VE and associated motor activity have an impact on spatial knowledge? The majority of the spatial cognition experiments use a joystick for the navigation, which provides little motor activity due to low displacement and the force applied by the hand (no vestibular information). But different authors [21,5] found that motor activity, body-based and vestibular information given by walking in VR (with treadmill or direct walking with a Head Mounted Display –HMD- for rotational movement and direction of the head) gave better results when vestibular information was present than when no vestibular information was provided. Ruddle and Lessels [20], for example, compared different interfaces (walking in VE/HMD, Keyboard/HMD and mouse/Keyboard) and found that the walking VR group performed better than the other groups for navigational search tasks (finding targets hidden inside boxes in a room-sized space). This was also consistent with the findings by Grant and Magee [5], which is, to our knowledge, the only research about walking motor activity and spatial transfer. The authors showed that people performed better on a wayfinding task in the real world if they had previously been exposed to a VE using a walking interface rather than a joystick. For Waller [24], the use of a joystick requires different attention levels which would interfere on spatial representations of a VE. Ruddle et al. [21] recently addressed the role of both translational and rotational vestibular information in VE on the accuracy of participants' cognitive maps (survey knowledge). To do so, they used different locomotion interfaces (translational displacements with walking or treadmill vs. no translational displacements with joystick), sometimes with the possibility of really turning the head (i.e., rotational vestibular condition or not) during rotational movement. They reported that walking, as well as the treadmill condition, significantly improved the accuracy of participants' survey knowledge, but, that vestibular rotational-based information had no effect. To summarize, results on interfaces and motor activity in a VE are sporadic and contrasted.

2.4 Spatial Cognition and BCI

As for as we know, there is no user study which focused on spatial cognition with BCI. However it has been shown that BCI could be used to navigate and explore real and VE by using only brain activity. For instance some groups have reported that a BCI could be used to freely navigate along a virtual street [7], in a virtual apartment [8] or in a virtual museum [11]. Navigation in real environments has also been achieved using a brain-controlled wheelchair [3]. This demonstrates that a BCI is a suitable input device to perform navigation tasks. For Lecuyer et al. [9], BCI have the same properties as a classical interface, as such it could be used to distinguish the cognitive component from the motor component in spatial cognition. But currently, no study addressed the impact of BCI use on spatial knowledge, most BCI research being focused on signal processing and assistive applications.

2.5 Spatial knowledge transfer from virtual to real environments

When VR is used as a medium for spatial learning, one key challenge is to understand what spatial knowledge learned from the VE is transferred into real life, and to identify the factors that promote these transfers. Previous findings indicated that spatial learning from a VE was similar to knowledge acquired in a real environment, irrespective of the type of participants [26], or even if patients suffer from traumatic brain injury. Different authors have also found a significant impact of the motor activity of the joystick. However, certain factors such as visual fidelity, retention delay, navigation mode [25, 26, 27], or video game experience [16] can also have an impact on spatial transfer. In the end, we found few experiments that studied spatial transfer from virtual to real by comparing different interfaces and associated level of motor activity.

3. METHOD

VR was used as a spatial learning medium using a spatial learning paradigm that involves acquiring a path, either in a real environment or its virtual replica [26, 27]. The acquisition path was assessed according to three conditions of navigation modes: in VR with either 1) a Treadmill (all body-based information); 2) a BCI (no body displacement and no body-based information), or 3) in real condition where participants learned the path in the real environment (all body-based information). After path acquisition, participants completed tasks for assessing their spatial knowledge.

3.1 Setup

3.1.1 The environment

The real environment was a $9km^2$ area near a hospital. The VE was a 3D scale model of the real environment, with realistic rendering (photos of several building facades were applied to 3D geometric surfaces) and urban sounds to make the simulation more realistic. Significant landmarks (e.g., signposts, signs, and urban furniture) were also included in the VE. The VE was laboratory-developed using Virtools 3.5™. Irrespective of the learning conditions, the itinerary was presented to participants on the basis of an egocentric frame of reference, at head height. It was characterized by an irregular closed loop, 780 m in length, with 13 crossroads and 11 directional changes.

3.2 Material

The material used in the darkened laboratory room was a DELL Precision M6300 laptop computer (RAM: 3GHz; processor: Intel Core 2 Duo T9500 2.60 Ghz) with an Nvidia Quadro FX 1600M graphics card (256Mo) and a resolution of 1024 x 768, a 2 x 1.88 meter screen, a projector (Optoma/ThemeScene from Texas Instrument) with rear projection. The participants were located two meters away from the display screen.

