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The influence of different sensory cues as selection feedback and co-location in presence and task performance

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Abstract For some applications based on virtual reality technology, presence and task performance are important factors to validate the experience. Different approaches have been adopted to analyse the extent to which certain aspects of a computer-generated environment may enhance these factors, but mainly in 2D graphical user interfaces. This study explores the influence of different sensory modalities on performance and the sense of presence experienced within a 3D environment. In particular, we have evaluated visual, auditory and active haptic feedback for indicating selection of virtual objects. The effect of spatial alignment between proprioceptive and visual workspaces (co-location) has also been analysed. An experiment has been made to evaluate the influence of these factors in a controlled 3D environment based on a virtual version of the Simon game. The main conclusions obtained indicate that co-location must be considered in order to determine the sensory needs during interaction within a virtual environment. This study also provides further evidence that the haptic sensory modality influences presence to a higher extent, and that auditory cues can reduce selection times. Conclusions obtained provide initial guidelines that will help designers to set out better selection techniques for more complex environments, such as training simulators based on VR technology, by highlighting different optimal configurations of sensory feedback.

Keywords Co-location · Feedback · Haptic · Selection · Virtual environments

1 Introduction

It is said that a user's experience within an application based on virtual reality (e.g. a training simulator) requires the inclusion of interaction techniques so as to not only allow the user to

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accomplish their task within the environment but also to enable them to elicit a feeling that they are actually working within the simulation [31, 46]. However, the development of these interaction techniques is still one of the main bottlenecks in the integration of virtual reality (VR) technology in nowadays applications (i.e. [7]).

Up to now and based on our experience in the development of a 3D training simulator for medical emergencies [36], the best inclusion criteria of sensory stimulation to indicate objects selection in terms of different human factors is still open to discussion for the design of a selection technique. This technique is necessary within these simulators in order to accomplish actions, such as providing medicines or applying treatments by activating different 3D controls. In particular, the study presented herein was made to answer questions, such as: Would the illumination of a 3D object or the sound emission associated with a control selection improve performance and presence? To what extent would the inclusion of more than one kind of sensory feedback benefit selection? Did the inclusion of haptic feedback improve these factors although visual and proprioceptive spaces are not spatially coincident?

Four main key points of this study are introduced below: presence, haptic, co-location and selection techniques. Presence has been defined in many different ways [8] but mainly attending to two main views: the Rationalist theory and the Ecologist view. Rationalist or Traditional theory understands that presence is linked to a non mediation sensation, while the Ecologist or Phenomenological view defines presence from a psychological point of view, as the capacity of remembering the interaction within the VE as an experience more than just mere images. In this study presence is understood as the sensation of being within a virtual environment (VE) to the extent that participants forget that their experience is mediated by technology [19]. Regarding haptic stimulation, this study considers an isotonic active force feedback, the application of force as a programmable function of position, in contrast with passive feedback, based on dissipating forces. The definition of a selection technique within a VE is commonly based on metaphors [5, 26]. These metaphors usually imitate selections within a real environment (e.g. natural hand metaphor maps movements of the participant's hand in movements of a virtual object) or extend human capabilities (e.g. ray casting and Go-Go metaphors use the viewpoint to select objects and extend the selection area). In this study, the selection technique was designed upon the natural hand metaphor and participants selected objects by "touching them" with a virtual stylus. The factor co-location is referred to within the literature as the existence of an isometric transformation between proprioceptive and visual workspaces [9].

When interacting with a VE, it is commonly understood that human factors depend on the amount of sensory stimulation provided [6], therefore both, task performance and mental workload have been analysed by considering the amount of limited resources required for the respective tasks undertaken [49]. Thus, the relation stabilised in multiple resources model [48] among sensory modalities and the resources used for perceptual and cognitive activities has led to useful outcomes for the design of complex applications, such as integration strategies of sensory cues with the goal of reducing mental workload for different tasks favouring presence [20], and the best stimulation combination for multitasks environments [13, 27]. However, within a multimodal VE, where the sensory cues can be limited in quantity and quality, perceptual processing may be different to that of other applications. Therefore, certain stimuli combinations may act to the detriment of cognitive activities instead of being a benefit. Moreover, further research is needed to include tactile/haptic input to the modalities dimension of the multiple resources theory [49].

Presence has been found to be a very useful construct in validating a VE in applications related to that of training simulators. This construct may ensure that skills learned within a training simulator hold certain validity within a real situation, which indeed is one of the main goals of these applications. However, presence reached by manipulating factors such as realism, content, sound and visual quality [43] may decrease if the VE responses to participants' actions or movements do not correspond to the environment quality. Thus, it is important to assess the effect of sensory feedback provided in presence, but this evaluation has been mainly made attending to particular stimuli, i.e. effects of stereoscopic cues and spatialised sounds have been addressed in presence for walk-through environments [15, 47] and haptic feedback has been reported as a performance aid for selection tasks within VEs [39, 42]. As a step forward, the study presented herein has focused on evaluating the effect of three modalities of feedback (visual, auditory and haptic cues) separately in terms of presence and performance for a selection task.

