Elements of the Dialogue between Virtual Reality and Neuroscience

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Abstract

In scientific history, researchers in the field of behavioral neuroscience have designed experimental devices aiming at controlling and manipulating both sensorial information and control systems, in order to study human behavior. The general goal is, by using controlled environments, to contribute to the understanding of sensorial, motor and cognitive determinants of the regulation of human sensori-motor control. From this point of view, virtual reality technology constitutes, for the neuroscientist, an evolution of already existing techniques. However, virtual reality represents also today the convergence and accelerating progress of numerous technical aspects of sensorial stimulation (3D and stereoscopic vision, spatial sound, ...), motion capture (mechanical, optical, electromagnetic, video graphic captors), and real-time interaction (due to the increasing computational power of microcomputers). Those characteristics are part of the basic definition of virtual reality, whose aim is to immerge the operator in a virtual world, in order to achieve optimal success of behaviors. From a neuroscientific point of view, however, those technological advances constitute an enlargement of the landscape of experimentally approachable questions, notably concerning the study of the "perception-action" functional coupling. In return, a neuroscientific approach might help define and refine the characteristics of an "optimally-designed" virtual reality system. Examples of this potentially rich dialogue between neuroscience and virtual reality will be given.

1. Introduction

Virtual Reality (VR) technology is basically defined as a computerized system, enabling one (or more) person(s) to visualize complex and/or massive data while interacting with the virtual environment they define.

Two major aspects of VR capture our attention. First, visualization is immersive, since the goal is to give the user the sensation that the environment and/or the objects that she/he is confronted with are really "there", that he/she is "inside" the virtual world. Secondly, the operator is able to interact in "real-time" with this environment.

These objectives are attained by using various interfaces that enable "real-time" updating of multi-modal sensorial information as a function of the actions and movements of the user in the virtual world. From our point of view, this emerging technology is rather susceptible to promote significant advances in the field of Behavioral Neuroscience, notably in the ecological approach to the "perception-cognition-action" coupling behavioral loop. It is in particular remarkable that VR systems enable researchers to generate controllable complex sensorial stimulation patterns, and to measure precise spatio-temporal aspects of human behavior in the presence of such stimulation. Manipulations of real-time interactions between the actor's behavior and the sensorial stimulation finally give the researcher the unique opportunity to "penetrate" the perception-action loop, in order to better understand the sensori-motor transformations and cognitive processing occurring in the central nervous system. In this sense VR techniques act as a "virtual electrode" (as a functional analogy to electrophysiology). Such parametric manipulations address classical problems, such as the nature of the sensorial information involved in a given task, or spatio-temporal aspects of motor coordination in skilled behaviors.

In return, Behavioral Neuroscience might contribute to bring new insight, hence favor technical advances, to "ill-posed" problems and "ill-defined" concepts, such as the role of immersion and of the sensation of presence in VR, or the behavioral meaning of "real-time" coupling in virtual world experiences. We suggest that the Virtual Reality will act as a theoretical landscape, in which Life Sciences and Technological/Computer Sciences will converge and reach a level of mutual enrichment.

2. Interactions between Virtual Reality and Neuroscience

2.1. Virtual Reality for Neuroscience

Looking back in scientific history, it is obvious that, due to the nature of the question itself, researchers in the fields of Psychology, Neuro-psychology and Behavioral Sciences have tried to manipulate both sensory information and action tools given to experimental subjects, in order to elucidate sensorial, motor and cognitive determinants of human behavior. In this framework, however, there are today significant (and accelerating) technical advances in the domains of sensorial stimulation interfaces (3D stereo vision, spatial sound, proprioception,…), motion capture (mechanical, video, electro-magnetic sensors) and "real-time" sensori-motor interactions (due notably to the never-ending increasing power of computers, notably in terms of massive data processing and rendering). All these technical advances provide the researcher with a new landscape of experimentally approachable questions, notably in the context of multi-modal sensorial fusion, temporal aspects of information processing and sensori-motor transformations, including the role of cognitive influences on "low-level" cortical activities. In this sense the quest for immersion in VR systems parallel the experimental approach of the neuroscientist, who tries to control at most the environment of a subject.