Description of the treadmill and the BCI Interfaces

The treadmill condition included an HP COSCOM programmable (speed, declination and acceleration) treadmill and a MS-EZ1 sonar telemeter. This interface enabled users to modify the VE's visual display in real time to match his/her walking speed, with a maximum speed of 6 km/h. The Sonar MS-EZ1 telemeter monitored the participant's movements on the treadmill which was divided into three parts (see Figure 1): one for accelerating (the front of the treadmill), one for walking normally (the middle of the treadmill), and one for decelerating (the back of the treadmill). Neither acceleration nor deceleration information was sent to the treadmill when the participant was in the walk zone. In contrast, when the participant walked into the acceleration or deceleration zone, the sonar detected length changes in the participant's position, and instructed the computer to accelerate or decelerate until the participant returned to the walk zone. Finally, the participant remaining in the deceleration zone for a prolonged period induced a stop in the VE. Participants were able to walk, accelerate, decelerate, and stop in the VE, thus receiving body-based information induced by the physical displacement of the participant on the treadmill. For rotational movement (and rotational vestibular information), the participant walked on the treadmill and was informed that his/her point of view in the VE would be controlled in real time by head rotations captured by motion capture (analyzed with 12 cameras OPTITRACK system, Motion point™): when the participant turned his/her head, the system updated the visual optic flow at a rate correlated with the head movement rotation angle (the greater the rotation angle was, the faster the modification in rotational optic flow was, reflecting natural head movements).

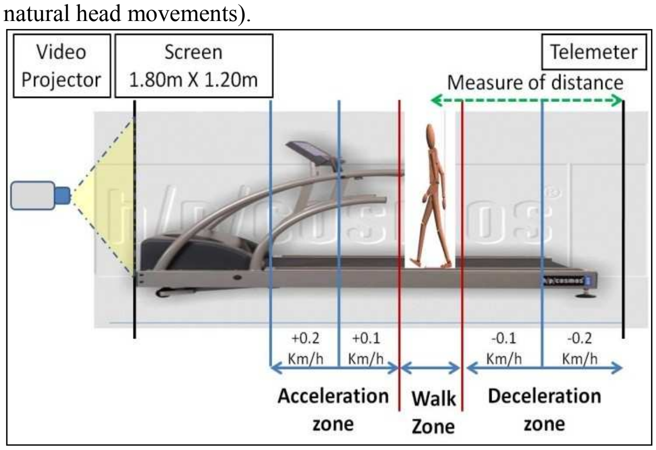

Figure 1: Treadmill interface and interaction techniques To accelerate, decelerate or stop in the VE.

Our BCI system was a two-class system, based on motor imagery tasks [14]. More precisely, participants had to imagine a left (or right) hand movement, which the BCI had to detect, to turn left (or right) in the VE. Our BCI was thus synchronous, which means that the EEG data analysis was performed at a specific time points and not continuously. Indeed, participants cannot interact any time but only on computer demand. Interaction was possible with the BCI system only when an arrow was presented at each intersection, indicating which hand motor imagery (left or right) the participant had to perform. Speed displacement in the VE was fixed to 4 km/h.

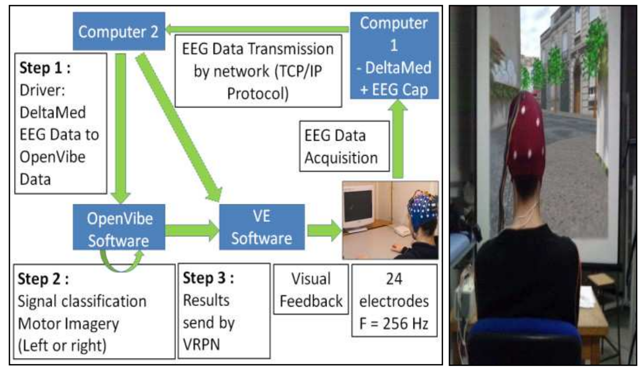

Figure 2: On the left, our OpenVibe BCI system. On the right, A participant with our BCI during a VR spatial learning task.

Our BCI was based on the OpenVibE software [15] which allows implementing easily a BCI with little knowledge on signal processing. Brain signals acquisition was done by a PC X86 equipped with an EEG Deltamed System composed of a 24 electrode cap. Communication between the VE and Deltamed system acquisition relies on the VRPN protocol, based on TCP/IP (see Figure 2). EEG corresponding to left or right hand motor imagery were identified using a classical processing pipeline [14, 15]. Precisely, band power features in the mu and beta bands (8-30 Hz) were extracted from laplacian channels over electrodes C3 and C4 and classified using a Support Vector Machine (SVM).

