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On the importance of reliable real-time sensorimotor dependencies for establishing telepresence

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Abstract

In the current paper we review the concept of (tele)presence as it relates to the active exploration of the virtual, remote, or real environments. The same sensory and brain systems responsible for a flexible mapping of our position within a spatial layout are also remarkably adaptable to include non-biological elements in the perceptual-motor loop, provided reliable, real-time sensorimotor correlations can be established. Telepresence technologies, especially those used in fluent teleoperation, essentially enable the remapping of far space to near space. The importance of actively exploring the environment through tele-bodily actions will be discussed, in particular as they relate to appropriate haptic feedback patterns for telepresence.

Keywords--- **telepresence, sensorimotor dependencies, perceptual-motor loop, near space, far space, haptics, teleoperation**

1. Introduction

Interactive systems that allow users to control and manipulate real-world objects within a remote real environment are known as teleoperator systems. Remote-controlled manipulators (e.g. robot arms) and vehicles are being employed to enable human work in hazardous or challenging environments such as space exploration, undersea operations, or hazardous waste clean-up. They also allow for transforming the temporal and spatial scale of operation, as is the case with for instance minimally invasive surgery. In teleoperation, the human operator directly and continuously guides and causes each change in the remote manipulator. Sensors at the remote site (e.g. a stereoscopic camera, force sensors) provide continuous feedback about the slave's position in relation to the remote object, thereby closing the continuous perception-action loop that involves the operator, the master system with which she interacts locally, and the remote slave system. In the context of telerobotics, telepresence is closely associated to the sense of *distal attribution*, the externalisation of the self to include remote tools that phenomenologically become extensions of one's own body, even if they are not physically part of it [1].

Whereas teleoperation systems enable the manipulation of remote real-world environments and objects within it, virtual environments (VEs) allow users to interact with synthetic or computer-generated environments. In its most well-known incarnation, VEs are presented to the user via a head-mounted display (HMD) where visual information is presented to the eyes via small CRTs or LCDs, and auditory information can be presented using headphones. Importantly, the HMD is fitted with a position tracking device which provides the necessary information for the computer to calculate and render the appropriate visual and auditory perspective, congruent with the user's head and body movements. Haptic information, although not yet usually included in present-day VEs, can be added through the use of for instance an exoskeletal glove or arm, acting both as sensor and actuator.

Telepresence (in relation to teleoperation) and virtual presence (in relation to VEs) both address the psychological phenomenon of presence – the sense 'being there' in a mediated environment – essentially a displacement of the participant's perception of self-location or an "illusory shift in point of view" as Dennett [2] phrased it. Perceived transparency of the medium is crucial, i.e. a sense of direct perceptual stimulation and potential for action, without an awareness of the remoteness in time or space of the simulated or reproduced realities.

Systematic research into the causes and effects of presence has started since the early 1990s, and is currently picking up speed. Although the terminology used tends to vary across authors, there appears to be a broad agreement on the major concepts. Fundamental understanding of presence is still quite rudimentary however, leading Alan Newell to comment that "researchers are working with only a seat-of-the-pants notion of the underlying concepts" and there is "an immense need for a theory and a plausible model of telepresence" (cited in [3], p.365). A generally accepted theory of presence has yet to emerge, but various approaches and models have recently been formulated (e.g. [3], [4], [5], [6], [7], [8]). Although each approach has its own specific background, focus, and terminology, several approaches appear mutually consistent such that an integration or synthesis at a later stage is conceivable.

In the current paper, we will review the concept of (tele)presence as it relates to the active exploration of the virtual, remote, or real environments. We will argue that reliable, real-time sensorimotor correlations are of essential importance in establishing a sense of presence.

2. Determinants of telepresence

A large number of factors that may potentially influence the sense of presence have already been suggested in the literature [3], [9], [10], [11]. Two general categories of variables can determine a user's presence: (i) media characteristics, and (ii) user characteristics. Depending on the levels of appropriate, rich, and consistent sensory stimulation, varying levels of presence can be produced. It is interesting to note that both non-interactive, photorealistic displays (e.g. IMAX 3D), as well as interactive, non-realistic displays (VEs) are able to engender substantial levels of presence, although interactivity clearly appears to be the more important factor of the two [12], [13].

