The Phi Angle: A Theoretical Essay on Sense of Presence, Human Factors, and Performance in Virtual Reality

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Abstract

The question of the relationship between the sense of presence and performance in virtual reality is fundamental for anyone wishing to use the tool methodologically. Indeed, if the sense of presence can modify performance per se, then individual factors affecting the human–computer interaction might have repercussions on performance, despite being unrelated to it. After a discussion on the sense of presence and the particularities it provokes, this work studies the psychophysiology of virtual reality. This in virtuo experience is understood according to a constitutive and reciprocal relationship with the subject's cognitive profile, made up of all the human, contextual, and motivational factors impacting the processing of immersion. The role and importance of performance in virtual reality is described in this framework in such a way as to be studied methodologically. The presence–performance relationship is discussed based on previous works and analyzed in terms of attentional resources. Finally, the degree of ecological validity of the performance is described as the factor modulating the relationship between the sense of presence and performance (the Phi Angle). Limitations, applications, and test hypotheses of the model are presented. This work not only aims to help explain the conceptualization of virtual reality, but also to improve its methodological framework.

1 Introduction

Over the past few years, virtual reality (VR) has emerged as a valuable tool in a large number of fields. The adaption has been accelerated by advancements in computer graphics, high quality off-the-shelf VR instruments, and the integration of programming tools into mainstream graphics engines (Cipresso et al., 2016, 2018). Among other areas, the tool has been used in education (Chen, 2009; Christou, 2010; Kamińska et al., 2019; Leung et al., 2018; Pantelidis, 2009), health (Freeman et al., 2017; Gregg & Tarrier, 2007; Scozzari & Gamberini, 2011; Wallach et al., 2011), and research (Bohil et al., 2011; Canning et al., 2020; de la Rosa & Breidt, 2018; Pan & Hamilton, 2018; Parsons et al., 2017). VR has the advantages of allowing potentially richer and more intuitive interactions with the computer system through the use of spatial controllers. Further, it allows the researchers to fully immerse the user in a virtual environment of their choosing, enabling wide-ranging control and flexibility

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with regards to the experimental setup. Indeed, VR gives the opportunity to obtain "the best of two worlds" (Minderer et al., 2016), mixing experimental control and ecological validity (Coleman et al., 2019; Parsons, 2015), which seems particularly relevant in the developing framework of embodied cognition (Clark, 1998). This ecological dimension is made possible by an inherent property of the tool: a well-designed 3D virtual environment will provoke a sense of presence, that is, the feeling for the participant of being physically present in the world of the experiment (Heeter, 1992; Sheridan, 1992), and therefore of acting and feeling as such.

In this theoretical essay, we investigate the relationship between this experienced sense of presence and task performance in VR. This is a crucial question. Indeed, if the sense of presence has a significant impact on task performance, the measured performance might be biased when compared between users who experience an increased sense of presence, as compared to users who poorly adapt to the immersive environment. This could be of great importance, notably in order to propose a reliable and rigorous methodology when VR is used for behavioral research or diagnostic evaluations (Cogné et al., 2017; Coleman et al., 2019; Parsons, 2015). In addition, we investigate in this essay whether personal factors, such as sensitivity to cybersickness, previous video game experience, and sex and/or gender might have an effect on the sense of presence in VR, and how this could modulate the task performance. If this is the case, using VR in contexts evaluating performance without accounting for these factors could lead to erroneous assumptions regarding the origin of interindividual differences on these tasks. A virtual neuropsychological test could outline performance deficits not based on the alteration of neural/cognitive processes, but rather on a perceptual and cognitive style nonadapted to immersion.

Despite the importance of the relationship between performance and the sense of presence for reliable, unbiased experimental results, very few authors have studied the question in-depth and we currently have rather limited empirical data to consider and assess this fundamental relationship. This has not changed since the early stages of VR (Barfield et al., 1995; Barfield & Weghorst, 1993):

> *Not only is it necessary to develop a theory of presence for virtual environments, it is also necessary to develop a basic research program to investigate the relationship between presence and performance using virtual environments. […] we need to determine when, and under what conditions, presence can be a benefit or a detriment to performance. […] When simulation and virtual environments are employed, what is contributed by the sense of presence per se?*

After reviewing what has been previously discussed in the field, this theoretical essay will try to advance the discussion and propose insights in order to address this question, notably by proposing new phenomenological concepts along with a novative theoretical model called the Phi Angle. Due to the global development of VR, it is now crucial to measure and understand the relationship between the sense of presence, which is an inherent and indispensable property for the functioning of the tool, and the reason for which it is used in research and health, the measurement of *in virtuo* performance.