3.3 Procedure

Each participant completed a three-phase procedure: (1) spatial ability tests and immersion propensity, orientation, shortcuts, map questionnaires, to assess the participant's characteristics (see below); (2) learning phase: training interface and the route-learning task under one of the three conditions (BCI vs. treadmill vs. real); (3) restitution phase with six spatial knowledge tasks.

3.3.1 Spatial ability tests, immersion propensity, orientation, shortcuts, map questionnaires:

The GZ5 test was used to measure spatial ability of participants. The Mental Rotation Test (MRT) was administered to measure spatial mental rotation abilities. The Corsi's block-tapping test was employed to measure the visual-spatial memory span. Three self-administrated questionnaires were filled in by the participants. One focused on spatial orientation in everyday life, the second one evaluated the ability to take shortcuts, and the third one, the ability to use maps, including seven questions each (for each responses were given on a 7-point scale). The higher the score the higher the subject's difficulties on one of these different themes. Measures of the immersion propensity were based on the questionnaire used by Girard and Turcotte [4].

3.3.2 Learning phase

- Real condition: Route learning under real conditions was the baseline, providing referential performances by learning a real route in an urban environment. The participants walked at their own speed, were instructed which direction to take at each corner, and were free to visually explore their surroundings. Learning position data was acquired using a Magellan™ GPS CrossOver, and a video was recorded using an AIPTEK™ DV8900 camera mounted on a bicycle helmet worn by the participant.

- Treadmill condition (VR):

Before VR exposition, each participant participated to a training phase, to get used to interacting with the treadmill. The initial training phase was considered to be completed when the participant was able to use the interface in another VE. Route learning in the treadmill condition was similar to the real condition. The directions were indicated verbally by an experimenter situated behind the participant. Position, time, collisions and interactions (acceleration, deceleration, turning left and right) were captured.

- BCI condition (VR):

Step 1) Learning to use a BCI:

The BCI use requires a long training time because participants had to learn to control their brain activity, and the computer has to learn this brain activity. The participants were equipped with the EEG cap (see Figure 2). The training was composed of six sessions distributed over three days (about three hours of training by session). The learning protocol was based on a standard protocol (see [14] for more details), which consisted to imagine movements of the left (or right) hand when a left (or right) arrow was presented on the screen. A visual feedback in a VE informed the participant about the motor imagery detected.

Step 2) Learning the path with the BCI:

Directions in route learning were given at each intersection by an arrow indicating the direction of the motor imagery that the participant had to execute. If the recognized computer command was incorrect (for example, if the system detected a right motor imagery while a left arrow was presented), the participant was redirected by the experimenter in the correct direction with a joystick.

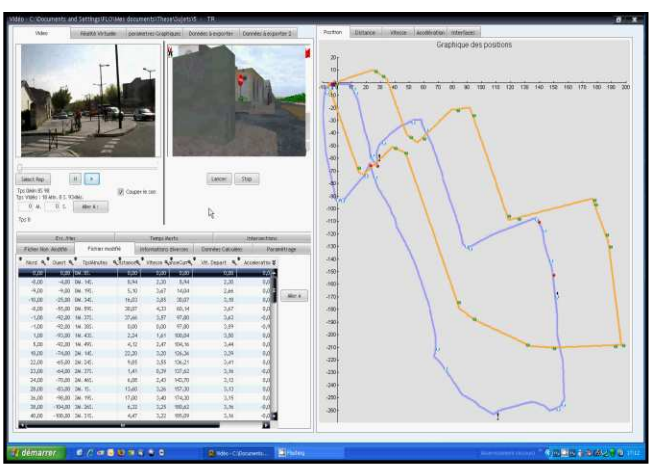

Figure 3: Analysis software to compare Virtual and real conditions.

In addition, after VR exposure (for the BCI and treadmill condition), the participants completed 1) a simplified simulator sickness questionnaire (SSQ) to measure the negative side effects of being immersed in graphically-rendered virtual worlds, 2) a questionnaire concerning the ergonomics of the interface used, and 3) a presence the questionnaire proposed by Girard and Turcotte [4]. Moreover, a software tool (see Figure 3) was developed to analyze the participant's positions, interactions, speed and time data in the VE or in the real condition, to ensure the similarity of path learning in real and virtual conditions.

3.3.3 Restitution phase

Six tasks were performed by each participant, in an order counterbalanced across participants.