Sheridan [14] proposed three categories of determinants of presence:

1. The extent of sensory information presented to the participant, i.e. the amount of salient sensory information presented in a consistent manner to the appropriate senses of the user.
2. The level of control the participant has over the various sensor and interface mechanisms (tracked HMD, dataglove, etc.). This refers to the various sensorimotor contingencies, i.e. the mapping or correlation between the user's actions and the perceptible spatio-temporal effects of those actions.
3. The participant's ability to modify the environment, i.e. the ability to interact with the virtual or remote environment and to affect a change within that environment.

These three factors all refer mainly to the media *form*, that is, to the physical, objective properties of the media technology. Importantly, presence research is about relating those media form variables to the human response. The experience of presence is the psychological-neurological counterpart of immersive technology. It is of clear theoretical and practical value to establish what the optimal mix of cues might be for different application contexts, or, if the optimum is unattainable, which elements are most critical to the experience of presence.

The first and third of Sheridan’s determinants are a reflection of bodily presence in a physical environment. Indeed looking at presence in the most immersive environment known to us provides one possible framework of what is needed to experience presence. However, perception is not a process of simple template matching. It is more than mere ‘sensing’ of the environment through our various sense organs and subsequently comparing these sensations against passive representations of stored information. Rather, it is a highly activity-dependent and embodied process, integrating sensory data from multiple sensory modalities, which are continuously being transformed by ongoing actions (including head and eye movements), and shaped further by top-down cognitive and emotional processes. How is sensory information used to build affordances of action in a given environment [15]? It is probably rooted in evolutionary processes of adaptation to interact efficiently on the physical environment. Thus, usefulness of information becomes a central notion, relating to the extent that sensory patterns are perceived by the user, recognized as informative, and used in order to finely tune responsive acts, which in themselves, change the environment [16], [17], [18]. This is a cognitive process. Several questions are involved in identifying the components of the cognitive process intertwined with usefulness of sensory patterns: what is the threshold of sensory patterns; what are the possible arrays of multi-sensory patterns so that a useful mental response is triggered?

Importantly, the participant's ability to modify the environment, the third determinant that Sheridan suggests, is not an isolated component. Looking again at a fully immersive physical environment shows that sensory patterns perceived are also used for, and changed by, bodily response [16]. A surgeon for instance knows how much pressure to exert while inserting a trocar, by the feedback force that she feels. Perception and action are tightly coupled, continuously interlocked phenomena: perception guides our actions, and our actions are continuously affecting the percept of the environment.

The way the world responds to our actions can be conceived of as a set of *reality tests* [6]. If the world transforms in a way that is consistent with our representations of the invariants of the physical environment, we are more likely to accept the world at face value – and will feel present within it, even if this world is mediated by technology. Examples of such ‘reality tests’ include appropriate movement parallax[1] as we move our heads, or appropriate haptic feedback as we move our limbs and skin with respect to surfaces and objects. An interesting extension of remote bodily presence is reported by Armel and Ramachandran [19]. They found that subjects project their real-hand sensations on a remote rubber hand, as if sensations originate in the remote hand, if synchronized tapping or striking on both hands are felt and seen. The

[1] Parallax refers to the fact that when two objects are at different distances from a moving observer, their viewing angles shift at different rates. Movement parallax occurs when the motion is self-induced or active (e.g. head movements), whereas motion parallax refers to the case when motion is imposed, or passive (e.g. motion pictures).

illusion is diminished if the real hand is visible. Armel and Ramachandran suggest that the illusion and skin conductance response were due to perceptual assimilation of the remote rubber hand into one's body image. This further suggests an illusion of perceiving sensory input from remote objects, as if being part of the user's body.

Sheridan's second determinant is different from the first and third – in that it does not correspond to a factor of presence in the physical reality - humans do not control interfaces in order to manipulate the environment. Hence this second determinant, the control over the interface, may indicate the level of 'transparency' of the interface [20]. Framed differently however, any tool that humans employ to perceive or manipulate their environment (a pair of glasses, a blind man's cane, a pencil) can be regarded as a piece of telepresence technology, an extension of the human body that becomes seamlessly incorporated in the continuous sensorimotor loop. While the user's acts of controlling interfaces may become automatic with extended experience, complicated control of an interface acts as a negative determinant in presence.

Determinants of presence in the physical environment may provide one possible theoretical framework for understanding presence, but not the only one. A sense of presence may also be achieved in environments that have no real-world equivalent, and the rules of interaction do not necessarily follow the rules of interaction in physical presence. See for instance the fast learning in video games that require artificial manipulation of objects. Adaptation to new consistent sensory patterns and new rules of action may allow emergence of presence in imaginary worlds.