2 Plethora of Senses of Presence

The phenomenon of the sense of presence, because of its intrinsic subjective nature, is easy to experimentally grasp when exposed to VR, but much harder to rationally define and measure, which is a particularity shared with many qualias (Kanai & Tsuchiya, 2012; Slater, 2009). This has led authors of the field to propose several definitions and models of the sense of presence, notably in VR, in order to describe and model it in a Cartesian way. Definitions of the sense of presence can be divided into two broad categories emphasizing two main dimensions: the inner presence dimension and the media presence dimension. The latter includes a well-known definition of the "illusion of non-mediation," which would occur when "a person fails to perceive or acknowledge the existence of a medium" (Lombard & Ditton, 1997), and focuses on the technological filter more than on the subjective feeling. In these views, the less artificial mediation is perceived between the individual and the virtual environment, the more present this individual will feel. In this framework, just as human perception is mediated by the senses, VR adds another sensory filter which is the immersion, altering the perception (Loomis, 1992a; Sheridan, 1992, 1996, 1999). Inner presence, on the other hand, is considered as a "broad psychological phenomenon not necessarily linked to the experience of a medium" (Riva et al., 2015). This sense of presence goes much further on the phenomenological aspect; it is considered a deep psychological construct, resulting from evolutionary neurological cognitive processes in relation with the broad construct of consciousness (Coelho et al., 2009; Riva, 2006; Riva & Waterworth, 2003). Considering this, it is no surprise that these inner presence definitions generally encompass embodied cognition and enactivist views (Clark, 1998; Lobo et al., 2018). For example, Zahorik and Jenison (1998) state that "presence is tantamount to successfully supported action in the environment." Developing these ideas, Riva et al. (2015) consider the sense of presence as the "intuitive perception of successfully transforming intentions into action." The same authors (Riva et al., 2015) even make the sense of presence the link between volition and cognition. On the other hand, media presence definitions usually consider traditional cognitive representational views through the distal attribution of sensation to artificial stimuli (Loomis, 1992a). These external stimuli are internally integrated through perception into a cognitive representation of the (spatial) environment, building a sense of being there (Loomis, 1992a, 2016, 1992b; Sheridan, 1992, 1996, 1999; Wirth et al., 2007). Indeed, it has to be noted that some authors have outlined the spatial dimension of the sense of presence, referring to it as "spatial presence" (Bryson, 2013; Heeter, 1992; Wirth et al., 2007) or "place illusion" (Slater, 2009, 2018), notably in contrast to "social presence" or "copresence," the sense of being with another being (Heeter, 1992).

Beyond the theoretical (and sometimes ontological) discussions on the nature of the sense of presence, differences between these approaches are also found in the tools used to measure the phenomenon. Indeed, there is currently no unanimously recognized reliable measurement method of the sense of presence. The different tools suggested in the field are too numerous to cover exhaustively here; therefore, only the main ones will be mentioned and we will refer to Grassini and Laumann (2020) for a review. Based on Grassini and Laumann (2020), the most used tool in the literature is currently the Presence Questionnaire (Witmer et al., 2005; Witmer & Singer, 1998), which focuses on the immersion and interaction, while the other mainly used ones, the Slater-Usoh-Steed Questionnaire and the Igroup Presence Questionnaire, focus more on the psychological dimension (Schubert, 2003; Usoh et al., 2000). Illustrating the media presence views, Steuer (1992) has suggested a "Turing Test" (Turing, 1950/2009) of VR in order to measure the sense of presence. Steuer (1992) considers that the sense of presence could be evaluated as the degree to which the participant does not differentiate the virtual environment from the physical one. Other measurement tools, used by both the inner presence and media presence supporters are based on the association between behavioral situations and physiological measurements (heart rate, skin temperature, respiratory rate). The idea is that the more an individual adapts their behavior (e.g., sidewalk) and their physiology (e.g., increased heart rate) to a specific virtual situation (e.g., a precipice), the more they experience a strong sense of presence (Insko, 2003; Meehan, 2001; Peterson et al., 2018; Wiederhold et al., 2003). From a media presence viewpoint, this is interpreted as an individual's psychophysiological failure to perceive the virtual environment as mediated and thus reacting as if the virtual precipice were real. From an inner presence viewpoint, the association between physiological and behavioral reactions and sense of presence is interpreted as the emergence of an automatic evolutionary sensorimotor process intended to allow the subject to act (enact) on the environment. One could argue here that these two interpretations are not entirely exclusive. Other psychophysiological tools suggested for measurements are eye-tracking (Duchowski, 2007; Laarni et al., 2003), electro-encephalogram (Clemente et al., 2013; Kober et al., 2012), near infra-red spectroscopy (Carrieri et al., 2016; Seraglia et al., 2011), or other nonverbal behaviors analyzed via machine learning in order to dynamically assess the phenomenon (Ochs et al., 2018).