2.2. Neuroscience for Virtual Reality

The above-mentioned characteristics of VR devices are an integral part of the definition of Virtual Reality, in the exact meaning that the general goal is precisely to immerge the user in a virtual world, in order to optimize his/her interaction in this world. This is true whether the more precise goal is industrial (virtual prototyping) or medical (psycho-therapy), to cite a few applications of VR. In this general context, we propose that data issued from experimental studies might be decisive in the definition of the characteristics of an "efficient" VR system. It is however obvious that these characteristics will be dependant on the specific context in which the device is to be used.

In particular, it would be pointless to try to design a VR system capable of presenting "all in the information in the world" in "absolute real-time". First of all, this is nowadays technically impossible (due, in particular, to the limited capacities of computer systems in processing huge databases). More important is the fact that we do not know yet what "all" means (in terms of information processing and action control). This is precisely one of the tasks devoted to Behavioral Neuroscience: to understand what and how information is processed in the central nervous system, in spatio-temporal terms.

To give a more concrete example of this problem, let us focus for a while on visual information processing. It is there evident that our visual perception of the surrounding environment is dependant on pre-attentive, attentive and cognitive activity, which results in this important fact that we never perceive the whole of the potential information that is out there, and that we often do not perceive twice the same thing. For instance, the influence of past experience will render "instantaneous" the recognition of an ambiguous or hidden picture that was so difficult to detect the first time. We can also refer to numerous studies demonstrating the role of attention in visual perception and the plasticity of a priori biologically determined aspects of information processing in the central nervous system (CNS), such as the size of receptive fields in the primary cortical visual area.

Concerning the role of attention in perception, inspiring is the fact that a subject will not perceive otherwise salient aspects of a visual scene when his/her attention is "focused" on other aspects of the same scene [1]. There is also the phenomenon known as "change blindness" [2], which corresponds to the amazing experience that drastic changes in a visual scene remain undetected when they are accompanied by transient "disturbances", which can be external to the subject (e.g. flicker in the image) or related to the subject's behavior (e.g. an ocular saccade). From these examples, it appears that the internal representation of the external world is incomplete and modulated by attention, since important events occurring in the environment can be "neglected", as long as they do not constitute a "center of interest" for the subject and/or his/her ongoing activity.

The message I want to deliver here is that it might not only be impossible, but also useless, to try to restitute the totality of the sensorial information coming from the "real" environment in a VR system. It might be more "efficient" to understand what information is necessary for what application. "Classical" approaches (like ergonomics) starting with an "analysis of the task" are still useful there, notably in terms of pertinent information and interactions constraints in a given task. To come back to more "up-to-date" subjects in VR research, we will, in the following, concentrate on two major problems: the effects of temporal lags in VR system and the definition of the concept of immersion/presence. These two problems are typical of the necessary conversation between Neuroscience and Computer Science. In particular, they can beneficiate from available results from basic research, but they also point the projector onto unsolved theoretical questions. The reader will note that our objectives, in this paper, is more to suggest that "technical" problems encountered by VR developers point to fundamental questions than to give an extensive review of the question(s).

3. Elements for a dialogue

3.1. Temporal lags

The first problem we want to address is that of the temporal delays that necessarily exist between the physical measure of the subject's behavior and the updating of sensorial stimulation, delivered as a consequence of this activity (this problem being obviously related to that of "real-time" processing). By manipulating experimentally these delays and/or the various delays between different sensorial interface modalities (vision, sound, touch, …), researchers will try to improve functional models of sensori-motor coordination and derive recommendations for the specification of VR systems.