The secret in generating the sense of presence is not in devising the ultimate technology that will imitate sensory patterns from a physical reality, but rather the minimal combination of sensory cues that are sufficient to generate the sense of 'being and acting there'. As Heeter [21] noted, "the alchemy of presence in VR is in part a science of tradeoffs". It is not clear at present how much each feature or perceptual cue contributes to eliciting a sense of presence for the participant (i.e. the relative weighting), or how these cues interact with each other. This is one of the issues presence research is currently aiming to resolve.

3. Remapping space through telepresence technologies

In general, the space that surrounds an individual can be meaningfully segmented into a number of ranges, usually three or four, based on principles of human perception and action. Several models have been proposed (e.g. [22], [23]), all of which distinguish between a peripersonal space (the immediate behavioural space surrounding the person) and a far or extrapersonal space. Referring to haptic space, the peripersonal space corresponds to what Lederman, Klatzky, Collins & Wardell [24] refer to as the manipulatory space, i.e. within hand's reach, whereas the extrapersonal realm would be regarded as ambulatory space, requiring exploration by movements of the body. Animal and human brain studies have confirmed this distinction between peripersonal and extrapersonal space, showing that space is not homogeneously represented in the brain [25], [26].

Neuropsychological evidence supports the notion that coding of space as peripersonal and extrapersonal is not only determined by the hand-reaching distance, but it is also dependent on how the brain represents the extension of the body space through tool use (the 'distal attribution' mentioned earlier). Berti and Frassinetti [27] describe a clinical case, patient P.P. who, after a right hemisphere stroke, showed a dissociation between near and far spaces in the manifestation of neglect. Using a line bisection task, the neglect was apparent in near space, but not in far space when bisection in the far space was performed with a projection lightpen. However, neglect appeared when in the far space bisection was performed with a stick (used by the patient to reach the line) and it was as severe as neglect in the near space. Thus, this study provides evidence that an artificial extension of a person's body (the stick) causes a remapping of far space as near space – essentially telepresence.

Like the stick in the Berti and Frassinetti study, telepresence technologies may overcome the boundaries of spatial segmentation. Telepresence can thus be viewed as an attempt to extend the personal space beyond the boundaries of the physical two meters. The boundaries of our spatial reach are defined by the focus of action, and are determined by the parameters of the interface. Within a virtual world, where sensory patterns are artificially mediated, one may touch a virtual object. Similarly, in a teleoperation environments, the user is capable of manipulating an object located at any distance, hence the diameter of personal space is extended to a particular diameter that matches the remote arm, and action space is all the remote visible space. Practically, with telepresence, the personal space and action space can be of an indefinite diameter. Vista space can then be regarded as the space that is not included in action space – the visual and auditory background. This ambient extrapersonal space plays an important role in spatial orientation, postural control, and locomotion, and is of particular relevance to presence in relation to non-interactive immersive environments, where layout and motion stimulate the peripheral visual system, controlling our more visceral responding.

4. Sensorimotor dependencies and the active exploration of environments

Perception serves the individual's need to control relevant moment-to-moment behaviour or action within a changing environment. The development of visual perception of object shape and environmental layout is strongly dependent on consistent correlations between vision and input from other sensory systems (mainly touch and kinesthetics) through active exploratory behaviour of the environment, establishing a stable yet flexible multisensory representation of space.

At a brain level, modality-specific feature maps can project onto one another through re-entrant connections, which allows disjunctive feature characteristics (e.g. visual and haptic properties of a stimulus) to be connected in the responses of higher-order networks. Sensorimotor correlations will initially be driven by the temporally ongoing parallel signalling between primary cortical areas receiving the sense data associated with stimulus objects at a given time and place. Next, stable feature correlations establish reciprocal connections between previously disjunct feature maps, thus allowing for higher order perception and categorisation of objects and environments [28], [29].

In a classic study, Held [30] convincingly demonstrated the relation between locomotor experience and the understanding of spatial relations. In an experiment involving dark-reared kittens, the study showed that kittens that were allowed to actively control their perception of an environment during a 42 days training phase, responded appropriately to a visual cliff – a test that requires depth perception and the understanding of spatial layout. In contrast, kittens that were only allowed passive perception during training did not show the appropriate reflexes, thereby providing support for the view that the development of depth perception is action-dependent. Observations in humans have led to similar conclusions. For instance, Verkuyl (in [31], p. 14) indicated that so-called Softenon children, who do not possess upper extremities due to the use of a sleeping drug in the early stages of the mother's pregnancy, had severe problems in 3D-perception.