Photograph classification task: twelve real photographs of intersections of the path followed were presented to the participants in a random order. Participants were required to arrange the photographs in chronological order along the path they had learned (the time allowed was ten minutes). The results were scored as follows: one point for a photo in the correct position and 0.5 point for each photo in a correct sequence, but not correctly placed along the path (e.g., positioning photos 4-5-6 in the right order but not placing them correctly in the overall sequence earned 1.5 points). This paper-pencil task assessed the participants' ability to recall landmarks and route knowledge within an egocentric framework [26, 27].

Distance estimation task: Each participant was asked to give a verbal estimation of the distance walked in the VE (in meters).

Directional estimation task (see Figure 4): This task was computer-based and consisted of presenting a series of twelve pictures of real intersections, taken from a walker's perspective, in random order. Each photograph was displayed at the top of the screen, above an 8-point compass. The participant had to select the compass direction they were facing on the learned path. We noted the percentage of errors and the angular error were averaged. Directional estimations are expected to be accurate when participants have acquired well-developed route knowledge.

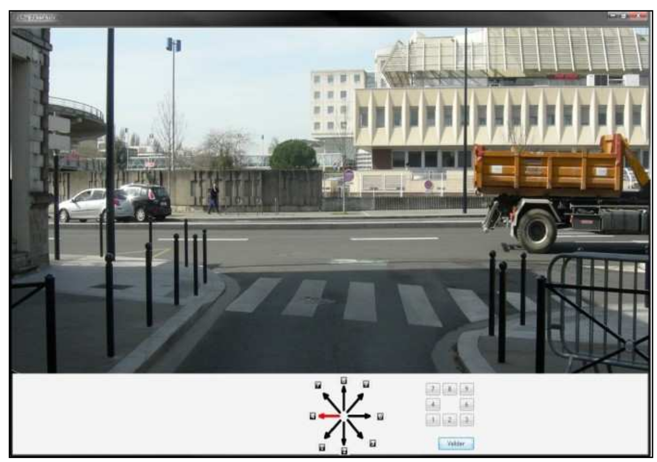

Figure 4: Screenshot of the directional estimation task And the starting point estimation task.

Sketch-mapping task: Participants had to draw a freehand sketch of the visualized route. The time limit was ten minutes. One point was scored for each correct change of direction. This paper-pencil task is known to measure survey knowledge [26, 27].

Point starting estimation task (see Figure 4): This computer-based task consisted of presenting a series of twelve pictures of real intersections, taken from a walker's point of view, in random order. Each photograph was displayed at the top of the screen, above an 8-point compass. For each photograph, the participant had to select the compass direction of the starting point of the learned path. We noted the percentage of errors and the number of angular errors was averaged. These direction estimations are expected to be accurate when participants have memorized a well-developed, map-like representation of the walked environment and measures survey knowledge.

Real wayfinding task: this task consisted of reproducing the learned path in the real environment. Direction errors were calculated and expressed in percentages. When a participant made a mistake, s/he was stopped and invited to turn in the right direction. This task may be considered as a naturalistic assessment of navigational abilities and spatial knowledge transfer, based on the use of landmarks, as well as route and survey knowledge [27]. In addition, restitution path software included the participant's position and time data analyses, in order to measure restitution speed (the same Magellan GPS CrossOver and helmet-mounted video camera were used for data capture).

3.4 Participants

Participants were 48 student volunteers from our university (24 men and 24 women): 20 students were assigned to the real condition, 20 to the treadmill condition and only 8 to the BCI condition, due to the time required to learn to use this interface (about 10 hours per subject), and the difficulties in having subjects on 3 different days and closely spaced in time. All participants had normal or corrected-to- normal vision and were right-handed, and had at least an A-level or equivalent degree. Their ages ranged from 18 to 30 years. We controlled the video game experience of subjects: half of each condition was constituted of video game players (who played a minimum of three hours by week during more than one year), and the other half of non video game players (who never played regularly to video games, and who were not old video gamers). The three composed conditions were balanced for gender and for video game experience (χ^2 procedure p>0.05). In addition, there was no significant difference in spatial abilities among the three conditions, as assessed with the GZ-5, the Mental Rotation Test (MRT) and the Corsi's block-tapping (respectively, p>0.300; p>0.800; p>0.900). No differences were found concerning the orientation, shortcuts and map questionnaires (p>0.200, p>0.400, p>0.400*)*. For the VR conditions, no differences were found for immersion propensity (p>0.600).