In conditions where the participant's hand or devices are always placed on a surface, auditory and visual cues are the main feedback modalities provided to indicate selection within a graphical user interface. However, within a typical set-up of a VE, which is aimed at being more similar to that of a real interaction (without a reference surface), haptic information should provide a faster selection awareness, which in turn, can result in an aid for a faster interaction. When touching an object, if haptic feedback is provided the contact perception and the avoidance of penetration should lead to a faster interaction. Indeed, based on the multiple resources theory [48], advantages should be gained by displaying haptic information within an environment where visual and auditory cues are already being processed (e.g. a training simulator that has been designed for medical emergencies with equipments in place that provide visual and auditory signals). In particular, the first hypothesis (**H1**) formulated in this study is: Haptic feedback is the main influence in both presence and task performance.

Very limited research has been conducted to evaluate auditory, visual and haptic sensory cues in the same testbed or experiment within a VE and moreover, attending to their influence in different human factors. Such an analysis would facilitate identifying the feedback modality with higher influence in presence and performance, and help to establish whether or not the inclusion of more than one modality would enhance them. A similar research approach about multimodality as the one proposed here can be found in ref. [14]. They have explored mental processing times during a 3D writing task under unimodal, bimodal and trimodal sensory conditions, providing auditory, visual and haptic stimulation. Faster processing times were related to a higher level of attention and, in turn, associated with a higher level of presence. Results showed that trimodal and bimodal conditions performed significantly better than conditions utilizing only one feedback modality. This is in contrast to results obtained during selection tasks in a 2D graphical user interface [16, 41], which highlights how selection tasks within a VE have different requirements [6].

Conditions of multimodality may lead to different effects than those expected for the addition of isolated stimuli influence, due to outcomes of multisensory integration. Cross-modal and intramodal integration has been widely evaluated within neurophysiology, and attending mainly to audiovisual integration in terms of basic stimuli such as flashes or tones (a detailed revision of studies addressing this topic can be found in ref. [40]). Research conducted to characterize sensory integration has reported processes of sensory dominances, adaptations to incoherencies and sensorial substitutions, such as the ventriloquist effect (in time and space domains), which can be useful to design interaction techniques within a VE; for instance, sensory mapping, sensory redundancy or improvement, illusions or substitutions and intersensorial predisposition and adaptation [3]. However, it is necessary to evaluate "how various factors combine to modulate multisensory integration under more realistic conditions using more ecologically-valid combinations of stimuli" (p. 68, [32]). To this end, instead of using isolated cues, the stimuli included within our study are associated with the context of a selection task.

Although haptic may be the most important source of feedback for a selection task, the visual awareness of the collision or the auditory cues provided is also important information in daily interaction. Indeed, some of the aforementioned studies of sensory stimulation have concluded on the importance of multimodality attending to different human factors. Thus, greater wealth of sensory feedback as provided within a VE is related to a more complete and coherent experience, which strengthen the sense of presence [51]. Regarding multimodality, a second hypothesis (**H2**) has been formulated in the study presented here: The combination of different sensory feedback modalities influences presence and task performance more positively than when they are provided individually.

The technique implemented to provide interaction within the VE or the devices used do not always allow spatial coincidence among stimuli provided. Indeed, it is quite common in desktop 3D applications a spatial misalignment between haptic and visual proprioceptive workspaces. However, the possible effects of this misalignment in human factors and in the sensory requirements have not been widely investigated within the field of VR and thus the main contributions can only be found within the area of psychophysiology. These studies have considered time and spatial incoherencies in isolated sensory cues [34] or between different modalities of feedback: auditory and visual [17], haptic and visual [9], haptic and auditory [23]. However, the assessment of human capabilities to tackle these mismatches and their influence on performance has to date mainly been evaluated attending to visual and auditory stimuli. Attending to these sensory cues, some researchers have emphasized the importance of spatial and temporal intersensory pairing [2, 45], while others have found evidence about the existence of brain mechanisms that maintain intersensory coherence [17, 35]. These studies have concluded that our perceptual system is able to accommodate a certain degree of discrepancy in the information received from different sensory modalities. Regardless these documented recalibration processes, it is also necessary to analyse whether or not the sensory needs may be affected by typical isometric transformations between visual and proprioceptive workspaces in applications based on a VE.