In this work, we believe that the reasoning and theoretical considerations we propose can be applied to the different definitions of the sense of presence. Beyond the different ontological conceptualizations of the representational/enactivist views (Coelho et al., 2009; Mantovani & Riva, 1999; Sheridan, 1999; Zahorik & Jenison, 1998), it is arguable that the two definitions of the sense of presence are not entirely exclusive of each other and that a common ground can be apprehended for this theoretical essay. Indeed, we consider that a global phenomenological apprehension can be elicited; we will simply consider the sense of presence in VR as a psychophysiological "sense of being there" (Heeter, 1992; Sheridan, 1992) phenomenon provoked by the interaction between bottom-up stimuli (the immersion, a computer-made sensory filter), and top-down processes (the perception, an organic-made sensory integration). Considering this, we have to agree that it can and does also occur outside of VR; in the nonvirtual world, the sense of presence also arises from the interaction between perception and a sensory filter, but the one in the nonvirtual world is constituted by the stimuli from the physical world. Because of its continuously occurring nature, we, as humans, are generally unaware of this sense of presence (or, more precisely we are continuously aware of it), making it invisible to consciousness, just as we are generally unaware that our reality is mediated by our senses (Loomis, 1992a, 2016). Just as we might be fully aware of nearsightedness only after we try out corrective glasses, VR, by creating a sense of "being there" that is not rooted in the physical world, makes the phenomenon salient. It is not surprising that the sense of presence has (re)gained interest in the scientific community since the advent of VR, as stated by Loomis (2016):

> *The amazement people feel when experiencing virtual reality has spawned a new branch of philosophical and scientific inquiry into what presence is, the factors that contribute to the degree of presence in virtual reality, and how the degree of presence affects the usefulness of virtual reality in research, training, treatment of phobias […].*

Within this framework, the study of the sense of presence has largely contributed to the development of empirical and theoretical phenomenological studies of perception (Loomis, 1993, 2016; Riva et al., 2015), as well as many ontological debates questioning the links between the sense of presence and consciousness (Mantovani & Riva, 1999; Riva et al., 2015; Sheridan, 1999; Zahorik & Jenison, 1998). On this matter, we also have to agree that the sense of presence is linked not only to consciousness, but also to action and attention and more globally to all the Cartesian psychophysiological concepts describing the phenomenological state of an individual (Coelho et al., 2009; Riva et al., 2015; Riva & Waterworth, 2003). The proximity between consciousness and the sense of presence is salient in the literature. For Sanchez-Vives and Slater (2005), presence is a "transportation of consciousness into an alternative virtual reality," and they advocate the use of the sense of presence in VR to study consciousness. In an inverted way, Loomis (1993) defends that "understanding synthetic experience must begin with the analysis of ordinary perceptual experience," emphasizing the phenomenological continuity between the sense of presence in the physical and the virtual worlds. This phenomenological continuity is rarely questioned, either by researchers adopting an approach of the "inner presence" or of the "media presence" (Loomis, 1992a, 1993, 2016, 1992b; Riva et al., 2015). Beyond the sensation of "return" experienced when leaving VR, phenomenological glimpses of the "sense of being there" in the physical world might appear when one awakes in an unfamiliar place and actively uses perception to rebuild a sense of presence, or with the use of mind-altering drugs or when confronted to psychiatric conditions (Barbosa et al., 2005). To go further in the sense of presence–consciousness relationship, neuro-imagery studies assessing the sense of presence in VR have outlined an association with activity in the insular cortex (Clemente et al., 2011, 2013, 2014), the brain area that also plays a key role in consciousness and awareness (Craig, 2009). It is also in the insula, and more particularly in the anterior insular cortex, that Seth et al. (2011) place the neurological substrate of their predictive coding model of conscious presence. While it is important to keep in mind the phenomenological nature of the sense of presence discussed by philosophers and psychologists and its relation with other fundamental concepts of epistemology (Coelho et al., 2009; Flach & Holden, 1998; Mantovani & Riva, 1999; Riva & Waterworth, 2003; Sheridan, 1999), the purpose of this essay is not to study