4. RESULTS

Dependent measurements and statistical analyses: each of the dependent measurements presented above were submitted to a one-way ANOVA analysis (3 learning condition: BCI, treadmill with rotation, real), with between-subject measures (see Table 1). Post-hoc analyses were carried out using Fisher's procedure. A Pearson's correlation was used to assess the relationships between the performances in the spatial restitution tasks, the tasks assessing spatial abilities, the presence questionnaire, the self-reporting questionnaire about spatial difficulties, the SSQ and the questionnaire about the interface ergonomics.
For the *Photograph classification task*, the ANOVA revealed a significant effect of the learning condition ($F(2,45)=4.01$; $p<0.05$; $\eta^2=0.15$) where results were better in the real condition than the two virtual conditions. Results in VR conditions were very close and post hoc comparisons showed a significant difference for the real condition compared to the treadmill condition ($p<0.05$), and a tendency between the real and the BCI condition ($p=0.06$).
No significant effect (p>0.100) was found for the *Distance estimation task*.

For the *directional estimation task*, no differences were found for errors percentage (p>0.200) or for mean angular errors (p>0.300).
For the *Sketch-mapping task*, the statistical analyses revealed no significant differences (p>0.200).
Concerning the *point starting estimation task*, no differences were found for the percentage errors (p>0.600) or for the mean angular error (p>0.900).
For the *Real wayfinding task,* the ANOVA analyses for the restitution speed revealed a significant difference ($F(2,45)=3.99$; $p<0.05$; $\eta^2=0.15$). Restitution speed was the slowest for the BCI condition, followed by the treadmill condition, and the real condition was the fastest. Post hoc comparisons showed only a significant difference between the real condition and the BCI condition, where restitution speed was significantly lowest for the BCI condition ($p<0.001$). For the errors direction percentage, the ANOVA analysis revealed no significant differences (p>0.100).

Table 1: Results of the spatial restitution tasks according to The learning conditions (real, treadmill or BCI).

		Real Environment	Treadmill	BCI
Wayfinding Task	Mean Speed	3.66	3.1	2.93
	(SD)	0.26	0.32	0.31
	Percentage Error	4.99	8.5	8.65
	(SD)	6.72	5.99	6.41
Photograph classification task	Correct Score	8.6	5.85	6
	(SD)	3.46	2.88	3.65
Directional estimation task	Percentage Error	19.23	28.07	22.11
	(SD)	14.22	19.7	16.16
	Mean angular error	104.86	87.09	81.02
	(SD)	56.81	42.85	25.38
Distance estimation task	Distance	865.1	1063	1355.62
	(SD)	636.28	587.43	544.61
Starting point estimation task	Percentage Error	45.83	50.83	46.87
	(SD)	17.62	17.91	19.38
	Mean angular error	82.59	81.43	81.95
	(SD)	29.51	15.5	25.38
Sketch-mapping task	Correct responses	11.15	10.45	11.87
	(SD)	2.41	2.26	1.45

For the last results, we compared the treadmill and the BCI condition using an unpaired two-tailed Student's t-test (with dof=26), the real condition was excluded because no interface was used in this condition.

SSQ and ergonomics of the interface used (see figure 5):
Concerning the SSQ questionnaire (based on only the two VR conditions, see Figure 5), no differences were found for discomfort, fatigue, eye pain, headaches, stomachache (respectively, p=0.07, p=0.44, p=0.93, p=0.48, p=0.39).
Concerning the ergonomics questionnaire about the interface used, the Student's t-test analysis revealed a significant difference for the possibility to rotate (t(-11.40); $p<0.0001$; $\eta^2=0.83$) in favor of the treadmill condition. To the question "The interface used was easy to use", statistical analyses revealed a significant difference for the treadmill condition compared to the BCI condition (t(5.41); $p<0.0001$; $\eta^2=0.53$). For the tiring question, the statistical analyses revealed no differences (p=0.52). It should be noted that for the BCI condition, 3 participants (out of 8) found

that it was a tiring interface. Concerning the last questions, we used a 7 point scale (0 = the worst and 7 = the best). All participants in VR conditions thought that the two interfaces were easy to learn; statistical analyses revealed a significant difference in favor of the treadmill condition (t(3.30); *p=0.028; η²=0.30*) for the learning of the interface used and for the understanding of the interface (t(3.56*); p=0.0015; η²=0.32*). 4 participants in the BCI condition found difficulties due to the precision of the interface, but no significant difference was found about it (p=0.18).