At the experimental level, the effects of temporal lags on human performance have been studied for a long time, in tasks such as the manual tracking of objects, using control systems coupled to the head or the hand. Driving simulation situations have also been extensively studied. It is there noteworthy that the "tolerable" lag (in terms of performance) is critically dependant on the task itself and on the action mode available. For example, So & Giffrin [3], in task where the subject had to reach a static target with a visible pointer coupled to the head movements, performance decreased significantly when the temporal delay was superior to 70 milliseconds. In condition where the hand was coupled to the control interface, delays were found to decrease performance for values over 100 milliseconds [4]. In driving simulators, Frank et al. [5] found that "tolerable" delays were up to 170 milliseconds. It is there clear that a fundamental and systematic approach to the "temporal lag" problem is required, in particular because the apparent fluctuant value of the maximum "tolerable" delay varies considerably from one task and one control system to the other. It is moreover clear that neuro-biological constraints have to come into play.

Beside that aspect, temporal lags have usually many sources. They can be due to the sampling frequency of a motion measurement system, to transmission delays between different systems or to the refresh rate of sensorial interfaces. Liu et al. [4] have studied the effect of a visual display refresh rate on visuo-manual tracking. Classically, a drop in tracking performance is observed for refresh rates inferior to 10 images per second. For low refresh rates, tracking behavior becomes saccadic, suggesting that subjects no longer execute a continuous tracking, based on motion signals, but rather shift to a succession of error reductions (based on position signals). Things become even more complex, if one considers that the effects of temporal lags are also related to the amplitude and velocity of the movements required by the task and also to the angular extent of the visual display. For instance, in the case where the head movements are coupled to the updating of the observer's point of view in a three-dimensional environment, temporal delays will introduce position errors (in 3D space) which are proportional to head velocity [6]. In this context, it seems that, for long delays, subjects may use adaptive strategies, such as reducing their "amount" of movements (which is not precisely the objective of an "efficient" virtual reality system).

Another important aspect of the same problem (which will lead us to the concept of immersion) is the angular extension of the stimulated visual field. Indeed, the size of the display (between a video terminal and a full-field panoramic visualization system) is suspected to affect the characteristics of movements executed by the user (notably eyes, head and whole-body movements). As a consequence, this will have an influence on the display position errors due to temporal lags. In particular, when comparing helmet-mounted displays, with display size inferior to 60 degrees, and panoramic displays, whose angular size reaches often 180 degrees (or more), Woodruff et al. [7] noticed that operators had fewer head movements to execute with "wide-angle" displays, which "naturally" reduced the negative effects of temporal lags.

3.2. Immersion/presence

A second example of the necessary dialogue between Virtual Reality and Behavioral Neuroscience is related to the concepts of immersion and presence (immersion being considered as an objective technology-related concept while presence would be rather reserved to the subjective sensation of being "there" [8]. There are, in this context, a number of enigmatic unsolved questions: In what sense and how does the sensation of the user of being inside a virtual world change basic characteristics of human information processing? In return, how do the spatio-temporal characteristics of the sensorial stimulation contribute to the sensation of presence? How do the characteristics of the user-VR system interaction contribute to the sensation of presence? Can we demonstrate that immersive interactive environments transform the frames of reference in which the sensori-motor transformations take place, transforming human performance as a consequence?

First of all, it is important to consider that the immersive aspect of a VR system is a major difference with other visualization systems, including interactive ones [9]. It seems that immersion has intuitively been considered as having, in general, a positive effect on performance, which is far from being proven in concrete cases. Obviously, terms such as "immersion" and "presence" require some work concerning their definition, since they appear to have both physical and psychological connotations. In first instance, one can accept the idea that immersion is obtained by substituting sensations originating from the virtual world to the "natural" sensations coming from the real world surrounding the subject. Immersion is by essence related to the multi-modal nature of the perceptual senses, and also to the interactive aspects of a VR experience. It has to be related to the temporal lag effects mentioned above. We will return to this point. Concerning the concept of presence, it is proposed as a quality of the sensation of being actually in a coherent world that a subject might experience when he/she is immersed in a VR system [8]. In this sense, it is clear that this "sensation" has both physical and psychological determinants. Here again, the supposed positive effects of the sensation of presence on human performance await indisputable arguments and data. This lack of demonstration might be related to the difficult task of measuring presence, which obviously relates to the fuzzy definition of the term itself. One can moreover argue that presence is not a goal in itself in all conditions. For instance, in situations of tele-intervention in hostile environments, it might be safe for the operator to keep its "distance" with the environment in which he/she has to carry out the mission. In this case, a sensation of presence might even have detrimental effects on performance. Here, the reader may not be convinced by such speculative arguments. However, will he/she agree with me that there is here a serious matter of debate, suggesting that it might be interesting to look for some sort of a trade-off between the sensation of presence ("being there" in the virtual world) and the "background" knowledge of the existence of a "real world"? Here again, an analysis of the activity (ergonomics) is required, assuming an "efficient" VR system can only be achieved by taking into account the nature of the task for which it is designed.