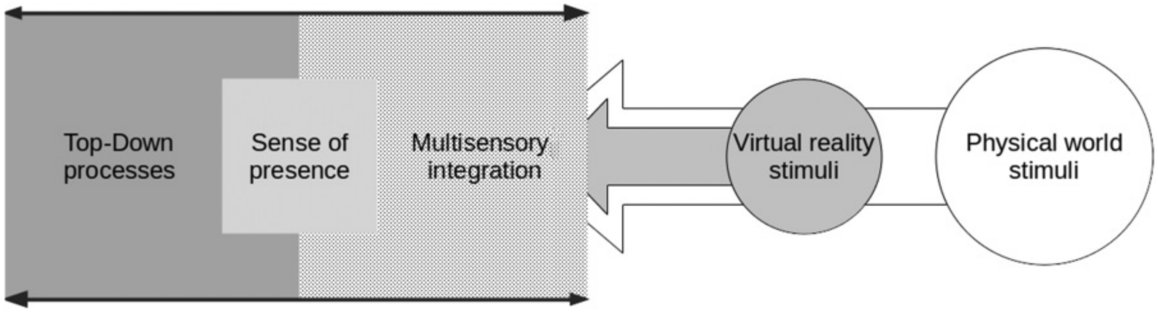

Figure 1. *A graphical representation of virtual reality as an additional layer between stimuli from the physical world and central processing of the brain, aiming to alter the multisensory integration and build a sense of presence in another (virtual) place. The quality of immersion can be considered as the degree and quality of virtual reality stimuli (grey arrow) superposing the physical world stimuli (white arrow) in order to facilitate multisensory integration toward a sense of presence in the virtual environment.*

the relation between the sense of presence and consciousness, so we will leave it at that so that discussions can be held on a broader common basis. Rather, we investigate the relationship between the sense of presence and performance, which is easier to study, since performance presents an observable dimension. However, before exploring this relationship, it is important to understand what particularities and problems VR induces for studying *in virtuo* behavior, notably the layering of presences.

3 Layering of Presences

Even if we agree, for the sake of argument, with the Cartesian representational view of Loomis (1992a, 1992b, 2016) stating that immersion is just another sensory layer between the external world and the subject, the supplementary layer of VR still adds something different that alters the experienced sense of presence (see Figure 1). The crucial difference between the physical world and VR experiences lies in the systematic and pervasive need for coherence of multisensory integration (Engel et al., 2012; Weiss et al., 2002). In the physical world, multisensory integration is generally undisputed, while it is widely challenged in VR, altering the sense of presence. If immersion, the objective properties of a VR system (Slater & Wilbur, 1997), were perfect enough to make the immersive system fully transparent and thus invisible to the user's perception, the question of the relationship between the sense of presence and performance would not matter, and probably not even exist. The physical environment would cease to exist to the senses of the participant, which is sometimes described as the ultimate goal of VR. Rather, participants would be fully present in the virtual environment and perceive, act, and feel just like they would in the physical world. However, today's VR systems are not perfect. Therefore, individuals experience a "flawed" virtual environment layered on the stimuli from the physical environment, mediated through an input/output interface. The experience of, and the interaction with, this interface depends on a potentially infinite number of human factors, both innate and acquired. Indeed, whether we consider the sense of presence as a dichotomous phenomenon (a subject being at each moment either present in the physical world or in the virtual world), a continuous phenomenon (a subject being at each moment present in the two worlds on different or similar degree), or a mix of both through the neurobiological continuity illusion (Berliner & Cohen, 2011; Kim & Biocca, 1997; Slater et al., 2003; Slater & Steed, 2000), it is unarguable that the layering of environments divides attention and consumes attentional resources because of the reliance on executive functions (Diamond, 2013), either to focus and update one environment or to inhibit the other one. Once again, this is due to the fact that top-down processes of perception are constantly in need of coherence across different bottom-up inputs (sometimes leading to perceptual illusions) as this coherence is mandatory in order to obtain a stable apprehension of the physical world (Engel et al., 2012; Weiss et al., 2002).