To summarize, the three main issues of this study are: to identify which sensory feedback affects more positively presence and task performance; to analyse whether the inclusion of two or even three feedback modalities together may enhance the results already obtained using only one of the modalities; and to evaluate what is the role of spatial alignment between visual and proprioceptive workspaces. Finally, the present work addresses these questions throughout an experiment performed within a platform based on the Simon game. In a first attempt, this testbed allows evaluating conditions of a more complex environment, controlling possible side effects thanks to its simplicity.

2 The testbed system

As can be seen in Fig. 1, the Simon device used as a testbed consists of four differently coloured buttons that show a random sequence through their lighting and with a different sound for each button. The game player must reproduce the sequence correctly by pushing the respective buttons with a stylus in the correct order.

Participants interacted with the system selecting buttons with the stylus of the Desktop PHANToM (from Sensable technologies) haptic device. Multimodal interaction was provided in the system; participants could touch the device, see the entire environment along with the visual cues associated with a sequence emission, and hear the sounds of the game. The system implemented three kinds of feedback: visual, showing when a button has been selected by illuminating it; auditory, emitting a typical beep of 300 ms; and haptic, applying

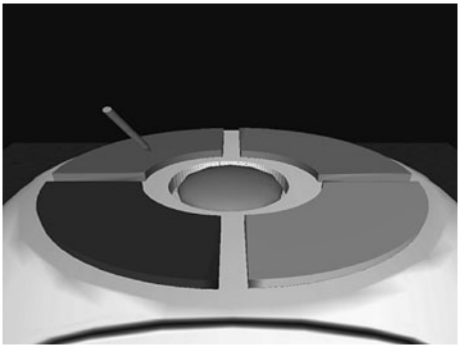

Fig. 1 Testbed: Simon device as used by the participants

forces as a programmable function of participants' hand position during button selection. These feedback modalities were provided as a collision indicator associated to buttons selections, although visual and auditory cues were also provided to emit the sequence that participants had to reproduce. Thus, once a button was selected, depending on the experimental condition, the feedback could be unimodal, providing only one of these three sensory cues (Audio: A, Visual: V, Haptic: H); bimodal with two of them present (AV, HV, AH); and trimodal (AHV), with all three kinds of feedback.

Participants played the Simon game within the platform in one of two possible configurations, attending to the spatial alignment between visual and proprioceptive workspaces. In one configuration, referred to as co-located (see Fig. 2a), participants interacted using the Reachin workstation with visual and proprioceptive workspaces aligned (using its mirror). Thus, participants could see the Simon device in the same place where they were interacting with it. In the other configuration, referred to as non co-located (see Fig. 2b), only the PHANToM device was used. In this condition, the Simon was shown on a vertical display while participants moved their hand within the PHANToM workspace. Stereoscopic vision in a backward condition (inside the screen) was provided in both setups.

3 Method

3.1 Participants

Thirty-two participants (twenty-three men and nine women) were recruited from the Telecommunications Engineering School at the University of Málaga. They volunteered to participate in experimental sessions. Participants were aged from 21 to 30 (μ=23.1; σ= 2.5). All the participants reported no previous experience with VR applications and force feedback devices. As the possible memory span, due to the different memory skills of participants, is controlled via the experiment design, no further analysis has been made about the features regarding other demographics aspects, such as gender or age.

3.2 Experimental design

The sequences generated on the Simon platform were configured with a fixed length of five steps and randomised. Results of a pilot study (in co-located and trimodal condition) indicated that five was the sequence length on average that was relatively easy to remember.

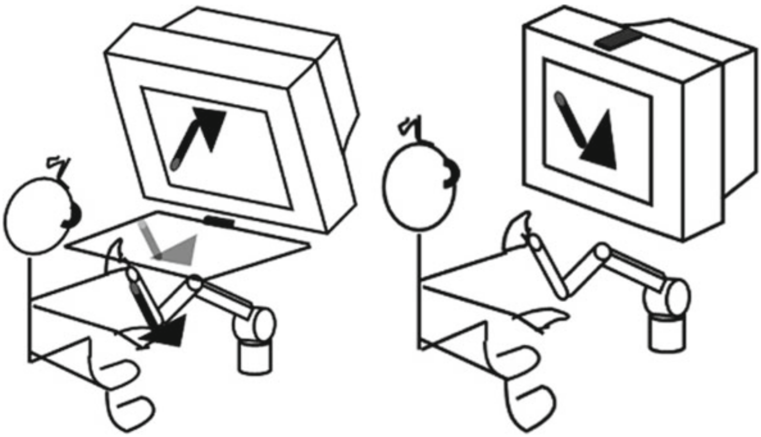

Fig. 2 Experiment configurations attending to the degree of coincidence between visual and proprioceptive workspaces

A previous study (described in ref [37]) with different interaction conditions reported that participants were able to reproduce on average an incremental sequence length of 11. Therefore, a value of five was chosen to extract the possible dependence of memorization capacity from performance measurements. Furthermore, to control the memorization span, the sequence length was not increased as it is in the Simon game. The sequence emission consisted of playing the sounds and illuminating the colours of the five buttons that make up the sequence. The interval between the sequence steps was 500 ms. The button lightning lasted 300 ms and the sound had a length of around 300 ms. The interval between sequences was 2 s.