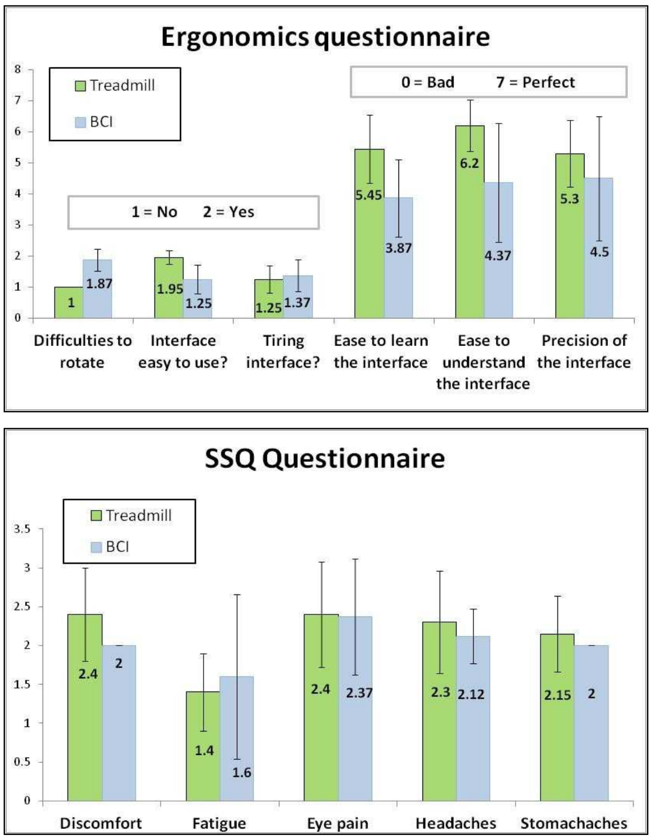

Figure 5: Ergonomics and SSQ questionnaire according to The treadmill and the BCI condition.

Presence questionnaire (see results on Figure 6):

The authors have decomposed this test in sub-scales and a global score. Concerning the realism sub-score, no difference was found (p=0.35). For the acting possibility subscale, a difference was found in favor of the treadmill condition (t(3.37) ; *p=0.002; η²=0.30*). The Student's t-test revealed no differences concerning interface quality (p=0.85), but a significant difference for the treadmill condition concerning the possibility to examine the environment (t(2.10); *p=0.04; η²=0.14*). No differences were found on the auditory presence (p=0.83) or for the haptic presence (p=0.45). Finally, the Student's t-test revealed a significant effect in favor of the treadmill condition (t(2.66); *p=0.013; η²=0.21*) for the global presence score.

Correlations:

For the *Orientation, shortcuts and maps questionnaire,* negative correlations were found between the percentage of errors for the starting point estimation task and the general orientation questionnaire. A negative correlation was also found between the shortcuts questionnaire and all the dependent variables of the starting point estimation task. Finally, a negative correlation was found between the percentage of errors for the starting point estimation task and the maps questionnaire.

Concerning the *SSQ and the ergonomics questionnaire*, no correlations were found with the scores of the spatial tasks.

Finally, for the *Presence questionnaire*, while we found correlations between the different subscales (not presented here), we did not found significant correlations between these subscales and the spatial knowledge measures of our different tasks.

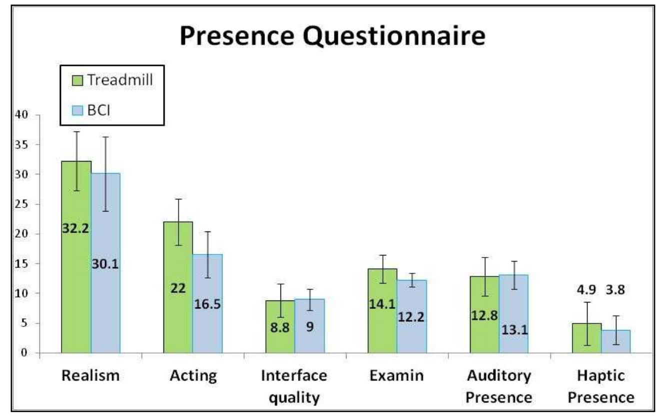

Figure 6: Presence questionnaire according to the treadmill And the BCI condition.

5. DISCUSSION

To recall, our study focuses on the impact of a motor activity on the transfer of spatial knowledge from virtual to real environments, by comparing two virtual learning conditions: 1) a treadmill condition which provided body-based information very close to a real waking activity, 2) a BCI condition where displacements were performed by brain activity (without any motor activity), to a real condition where participants learned a path while walking in the real environment. Six different restitution tasks were presented to the participant in order to evaluate if the motor activity had an impact on these tasks, known to measure transfer, egocentric and allocentric knowledge.