In other words, maintaining a sense of presence in a virtual environment, which requires the construction of a coherent multisensory spatial representation of the environment while inhibiting physical world stimuli (Wirth et al., 2007), consumes a certain amount of attentional resources. The amount of resources consumed this way is dependent on the interaction between the quality of immersion (Cummings & Bailenson, 2016) and the quality of multisensory integration processes. What is important to note here is that the processes that form the very broad concept of perception present large inter-individual differences, from global cognitive and perceptive style strategies (Witkin, 1949; Witkin et al., 1962) to very narrow temporal resolution (Cecere et al., 2015; Costantini et al., 2016). In addition, many different human factors have been outlined to impact the sense of presence susceptibility and manifestation; these interindividual differences in the way of interacting with immersion might at least partially explain why the sense of presence is so different from one person to another when confronted with the same virtual environment (Alsina-Jurnet & Gutiérrez-Maldonado, 2010; IJsselsteijn et al., 2000; Maneuvrier et al., 2021; Sas, 2004; Slater & Wilbur, 1997). Considering this, it seems crucial to investigate the variables impacting the economy of attentional resources in VR in order to fully explore and apprehend the presence–performance relationship.

4 Human Factors

Trying to exhaustively list all the human factors impacting the VR experience would be in vain, but the main ones studied in the literature can and should be cited in order to visualize the relationships between the different phenomenons. The most prevalent human factors revolve around the efficiency of the multisensory integration and the resolution of perceptive mismatch, which makes them deeply intertwined. The most famous one is cybersickness, the manifested negative symptoms caused by VR exposure and often interpreted as resulting from an uncorrected perceptive mismatch (Bos et al., 2008; Reason & Brand, 1975; Rebenitsch & Owen, 2016; Stanney et al., 1997). Negative symptoms of motion sickness like the ones of cybersickness are often considered as the result of evolutionary processes, intended to expel a potentially toxic ingested substance (Treisman, 1977). Contrary to simulator sickness symptoms, which are mostly constituted by disorientation symptoms, cybersickness symptoms are mostly constituted by oculomotor symptoms (Stanney et al., 1997). Among the broad family of motion sickness, cybersickness is considered as dominantly visually induced, sometimes called “visually induced motion sickness,” (Bos et al., 2008; Stanney et al., 1997). For what interests us here, and after many debates and studies, we can now defend that cybersickness is negatively associated with the sense of presence, as found empirically in Maneuvrier et al. (2020, 2021), in Weech, Kenny, et al. (2020) and as synthesized by the recent review of Weech et al. (2019). However, it is difficult to induce a causality here. Indeed, it is possible that cybersickness symptoms reduce the sense of presence, notably by degrading the attentional resources allocated to the virtual environment. This degradation of attentional resources could be, for example, caused by the sensory reweighting, and notably down-weighting of visual cues in order to resolve the perceptual conflict (Maneuvrier et al., 2021; Weech et al., 2020). Another explanation for cybersickness to reduce the sense of presence might be that the negative symptoms drive attention and awareness toward the participant’s own body, reducing the amount of attentional resources devoted to the virtual environment. The other way around is also possible, as the sense of presence might reduce cybersickness by driving attention away from the negative symptoms (Weech et al., 2019). Finally, it is also possible that individuals who are more prone to cybersickness are also, because of more rigid multisensory mechanisms, less prone to the sense of presence, upstream of the two processes (Wirth et al., 2007). Regardless of the direction of causality between cybersickness and the sense of presence, it is not debatable that the perceptive mismatch symptoms and regulation is an integral part of the psychophysiology of