The independent variables were the presence or absence of the three different sources of sensory feedback generated to indicate selections and the co-location condition. A 2×2×2×2 mixed between-within-subjects experiment design was employed. The between factor was the co-location variable (two levels: group co-located (C) and group non co-located (NC)) and the within factors were the three types of sensory feedback: visual (two levels: present or absent), auditory (two levels: present or absent) and force feedback (two levels: present or absent). Note that visual information about the Simon device was always present.

Participants were randomly divided into two groups of 16, group C and group NC, as shown in Fig. 2. Each group interacted with the system in eight blocks, differentiated by the feedback condition: block NFB (without any feedback, just the visual awareness of the collision between the wooden pointer and the button), three blocks with unimodal feedback (A, V and H), three blocks with bimodal feedback (AV, AH and HV) and the block AHV with the three kinds of feedback. Participants reproduced five sequences in each block and the block order was randomized.

3.3 Procedure

On arrival to the laboratory, participants completed consent forms and certain personal questions (e.g. age, computer and games experience, etc.). Participants also received all the task instructions and read the questions administered after every block. To clarify the game mechanism, they were instructed about the interaction process and the answer procedure during a training phase where they were able to reproduce one sequence under each feedback condition. They were also made aware of the fact that both their rapidity (time between buttons pressings) and accuracy (number of correct sequences reproduced) were measured, and they were told that their main goal was accuracy.

3.4 Measurement mechanisms

The sense of presence was measured using a free-form questionnaire of three items based on the Slater-Usoh-Steed questionnaire [30]. Each item, listed in Table 1, was rated on a Likert scale of 1 to 7, where 7 meant very much, and presence was operationalised as the number of items rated over 5 (SUS factor ranged from 0 to 3). Instead of a validated presence measure, such as PQ [51], this questionnaire was used for two reasons. First, the experiment duration did not allow using a questionnaire of a high number of questions. Second, the VE used was reduced to a 3D device, and it was necessary to ask for questions more closely related with the experience in this controlled environment, than for general aspects as those of the PQ.

Task performance was operationalised via two measurements: one concerning accuracy, computed as the number of correct sequences reproduced (referred to from now on as Score). The Score was always ranged from 0 to 5 because the number of trials in every block was five. The other measure, the time elapsed between buttons pressings (referred to from now on as Time) concerns rapidity. This measure allows identifying the feedback modality processed faster, because the motion action was always the same among conditions.

4 Results

For each of the dependent variables (Presence, Time and Score), a four-factor repeated measures ANOVA with co-location as a between-subjects factor was performed. Average results obtained in the eight blocks of trials were also computed to analyse the best interaction condition. An initial analysis of presence results can be also found in ref. [38].

4.1 Influence of feedback modalities

As shown in Table 2, the ANOVA made for task performance reported main effects of the three modalities of feedback in the Score (H: $p=.009$; A: $p=.01$, V: $p=.007$), while only auditory feedback ($p=.002$) led to a significant reduction of selection times.

Table 1 Items used to measure presence based on those proposed in SUS questionnaire [21]

Label	Item	Answers
Touch	I had the sensation of touching the Simon device which appears in the virtual environment.	1 2 3 4 5 6 7 (Not at all) (Very much)
Reality	There were times during the experience when the virtual environment was a reality for me.	1 2 3 4 5 6 7 (At no time) (All the time)
Device	The virtual environment seems to me more like.	1 2 3 4 5 6 7 (Images) (A Device)

Table 2 Task performance results for group C (spatial coincidence between visual and propioceptive workpaces)*,**

Measures		Haptic		Auditory		Visual	
		H	NH	A	NA	V	NV
Score	M	3.51	3.10	3.51	3.10	3.46	3.14
	F(1,30)/p	7.7/***.009***		7.3/***.01***		8.2/***.007***	
	η^2	.20		.19		.21	
Time (ms)	M	1,036	1,111	1,016	1,130	1,061	1,085
	F(1,30)/p	*2.9/.09*		12.1/***.002***		0.5/*.48*	
	η^2	.08		.28		.01	
Presence	M	1.39	0.10	0.73	0.76	*0.75*	*0.75*
	F(1,30)/p	69.3/***.0001***		0.11/*.73*		0.0/*1.0*	
	η^2	.69		.004		.0	