5.1 Motor activity and spatial transfer

For the photograph classification task, our results showed a significant difference in favor of the real condition compared to the two others conditions. Post hoc comparisons also showed a significant difference between the real condition and the treadmill condition and a tendency between the real condition and the BCI condition, but none between the BCI and the treadmill condition. This task consisted in measuring chronological sequences of intersections photographs of the real environment with an egocentric point of view, which would involve the episodic memory, and more precisely the temporal component. Our results suggest that motor activity (the treadmill condition) does not improve performances compared to a condition without motor activity (BCI). However, the best results are for the real condition, which should mean that the visual information provided by this last condition seems to be more important than motor activity for this task. Our results are in accordance with Wallet et al. [27] who found for the same task, that the visual fidelity of an environment is more important than the interaction (passive -no interaction- vs. active mode -joystick interaction). Efforts to improve the visual rendering of our VE to make it close to the real environment could confirm these results.

Surprisingly, for the distance estimation task, no differences were found, whatever the learning conditions used, meaning that motor activity would not be important for this type of task. For certain authors, in VE [21] or real environments, body displacement are important to evaluate egocentric tasks such as distance estimations. But for others [17], visual information would be sufficient. Three explanations can be summarized as follow: 1) visual information may be sufficient for spatial knowledge transfer 2) the neuromuscular theory of Abernethy et al. [1] affirms that there would be a similitude between a performed movement and an imagined movement; in our BCI condition, the motor activity would be "symbolic", meaning that body-based information would be stimulated without the effective displacement 3) For the BCI condition, only eight participants are presented; it would be interesting to increase the number of participants in order to confirm our results.

No differences were found for the directional estimation task. This task consisted in the reminding of an egocentric point of view of a real intersection associated to an action. Once again, the motor activity provided by the real walking or walking on the treadmill does not improve performances compared to the BCI condition. One other explanation could be that BCI participants had a long training period where they saw arrows to indicate a hand movement to imagine. Maybe these indications could increase the learning by combining an arrow to a direction. A solution would be to use a verbal BCI system to delete this visual aid.

No differences were found concerning the measures of allocentric knowledge (i.e. the starting point estimation task, and the sketch mapping task), knowledge acquired with repetitions and manipulations of spatial information. Nevertheless, most of the dependant variables of these two tasks were correlated with our questionnaire about self-reporting of using maps, shortcuts or general orientation. These results mean that allocentric knowledge would be more linked to cognitive processes and real life experience than the motor activity or the tasks used. Once again, BCI seems to be sufficient to acquire this type of knowledge.

Concerning the wayfinding task, our results showed no significant differences between the three conditions for the percentage of errors, meaning that motor activity and body-based information induced by walking are not essential to increase spatial knowledge transfer. Our results for the treadmill condition are in accordance with other experiments which showed that body-based information is important [21] when walking in a VE (not a transfer task). Nevertheless, our BCI condition could be compared to a passive exploration mode, with the participants not moving except that they could interact. Here, our BCI condition proposed results similar with the treadmill or the real condition, meaning that the possibility to interact in the VE seems to be more important than motor activity. Different authors who compared active exploration to a passive exploration [25, 26, 27] often showed that the real condition was the best condition to acquire and to recall spatial knowledge, but also that active exploration (often with a joystick or a keyboard and a mouse for the displacement, which do not provide body-based information or vestibular information) was better than a passive exploration. Maybe joystick or mouse interfaces involve an important learning phase and large attention as already said by Waller [24] which had a bad impact on spatial cognitive processes. Or maybe our BCI and the absence of motor displacement permitted to be more vigilant than with a joystick where motor activity is required. Indeed, even if participants had to limit their motor movements during BCI use, they might have still done some minor movements. In the future, a joystick condition could provide information about a small motor activity during a spatial navigation task. It is to note that statistical analyses showed that the restitution speed was the worst for the BCI condition in comparison to the real condition, indicating that the interface used could have an impact on the speed of spatial transfer. More precisely, the motor activity of the treadmill condition enabled to obtain time and spatial performances that were very close to the real condition, while no motor activity provided by the BCI condition allows similar spatial transfer performances but in a longer time. Maybe the fact that the displacement speed in the BCI condition was fixed and not controlled by the user and the interactions occurred only at the intersections, may have an impact on the spatial information acquisition. A new BCI condition with the possibility to modify the displacement speed and to choose its orientation (an asynchronous three-class BCI) at any time may give new information about the impact of motor activity on spatial restitution time.