Similarly, telemanipulation experiments using the Delft Virtual Window System [32], [33] demonstrated a significant perceptual advantage of active observers, whose head movements controlled the movements of a remote camera (generating movement parallax), over passive observers, who received identical visual input (i.e. motion parallax), yet without the ability to actively change the viewpoint. This is in line with results found in relation to virtual environments, where Welch et al. [12] showed that participants who had active control over a simulated environment indicated higher levels of presence than participants who were passively exposed to the same environment.

Studies of adaptation to prismatic displacements provide further support for the importance of establishing reliable sensorimotor correlation maps through actively negotiating the physical environment. Held & Hein [34] studied prismatic displacements in humans under three conditions: active arm movement, passive arm movement, and no arm movement. In the active arm movement condition the subject swung her arm back and forth in the frontal plane, in the passive condition it was transported in the same manner by means of a moving cradle to which it was strapped. Results, as measured in terms of visual-motor negative aftereffects, showed that adaptation was only produced in the active movement condition and not in the passive or no-movement conditions. Another classic experiment on visual displacement [35] used lenses that turn the world upside-down. The study showed that full adaptation to this situation (i.e. seeing the world right side up again) occurred after a few days only when subjects were allowed to actively explore a complex world. When a subject was simply pushed around in a wheelchair, he did not show this perceptual adaptation to the lenses [35]. Active exploration not only influences the perception of spatial layout, but also facilitates subsequent recognition [36]. The neural basis of object and space perception provides further evidence that sensory and motor representations are closely tied together. Our peripersonal visual space appears to be represented to a large extent in terms of movement-based space, i.e. space in which objects are reachable or graspable (e.g. [25]).

5. Haptics and telepresence

Telepresence can be interpreted as the sense of 'being there', which often is mainly based on visual appearances. The view taken here is that telepresence applications largely require tele-bodily-actions, which need to be finely tuned in real time, to feedback from the environment. Hence presence includes here the capability to manipulate objects, at least as efficient as in the physical environment. What are the 'appropriate' haptic feedback patterns that lead to emergence of presence? Several factors have been suggested.

1. *Consistency of haptic patterns in time* - haptic patterns are consistent with haptic memories of past similar experience. Through manipulation of objects in the environment since first days of life, the user has developed a reservoir of image-schemata that relate patterns of distribution of forces on the hand to particular information/interpretation [15], [37]. If the patterns of force felt are not familiar, there is no information conveyed. New patterns may be learnt, given that the haptic feedback is consistent. Thus, this first factor refers to the cognitive-bodily capability to identify a pattern of force exerted on the hand as meaningful [17].

2. *Consistency across users* - requires that different users that experience a similar haptic pattern in a similar context, will extract a similar interpretation. This is especially crucial for haptic collaboration. For instance, two surgeons working remotedly through a tele-surgery system, and 'touch' a bone, will both interpret the haptic pattern as 'this is a bone' [38].

3. *Consistency across sensory modalities* - this requires that the information conveyed by haptic patterns is consistent with the information conveyed by other sensory modalities in a given context. This may be considered as coherency of the sensory array.

The first two conditions suggest a 'haptic language'-like reference system. By reference system we mean that a haptic pattern, a spatial field exerted and sensed by the body, is attributed a meaning. The cognitive-bodily system includes a loosely defined system of haptic patterns and associated meanings. Not only one individual uses haptic patterns to extract meanings - these meanings are shared by other users that share the same experience. Indeed a haptic language was identified in remote, fine manipulation in a telesurgery system [38], and more recently in mobile telecommucation using so-called 'squeezy' phones.

Haptic patterns are then used to construct interpretations about the environment. The user integrates the various interpretations into a hypothesis about presence in a particular world. This process is similar to using visual cues to construct a hypothesis about visual presence in a particular world [4], [39], [40], [41].

Fulfilment of the above three types of consistencies suggests that the feel of presence during action on the environment emerges out of resonance between haptic patterns experienced and past memories. Resonance is then, the level of mutual synergy between sensory patterns and purposeful acts of the hand on the environment. The 'hand' develops expectations as to the kinds of haptic sensations involved in a particular action. If the haptic feedback is different from the expected, and inconsistent, resonance will not occur. Resonance occurs when sensory memories are activated by sensory cues perceived from the environment, and simply describes whether one can rely on sensory input to support successful action [17].