VR as the negative counterpart of the sense of presence (Maneuvrier et al., 2021; Weech, Kenny, et al., 2020). It should be noted here for our future reasoning that negative symptoms of perceptive mismatch are often considered as impacting cognitive abilities, notably by reducing or driving away attentional resources (Gresty et al., 2008; Gresty & Golding, 2009; Maneuvrier et al., 2020; Nesbitt et al., 2017; Strózak et al., 2018; Szpak et al., 2019; Yen Pik Sang et al., 2003). However, this result has recently been questioned by Varmaghani et al. (2021) who found no impact of cybersickness on spatial and attentional performance as measured on a traditional neuropsychological test after the VR exposure. These and other authors (Maneuvrier et al., 2020) point to the possibility of a threshold effect of cybersickness symptoms.

Occupying a prominent place within the interindividual factors that can explain both cybersickness and the sense of presence, the previous video game experience of the subject is often suggested in VR studies. Indeed, the practice of playing video games (just like VR), can be seen as an habituation to perceptive mismatch because of the exposure to a continuous incongruous visual flow (Howarth & Hodder, 2008). Video game experience is often found as negatively associated with cybersickness and positively associated with the sense of presence (De Leo et al., 2014; Gamito et al., 2010; Knight & Arns, 2006; Lachlan & Krcmar, 2011; Maneuvrier et al., 2020; Stanney et al., 2003; Weech, Kenny, et al., 2020). However, some studies found no relationship between video game experience and the sense of presence or cybersickness (Alsina-Jurnet & Gutiérrez-Maldonado, 2010; Ling et al., 2013). Beyond the threshold potential effect, one thing to consider in this regard is the fact that video games bring together very different activities. From a sensorymotor point of view, playing a puzzle game or a matching game on a phone in the subway is very different from playing a first-person racing game or a real-time strategy game on a large computer screen. This is why some authors have differentiated the terms and activities of "casual games" versus "intensive games." "Casual games" involve simple rules with simple completion, are often solo-player, do not require training to perform, are usually cross-platform (generally played on smartphones), and use a low amount of computational resources (Baniqued et al., 2013; Juul, 2012; Kuittinen et al., 2007). "Intensive games," on the other hand, are generally played on PC or gaming console, rely vastly on computational resources, and require a certain amount of training time to be learned. They are often multiplayer based, are challenging without a definitive completion, and cannot be fully mastered, with the most skilled players becoming professionals in the E-sports scene (Bosser & Nakatsu, 2006; Green & Bavelier, 2003; Kapalo et al., 2015; Rehbein et al., 2016; Saputra et al., 2017). Although these two categories still seem very broad and further studies are needed to specifically assess the processes involved in different types of video games (Green & Bavelier, 2003, 2006, 2007, 2012), it is easy to understand that the type of games played will have very different effects in VR, on both the sense of presence and cybersickness. Yet again is it hard to tell the direction of causality; it is possible that individuals who are more prone to cybersickness and less likely to experience a sense of presence find video games less appealing, just as it possible that playing video games enhances the sensibility to sense of presence and provokes a habituation to cybersickness. Another mixed possible interpretation might be that playing video games enhances the regulation of the perceptive mismatch, triggering fewer cybersickness symptoms, which in turn have less deteriorating impact on attentional resources and thus on the building of the sense of presence.