* Influence of sensory feedback in task performance and presence in conditions with: haptic feedback present (H) or absent (NH); auditory feedback present (A) or absent (NA); visual feedback present (V) or absent (NV). ** Rows show average values for the different conditions and F, p and η^2 values taken from an ANOVA analysis with $n=32$

Figures 3 and 4 show average results and error bars (95 % Confidence Intervals - CI) obtained in all the blocks (See only global results in left panel). As they are paired data, no conclusions could be raised from confident intervals [10], and t-tests were made to analyse differences between unimodal blocks (A, V and H) and block NFB. Significant differences were found in block A (A-NFB=0.87, $t_{31}=3.05$, $p=.005$) for Score and in blocks A and H for Time (A-NFB= 216 ms, $t_{31}=2.93$, $p=.006$; H-NFB=192 ms, $t_{31}=2.16$, $p=.039$). Thus, task performance results did not clearly confirm H1, indeed auditory feedback had a more relevant effect than haptic feedback. This positive influence of auditory cues in selection times, a measurement more closely related to perceptual processing, was already reported by Hecht and Reiner [14]. With the aim of determining which feedback modality was processed more quickly, they evaluated the time in which the participants recognised feedback whilst performing a writing task within a VE. They concluded that auditory and haptic cues were processed and detected at almost the same time. However, the study presented here has demonstrated that auditory cues played an important role not only in selection times but also in the score, a measurement more related to a cognitive processing. The highest influence of haptic stimulation in performance was formulated based on the resource theory, because this information was not expected to overload a task more related to visual and/or auditory cues. Furthermore, attending to motor skills, the awareness of selection through the contact detection provided by haptic feedback was expected to have a stronger impact in selection times. However, as we describe in the last subsection, a significant interaction between haptic feedback and co-location factors may have also affected these results.

Results of presence (SUS factor) showed that only haptic feedback ($p<.001$) had a significant influence. Indeed, as can be seen in Fig. 5 and paired t-tests indicated, only presence elicited in block H was significantly higher than presence in block NFB. This result confirms that H1 was clearly supported by presence results and that haptic feedback was the modality that has yielded the most evident influence in presence. A similar finding was also reported in the aforementioned studies for selection [14, 16, 41], but as noted, they did not measure presence directly. Jacko and Vitense [16, 41] evaluated interaction in 2D applications and Hetch and Reiner measured this influence through measurements of mental workload or attention, which were further related to presence. As pointed out by Hecht and Reiner [14], this association was made because the link

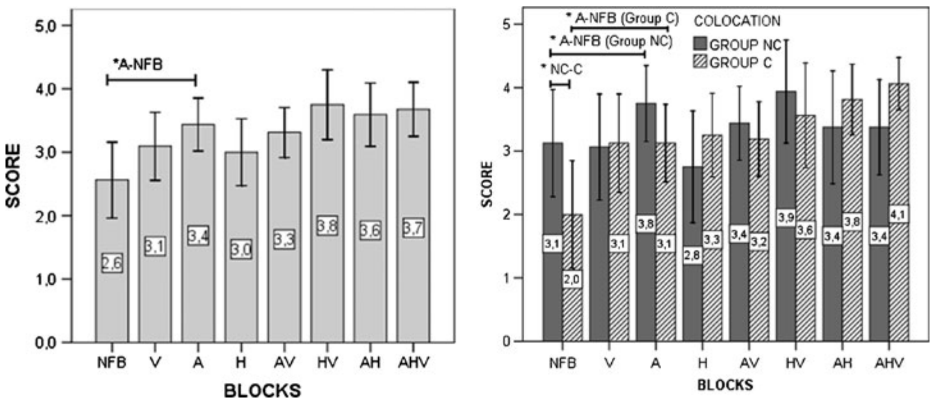

Fig. 3 Average score (error with 95 % CI) and significant differences (* $p<.01$) between blocks used to analyse hypotheses. Global score (*left panel*) and separate results for groups C and NC, (*right panel*) in each feedback condition: NFB (without), V (visual), A (auditory), H (haptic), AV (auditory-visual), HV (haptic-visual), AH (auditory-haptic), AHV (auditory-haptic-visual)

between mental workload and presence was already documented within literature. Nevertheless, Nunez [24] has clarified this relationship, establishing that in order to relate attention to presence, the cognitive processing involved in processing stimuli of the VE should be separated from the cognitive processing needed to draw inferences and make decisions, processes in which presence is more likely to be produced. For this reason, a presence measurement based on questionnaires should be more suitable for establishing the influence of certain stimuli on presence within a study where the sensory stimuli is controlled by variables that change among experimental conditions.