Resonance can be described as a cycle of exploration of the environment. It includes: recognition of sensory patterns and their associated interpretations, motivations, intentions and goals that determine action that in turn lead to new sensory patterns, etc. [42]. To enable recognition, new haptic experience is interpreted in view of past memories of contexts and sensory-haptic experience [43]. If new sensory input follows selected cues of sensory memories, acts are finely tuned with sensory input, i.e. acts can be viewed as supported by the environment. This can be described as a closed cycle of interaction between an individual and the environment, tuned to explore the features of the environment, in order to formulate a hypothesis of presence. Figure 1 is a description of the exploration cycle from the point of view of the individual – the integration of cognitive and bodily acts to generate presence (for an extended description, please see [17]).

6. Conclusion

In line with the determinants of presence suggested by Sheridan [14], the perception of ourselves as part of a space not only depends on a passive perception of spatial layout but also on the ability to actively explore an environment, allowing the perceptual systems to construct a spatial map based on sensorimotor dependencies (see also: [44]). As mediated environments support real-time action at a distance or in virtual space, the participant is able to control certain aspects of the environment, and, as a consequence, his or her perception of the environment. By incorporating telepresence technology that supports our bodily perceptual and control movements as part of the ongoing perceptual-motor loop, the correlations between motor actions and multisensory inputs remain intact, thereby confirming one of our most important reality tests. This conception of presence places a clear emphasis on the possibilities of interaction in the peripersonal or manipulatory space, the space in which sensory and motor systems act in unison to grasp and manipulate objects, and less on the extrapersonal or ambulatory space, which seems to be particularly important for the presence-generating abilities of non-interactive media applications (e.g. widescreen cinema). *Being there* becomes the perceived ability to *do there*, as perception critically depends on successfully supported action - in line with the ecological aproach to perception [45], and its subsequent application to VEs [46], [47].

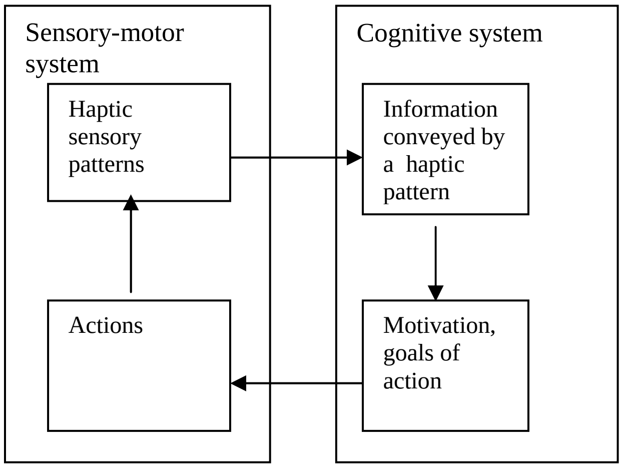

Figure 1. The integration of cognitive and bodily components in the exploration cycle of the environment

In order for sensorimotor correlations to be mapped by the brain, they need to be reliable, robust, and without significant delays. Haptic sensory patterns need to follow the constituents of a haptic reference system: the sensorimotor patterns need to be consistent in time, so that sensory-haptic memories are developed, consistent across human users, and consistent across sensory modalities [38]. It should be noted though that telepresence does not necessarily occur immediately as a consequence of a stable correlation between local actions of the operator affecting remote effectors, and remote sensors feeding information back in real-time to the senses of the operator. Because of the intermediate interfacing technology, considerable practice may be required before teleoperators can fully experience a sense of telepresence, indicating that the lawful relation by which efference governs afference needs to be modelled in the brain [1], [48]. Nevertheless, the same sensory and brain systems responsible for flexibly mapping spatial layout and our position in real world environments, are also remarkably adaptable to include non-biological elements in the perceptual-motor loop, be they a blind man's cane or an advanced teleoperator arm. When we interact with virtual or remote environments using intuitive interaction devices, isomorphic to our sensorimotor abilities, the real-time, reliable and persistent chain of user action and system feedback will effectively integrate the technology as a phenomenal extension of the self. This fluid integration of technology into the perceptual-motor loop eventually may blur the boundary between our 'unmediated' self and the 'mediating' technology [8].

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