Another interesting concept that could shed light on the psychophysiology of VR is the field dependence/independence dimension. Field (in)dependence is a perceptive style continuum following a normal distribution and revealing different strategies of the perception–cognition coupling: more field-dependent individuals predominantly use visual cues and a holistic approach, whereas more field-independent individuals rely less on visual cues and use a more analytical approach (Evans et al., 2013; Messick, 1976; Witkin et al., 1967, 1977; Witkin & Goodenough, 1981). This concept of field (in)dependence is interesting in VR, as it is suggested that field-dependent people have more difficulties handling the visual flaws and incoherence in the predominantly visual virtual environment, leading to a decreased feeling of the sense of presence (Hecht & Reiner, 2007). In addition, field dependence is positively associated with susceptibility to motion sickness (Cian et al., 2011; Kennedy, 1975), which has been suggested as the result of the prevalence of the use of visual information, incongruous with other perceptive systems in VR. Indeed, visual stimuli mismatch with other sensory system is at the heart of perceptive conflicts in simulators or VR, leading to cybersickness (Bos et al., 2008; Stanney et al., 1997). On this matter, Maneuvrier et al. (2021) recently measured field dependence before and after a virtual exposure, along with sense of presence and cybersickness. They found that participants reporting low levels of presence and high levels of cybersickness significantly reduced their field dependence, switching to a less visual perceptive style, which is discussed as a compensatory reweighing mechanism. Besides the interpretation, this outlines the fact that the mentioned human factors are truly intertwined and difficult to apprehend independently. Finally, it is particularly interesting to note that field independence is associated with spatial abilities and seems to be increased by playing 3D games during childhood (Boccia et al., 2016; Evans et al., 2013; Levine et al., 2016). This could not only explain why gender differences are regularly reported, with women being recurrently described as more field dependent than men (Onyekuru, 2015), but also be associated with the spatial components of the sense of presence (Wirth et al., 2007). However, one should be cautious in stating that women are more field dependent than men, since an effect of stereotype threat has been shown; in their study, Drążkowski et al. (2017) found no difference between the two genders once the experimenter's gender variable was controlled.

Yet, the gender (or sex) factor by itself is often suggested as playing a role in the way an individual experiences VR, with explicit research like the one called "Is virtual reality made for men only?" (Felnhofer et al., 2012), in which the authors found different levels of sense of presence between men and women. This difference is sometimes (partially) found in the literature (Gamito et al., 2008; Lachlan & Krcmar, 2011; Nicovich et al., 2005; Slater et al., 1998), while other studies showed no differences at all between genders on the sense of presence (Maneuvrier et al., 2020; Weech, Kenny, et al., 2020). However, Maneuvrier et al. (2020) found an association between the feminine gender and cybersickness. Indeed, women often report more symptoms of cybersickness than men (Shafer et al., 2017; Stanney et al., 2003), even though this effect is not systematic (Gamito et al., 2008; Ling et al., 2013; Weech, Kenny, et al., 2020). Of note, it is unsure if this effect should be attributed to the culturally gendered education or to biological differences. It is possible that the fact that women are less inclined to play video and 3D games does not train their abilities to regulate or inhibit a perceptive mismatch. On this question, it is particularly interesting to see that while men and women report approximately similar levels of video game experience (Entertainment Software Association, 2019), the two genders still differ widely on the type of video games and media used. Women dominantly play "casual games" (puzzles, matching games) on smartphones or tablets, while men dominantly play "intensive games" (first-person shooter, real-time strategy) on computers or gaming consoles (Bosser & Nakatsu, 2006; Kapalo et al., 2015; Rehbein et al., 2016; Saputra et al., 2017). Besides cultural aspects, it is also possible that biological differences, notably in the susceptibility to sensory conflict as an evolutionary process (Treisman, 1977), or in hormones secretion rates (notably vasopressin), enhance the susceptibility to negative symptoms for women (Clemes & Howarth, 2016). Other explanations might be differences in the field of view between the two sexes, increasing the flicker perception among women, thus leading to cybersickness (LaViola, 2000). In addition, it has been suggested that the size of head-mounted displays is generally not adapted to women, which enhances the emergence of cybersickness (Stanney, Fidopiastis, et al., 2020); once the interpupillary distance controlled, Stanney, Fidopiastis, et al. (2020) found no cybersickness differences between men and women. Finally, it has been argued that men might under-report their symptoms of cybersickness in order to socially appear stronger (Rebenitsch & Owen, 2016).

There are many other factors that have been found or suggested as potentially impacting the VR experience, notably on the sense of presence sensibility: age (Paillard et al., 2013; Stanney et al., 1998), emotions susceptibility (Aymerich-Franch, 2010; Riva et al., 2007; Västfjäll, 2003), personality traits like openness, neuroticism, absorption, and extroversion (Dewez et al., 2019; Kober & Neuper, 2013; Sacau et al., 2008; Weibel et al., 2010), and suspension of belief (Laarni et al., 2015; Witmer & Singer, 1998). In addition, it is arguable that the amount and quality of pools of attentional resources (Navon & Gopher, 1977) available for the sensory, cognitive, and motor experiencing of VR will be different for each subject. These differences might be based on intrinsic factors (cognitive reserve) and extrinsic factors (motivational, contextual), further increasing the interindividual differences (Bystrom et al., 1999; Draper et al., 1998; Draper & Blair, 1996; Wirth et al., 2007). All these variables affecting the way individuals experience VR (see Figure 2) highlight the need to understand the relationship between presence and *in virtuo* performance in order to prevent a priori interindividual factors from producing strong a posteriori outcomes which could not be directly imputable to what is actually measured, namely task performance.