4.2 Multimodality

The ANOVA performed for the score also reported a significant interaction between auditory and visual modalities of feedback ($F_{1,30}$=4.2; $p=.04$, η^2=.13). This interaction indicated that auditory

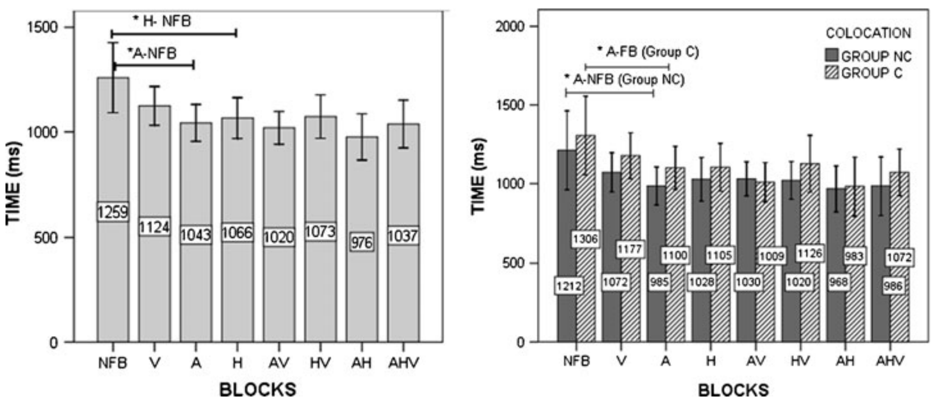

Fig. 4 Average selection times (error with 95 % CI) and significant differences (* $p<.01$) between blocks used to analyse hypotheses Global times results (*left panel*) and separate results for groups C and NC (*right panel*), in each feedback condition: NFB (without), V (visual), A (auditory), H (haptic), AV (auditory-visual), HV (haptic-visual), AH (auditory-haptic), AHV (auditory-haptic-visual)

cues captured the effect of visual cues, thus the buttons lightning meant an improvement for the score only in conditions without auditory feedback. Thus, in contrast with the slight improvement of blocks HV and AH (See Fig. 3, left panel), the score achieved in block AV was lower than in block A (unimodal trial with the highest score) and the score achieved in block AHV did not improve results obtained in bimodal blocks. The capturing effect of auditory cues over visual ones has already been reported in studies of intersensory recalibration attending to the simultaneity perception of visual and auditory stimuli with certain time asynchrony [17].

As can be seen in Fig. 4 (left panel), results obtained in bimodal blocks did not show either a significant reduction of times achieved only with auditory feedback. Indeed, a significant interaction was found between haptic and visual cues ($F_{1,30}$=4.2, p=.04, η^2=.12), indicating a negative effect in time of illuminating the buttons when haptic feedback was provided. Thus, performance results did not confirm H2 for all the sensory combinations. This outcome indicated that within a VE the combination of certain stimuli may overload perception processes acting negatively for tasks such the one presented here in which cognitive processes are also involved, which gives further insights in the role of haptic in multiple resources theory [49].

Considering presence results displayed in Fig. 5, once haptic feedback was provided the addition of visual or auditory cues had a positive influence on the sense of presence (without significant difference). In contrast, the reduction found in the trimodal modality was explained by a significant interaction between visual and auditory modalities of feedback ($F_{1,30}$=4.6, p=.04, η^2=.13). As in the score results, the simultaneous illumination of the button and the sound emission did not have a positive effect in presence.

Typically, the inputs from different modalities provide redundant and supportive information, allowing the perceiver to form a mental model of the physical world [11]. Therefore, presence and performance while selecting objects should improve with multimodality. Accordingly, in ref. [14], presence results were better in trimodal and bimodal modalities. On the other

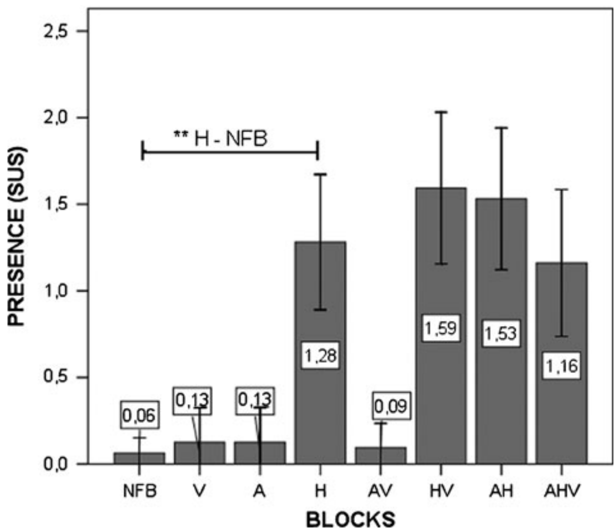

Fig. 5 Average presence (SUS: number of items rated above 5; error with 95 % CI) in each block (feedback condition): NFB (without), V (visual), A (auditory), H (haptic), AV (auditory-visual), HV (haptic-visual), AH (auditory-haptic), AHV (auditory-haptic-visual). Significant differences (**p<.001) between blocks used to analyse hypotheses