To give a more precise example, we can think of the extensive work carried out on the sensation of vection (the illusory sensation of self-motion through the environment). In situations where a subject is placed in a moving room, a strong sensation of self-motion and/or compensatory postural readjustments can be induced [10]. When we compare these effects with those obtained with frontal visual stimulation, even wide-field stimulation [11], it seems reasonable to accept the idea that stimulation of peripheral parts of the visual field plays a decisive role in vection, maybe by transforming spatial frames of reference [12]. In this context, it appears that immersion refers to physical aspects of the sensorial stimulation, being related to the stimulation of the whole visual field. In driving and flight simulators, researchers have reached empirically the same conclusion: it is accepted that the stimulation of the entire visual field is required to achieve optimal performance and a satisfying skill transfer from learning to real situations. Immersive systems such as the CAVE ® are an example of this type of configuration [13]. They differ strongly, in this respect, from helmet-mounted displays, which allow a narrower field of view. We suggest that immersive displays are "efficient" in situations where the subject has to move through the virtual environment. This might not be true in other tasks, such as the manipulation of objects in a static environment. Here again, it seems vain to search for an all-purpose VR system. Moreover, we will now turn to potential problems related to an immersive system.

3.3. Side effects of VR systems

In situations of Virtual Reality, immersion itself (linked as we saw before to the characteristics of the sensorial stimulation and to the human-system interaction design) can lead to undesired side effects, similar to what has been observed for long in driving or flight simulators using wide-angle projection systems [14]. Such "simulator sickness" [15] certainly shares common grounds with "motion sickness", whose origins remain, until today, a matter of investigation [16]. These unwanted effects seem to result, at least partly, from conflicts between different sensorial modalities. To summarize, simulator sickness refers to three major symptoms: visual fatigue, spatial disorientation and nausea [17].

In this context, the increasing power and complexity of VR systems (notably concerning multi-modal sensorial stimulation and interfaces) is rather susceptible to create potential problems and conflicts (due for instance to temporal incongruence between different sensorial inputs and feedbacks). It is thus suspected, if not assumed, that potentially sickness-inducing situations are those in which motion signals transmitted by the eyes, the vestibular and proprioceptive systems are conflicted and/or are not consistent (in the spatial as well as the temporal domains) with the subject's anticipation (as a function of his/her action in the environment). The above mentioned problems related to temporal lags are clearly involved here, since, for instance, delays between the subject's head movements and the consecutive transformations of the 3D visual scene are known to be involved in visuo-vestibular conflicts, resulting in motion sickness. Much experimental work is required here, in order to understand the temporal dynamics of visuo-vestibular interactions [18].

More generally, a rapid sketch of factors related to side effects of VR systems can be drawn. First, physical and psychological characteristics of subjects are implicated. For instance, young children are more susceptible to motion sickness than adults (which might be linked to developmental aspects of cortical maturation and sensori-motor coordination). There is also a gender effect (women are statistically more affected than men), however the determinants of this type of effect are obscure for now. The ethnic origin of populations, and the health status (sleep deprivation, drugs) are also a determining factor, as well as the perceptual style or the attention capacities of a subject [17].