Of course, our BCI condition contained only eight participants. Moreover, the learning phase of this interface was longer than the treadmill condition and could have an impact on performances. But our results are the first ones which compared a BCI to another interface. Moreover, we tried to clearly distinguish the motor component of the cognitive component in spatial cognition, and tried to evaluate the impact of the motor activity during a navigational task in a VE. Results pointed that motor activity and body-based information are not essential if the cognitive processes, the ability to act and to understand its interaction are not interfered by motor processes. It is also important to note that is unlikely that gaming or interface experience played a major role because these two VR interactions were totally novel and unknown of all the participants. It would be interesting now, to increase the number of participants in the BCI condition, and to compare the performances of the treadmill and the BCI conditions to a joystick condition, in order to confirm our results about the motor activity of a less natural interface than the treadmill.

5.2 Ergonomics and presence questionnaires

This section concerns more precisely self-report of users about the two VR interfaces. The goals here are to determine the differences between the walking interface and a BCI, in order to give some guidelines concerning navigational interactions in a VE.

For the realism of the simulation, we did not found significant differences, meaning that the high level of motor activity of the treadmill condition had little impact on the realism compared to the BCI condition. It is to note that there was no difference for the haptic and auditory feedback, meaning also that the motor activity was natural for the treadmill condition, and similar to the BCI. Maybe a less natural and transparent interface such as a joystick may give new information about realism perception.

In contrast, the possibility to act, and to examine the VE were significantly better for the treadmill compared to the BCI condition. These results showed that our walking VR condition allowed the participants to explore and to navigate more easily in the VE. Our results also showed that the treadmill condition was easier to learn, to understand, to use and to perform than the BCI condition. The use of the treadmill seems to be more natural and transparent to use than the BCI. This may be due to the fact that 1) the treadmill is a walking interface where the interaction is very close to real walking and participants did not have a long training to use it strongly; 2) the interactions in the BCI condition were synchronous, i.e., participants had to perform their mental tasks very few times and should not do so when they want but only at the intersections. Therefore, it seems that the possibility to act and to examine the VE were the worst for this condition. But for this last condition, maybe attention processes were less used due to the little amount of interactions, improving the processes necessary to acquire spatial knowledge, and explaining similar results between the two VR conditions.

A significant difference was found concerning the total presence score in favor of the treadmill condition. Finally, the presence may be more strongly related to the navigational possibilities offered to the users than to the interface they used. But even if the treadmill condition permitted the users to explore more easily and more naturally the VE than the BCI condition, performances in term of spatial navigation were equivalent. This means that even if the sense of presence is high, it does not improve performances. Moreover, it seems that cognitive processes are more important than motor processes for spatial cognition. It is also important to note that whatever the interfaces used, no significant statistical differences were found concerning the SSQ, and no correlations were revealed with the spatial restitution tasks, and the SSQ or the presence questionnaire. So, performances on spatial tasks cannot be explained by the limitations of the interface used.

A natural interface such as the treadmill condition, which is easier to use, would not be necessary better than another navigational interface, maybe less intuitive. These results could be supported by the statistical analyses concerning the quality, the precision, or the fatigue caused by the interface used, which were not different between the treadmill and the BCI. Even if some differences appeared concerning the presence and the ergonomics of the two interfaces in favor of the treadmill condition, results in term of spatial transfer performances are equivalent, and not correlated with the ergonomics score. We may wonder whether it is necessary to use more complex BCI (e.g. asynchronous and/or three-class BCI) given that the transfer performances achieved with a simple BCI seem satisfactory.

6. CONCLUSION

Whatever the tasks performed, our results showed two surprising and important points: 1) walking in a VE with a treadmill permits users to acquire and to transfer spatial knowledge [5] in a similar manner as a real condition; 2) Our BCI condition also showed that it was possible to store and to recall spatial knowledge as in a real condition, only based on visual information and mental interactions. This suggests that the motor activity, vestibular information and body-based information are not essential to acquire and to recall spatial knowledge. Future work could consist in comparing our results with an interface less transparent and natural than our walking interface as a joystick, and to increase the number of subjects in the BCI condition, which could further support our results. Finally, it seems to be more important to favor the understanding of the interactions, the VE, and the cognitive processes adapted to people using the interface than the motor activity. But more generally, our results suggest that the BCI could be a promising tool to study and diagnose diseases where spatial cognition or motor processes are altered, such as the Parkinson's disease. Indeed, it could enable researchers to detect and diagnose what processes (cognitive and motor) are damaged and impact spatial cognition and/or daily activities, and thus to propose adapted solutions.

7. REFERENCES

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