hand, when different modalities do not convey the quality of information encountered during normal interaction, these modalities do not necessarily carry equal weight in influencing the model, because perceptual processing of this information may become overloaded. This study has shown that the integration of the three modalities of feedback considered (visual, auditory and haptic) did not influence presence positively. This is not in accordance with Hetcht's research. Similar findings, concerning the trimodal condition not being the best, can also be found in ref. [16] and [41] for a 2D graphical interface attending to mental workload, which agree with results obtained in this study for task performance and presence.

4.3 Influence of co-location

In the ANOVA performed, co-location factor did not show a significant effect for any of the three human factors considered. However, a significant interaction was found in the score between co-location and haptic feedback ($F_{1,30}=7.3$, $p=.01$, $\eta^2=.19$). As can be seen in Fig. 6, the score achieved was affected by haptic feedback only in group C. This interaction indicated that the positive influence in the score of haptic feedback was only evident when there was spatial alignment (group C), and that in this condition sensory needs were higher (lower score without feedback). Furthermore, despite no significant difference among conditions in group NC (Fig. 3, right panel), the score reduction found in block H in relation to rates achieved in block NFB indicated that the inclusion of this feedback made incoherence higher, reducing participants' capacity to correctly reproduce sequences. In contrast, for group C, the three kinds of feedback led to a significant improvement in the score (H-NFB=1.25, $p=.03$; A-NFB=1.12, $p=.03$; V-NFB=1.12, $p=.01$).

Thus, score results of group C confirmed H1 and H2, because haptic feedback had the most positive influence and the addition of more than one modality of feedback led to an incremental

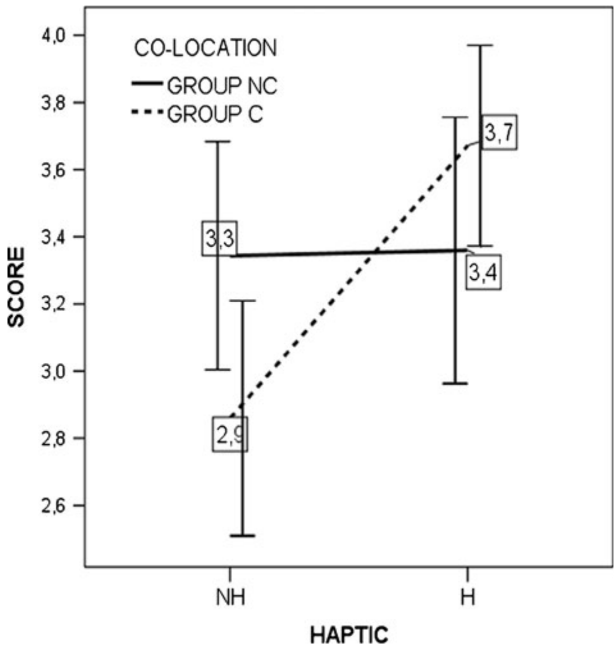

Fig. 6 Interaction between haptic and co-location factors in score results

improvement. However, for group NC, the score achieved without feedback was only improved significantly in blocks A and HV. One potential explanation of these results (although ad-hoc and preliminary) is that in a set-up without correspondence between visual and proprioceptive cues, auditory feedback had a higher influence in cognitive tasks and that haptic feedback required additional visual information (button lightning) to overcome the lack of spatial alignment. Furthermore, the significant difference found in the score achieved in block NFB between groups (C-NC=1.25, p=.05) and average results in the different blocks for each group (See Fig. 3, right panel) indicated that co-location benefits more from multimodal feedback than non co-location. These differences in sensory needs may be due to the previous experience of participants in interacting with a PC using a mouse. Participants are used to interact in non co-located conditions when they work with computers and the only feedback perceived for icon selections is visual and/or auditory. It seems that to reach the best score results, it is necessary to provide more sensory feedback in a coherent set-up, because interaction in real life relies on more complete sensory information.

Previous conclusion was also corroborated by selection times. A paired t-test performed to analyse differences between blocks (See Fig. 4, right panel) indicated also that the positive influence of auditory feedback was mainly due to results of group C. In this group, the inclusion of auditory cues led to a significant improvement of selection times in blocks AV and A compared to the condition without any feedback.

Our findings might be explained by extrapolating the Masahiro Mori theory, 'The Uncanny Valley' [22], based on human interaction with robots or virtual avatars, to the interaction within a VE. According to this theory, as the environments get closer to 'real', participants begin to relate to the VE in a natural fashion. Thus, deviations from natural become increasingly objectionable. For instance, when participants interacted with a VE in the same way that they normally do with a computer, under a non co-located condition, the expectations were lower than under a co-located condition.