It is also reported that, when facing simulator-induced sensori-motor conflicts, subjects develop adaptive strategies aiming at reducing the conflict [19], as already mentioned earlier. This phenomenon deserves particular attention from researchers, since a successful adaptation to a simulator distorted "reality" may result later in a lack of adaptation to the "natural" conditions experienced in the real world. Further, it can be suspected that such adaptation to "abnormal" interaction conditions might result in "abnormal" behaviors and perception. This poses a problem in all conditions in which a VR developer tries to achieve positive transfer between the VR experience and the real world (for instance in conditions of training or virtual prototyping).

Secondly, the technical and physical characteristics of the VR system itself obviously come into play. Here, much attention has been devoted to visual interfaces [20]. Among other factors, luminance, contrast and spatio-temporal resolution of visual displays are clear determinants of human performance in VR. For instance, flicker in the visual display is a limiting factor, with multiple correlates (refresh rate, angular size of the display, ..). Note also that refresh rate can induce reversals of perceived motion or a loss of the perceived continuity of motion. Such effects are typically termed temporal aliasing, and there are related to complex interactions between display physical characteristics and the peripheral and central cortical mechanisms of visual information processing. In this domain, it might be fruitful to search for a "satisfying" (in terms of human performance and perception) solution of compromise between temporal and spatial display resolutions, taking into account both the human information processing capacities and the "state-of-the-art" of graphical computer and projection systems. This comes back, again, to the imperious necessity of the collaboration between Brain and Computer Sciences. Concerning temporal lag effects, a recent research suggests that the sensation of presence is "lost" for delays superior to 300 milliseconds [21]. It seems that, for such long delays, subjects no longer perceive the logical interaction between their head movements and the transformations of the visual scene. A future line of research might investigate the relationships between temporal delays, the sensation of presence and "VR sickness", only partial and limited data being available at the moment.

Finally, and logically, the subject's task itself is involved in side effects of VR. Well known is the fact that, in a car, the driver is less prone to motion sickness than the passenger. However, the reasons for that are not clear, but seem to be related to sensori-motor anticipation [22], the driver being able to anticipate the sensorial consequences of his/her actions, while the passenger is in a passive state of perception of "unwanted" stimuli. Once it is said that interactivity is thus necessary in a virtual world, it remains to define the conditions of this interaction. For instance, it is now common to use head tracking as an updating interface. This type of coupling might however be inappropriate in conditions where the subjects are to move around in a large-scale virtual environment. Locomotion interfaces are becoming available, such as treadmills. However, we can suspect that this will pose new questions, related to the problems we just mentioned (temporal lags, immersion, side effects).

4. Perspectives

To sum up, it appears that the development of VR systems, while promoting new research in Behavioral Neuroscience, will logically depend on new data and models of sensori-motor coordination originating from this research. It is also clear that the definition of an "efficient" immersive and interactive VR system will result from a satisfying compromise between the subject's task, the neuro-psycho-physiological determinants of human behavior and the available technological solutions. We certainly did not provide definitive answers to all the questions mentioned here. We moreover presented a very partial view of a few problems. Our aim was nevertheless, to try to convince the reader, first of the necessity of a fundamental approach to these problems and secondly of the difficulty of the definition of a precise and unified methodology to solve these problems.

Our message is simple. There is a need for strong interactions between Brain and Computer sciences, and Virtual Reality might act as a catalysis system. This has to be a true collaboration. In particular, it would be misleading for neuroscientists to use VR developers as research assistants and for VR scientists to await "on-the-shelf" solutions from Behavioral and Brain sciences. We are in this sense clearly calling for propositions of collaboration. Our common project, here in Marseille (Université de la Méditerranée, Marey Federal Research Institute) is to build a Virtual Reality complex, whose definition should benefit from the start from such collaboration. We believe in particular that Behavioral Neuroscience can approach experimentally concepts such as that of "immersion", and help replace largely empirical today solutions for VR design by experimentally validated ones. We also think that, studying questions like the definition and the role of the "sensation of presence" will require also the participation of the Cognitive and Psychological Sciences .

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