4.4 Correlation analysis

A Pearson's correlation analysis was conducted in order to identify whether or not there is any significant relation among presence and the two performance measurements, Time and Score. A global correlation analysis was carried out considering together results obtained in all the feedback conditions, but for group C and NC separately. A more detailed analysis was also carried out with results of each feedback condition, with the goal of analysing the possible effect of the feedback modalities in the relation among dependent factors.

In global terms, correlation between score and time measurements was not significant (Group C: R=−.09, $p=.31$; Group NC: R=−.12, $p=.16$), indicating that participants' performance remembering sequences was not significantly related to their selection speed. The detailed analysis reported a significant or nearly significant relation between these measurements only in group NC and for blocks: NR (R=.54, $p=.02$), A (R=-.40, $p=.06$), AV (R=−.64, $p=.007$) and AHV (R=−.50, $p=.04$). No relation was found in the other feedback conditions. The significant relations indicated that in block NR, without any selection feedback, higher values of score were related to a slower selection (higher selection time). However, when auditory feedback was provided (blocks A, AV and AHV), a faster interaction was related to higher scores. These results lead to conclude that in an interaction condition without spatial alignment, auditory cues act as a link between cognitive and motor skills associated with targets selection. However, correlation results of group C indicated that the memorization capacity needed to reproduce these short sequences did not depend on the selection speed. Thus, it seems that the existing spatial misalignment that participants of group

NC should tackle overloaded the mental processing needed for the Simon task, by making the score depends on the selection speed.

As for the sense of presence, a significant moderate relation was reported between Score and SUS factor (R=.38, $p<.001$) in group C. Thus, in this group higher levels of presence were associated to a higher score, which is the measurement that is more related to cognitive skills, whilst no relation was found with Time measurement. A more detailed analysis indicated that there were only evident and significant or nearly significant relations in blocks with haptic feedback (H: R=.65, $p=.006$; HV: R=.48, $p=.05$; AH: R=.45, $p=.08$; AHV: R=.47; $p=.06$). However, for group NC, presence was slightly related to performance measurements (Time: R=−.19, $p=.03$; Score: R=.14; $p=.10$). Furthermore, a more detailed analysis indicated that this relation was only due to results obtained in block AV. Presence results obtained in this block were significantly related to both measurements, Score (R=.59, $p=.01$) and Time (R=−.62, $p=.01$).

The relation between presence and performance has been widely investigated in order to assess the extent to which factors that enhance one of them have also a positive influence on the other factor, and it is a topic considered in the design of VR applications for training and learning. Many studies [1, 33, 50] have suggested that although it is not clear that presence elicited in a VE improves task performance, some empirical evidence show the existence of a relation; whilst others did not find solid evidence of it [4, 44]. This relation has been evaluated considering different tasks. Thus, it has been confirmed in specific tasks related to: memorizing and fact recognition speed [18], spatial knowledge [29], position control or tracking [12], searching [25], sensory-motor skills [21, 50], but it has not been found in psychomotor tasks [1, 28]. Results of the study presented here have indicated that this relation may also depend on the sensory needs covered during the interaction with a VE. Thus, for selection tasks made on a co-located setup, there is a relation between presence and performance when haptic feedback is provided, whilst for a non co-located setup this relation was only evident when button selections were indicated by auditory and visual cues, which are indeed the cues usually provided for 2D interaction in a non co-located setup.

5 Conclusions

One of the questions that motivated this research was whether or not we can prove that the spatial alignment between proprioceptive and visual workspaces could cause participants to feel a different reaction to any deviations in a VE from a natural one. The findings above substantiate this claim and the main design implication is that if the quality of the sensory outputs cannot be accurately controlled, great efforts should not be taken in making coincident visual and proprioceptive workspaces.

Through the experiment performed in this study, the resulting data clearly highlights the main effect that different sensory modalities of feedback have on presence and task performance. Thus, results obtained indicate that in applications where the main goal is to achieve a high level of presence, the selection technique included should provide haptic feedback. In contrast, auditory feedback appears as the most relevant information to increase participants' speed interaction. Therefore, auditory feedback should be provided in task-oriented applications where the main goal is to achieve high performance rates, in targeting selection tasks within VE.

Finally, through analysing different configurations of feedback, we have also been able to evaluate the effect of multimodality. Contrary to our initial hypothesis about the benefits of providing more than one feedback modality simultaneously, this experiment has also proven the complexity beneath the possible integration of modalities and how multimodality may influence different factors, such as presence and performance. Thus, different optimal configurations were encountered depending on the factor measured and the co-location condition.

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