5 Cognitive Profile and in virtuo Experience

Based on these human factors and the global framework of VR, we can consider each individual to present a unique and dynamic combination of every impacting variable constituting a *cognitive profile* more or less adapted to the immersive experience. To sum up, this *cognitive profile* is made up of all the interacting acquired and innate behaviors, in particular (i) the construction of multisensory integration (field dependence, sensitivity to perceptual conflict), (ii) certain executive functions (inhibition, flexibility, visuospatial skills) and their supporting attentional resources (Diamond, 2013; Navon & Gopher, 1977), and (iii) his/her relationship to human–computer interaction: practice of video games, sensorimotor skills, self-evaluation of performance, susceptibility to stereotypes threat (Bonnot & Croizet, 2011; Koch et al., 2008; McGlone & Aronson, 2006). This *cognitive profile* will, when confronted with the sensory filter that is immersion, interact with the properties of the VR system to alter the natural multisensory integration and induce a sense of presence in the virtual environment rather than in the physical place.

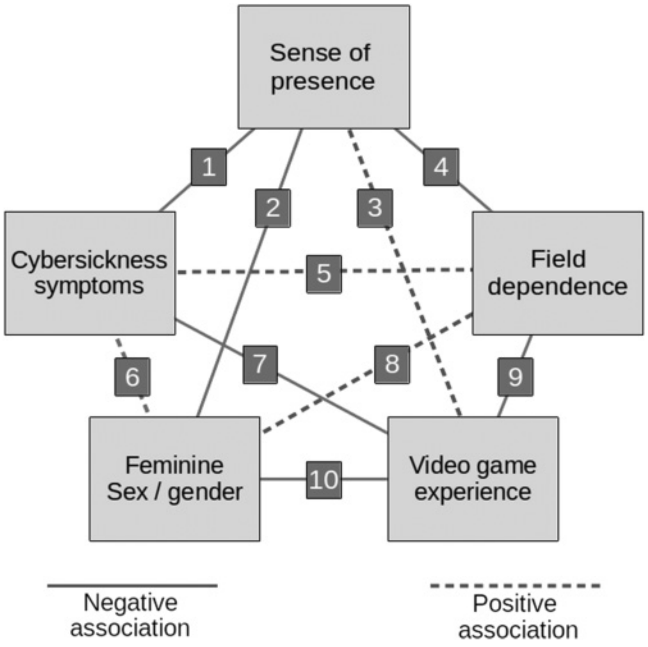

Figure 2. *A graphical representation of the major intertwined human factors impacting virtual reality experience and some suggested relationships in the literature. 1: (Weech et al., 2019); 2: (Felnhofer et al., 2012; Gamito et al., 2008; Slater et al., 1998); 3: (Gamito et al., 2008; Maneuvrier et al., 2020); 4: (Hecht & Reiner, 2007; Maneuvrier et al., 2021); 5: (Cian et al., 2011; Maneuvrier et al., 2021); 6: (Maneuvrier et al., 2020; Shafer et al., 2017); 7: (Maneuvrier et al., 2020; Weech, Kenny, et al., 2020); 8: (Onyekuru, 2015); 9: inferred from (Evans et al., 2013; Levine et al., 2016; Pithers, 2002); 10: (Entertainment software association, 2019; Rosa et al., 2016).*

Since VR is flawed (and not absolutely invisible), the interaction between the *cognitive profile* and the immersion will not only induce a sense of "being there," but also negative effects like cybersickness, or even the awareness of using an interface (Lombard & Ditton, 1997). This interaction between immersion (system factors) and *cognitive profile* (human factors) explains the nonlinear distribution of negative symptoms, depending, for example, on the type of task performed (Lawson, 2014). Some systems will trigger more cybersickness,

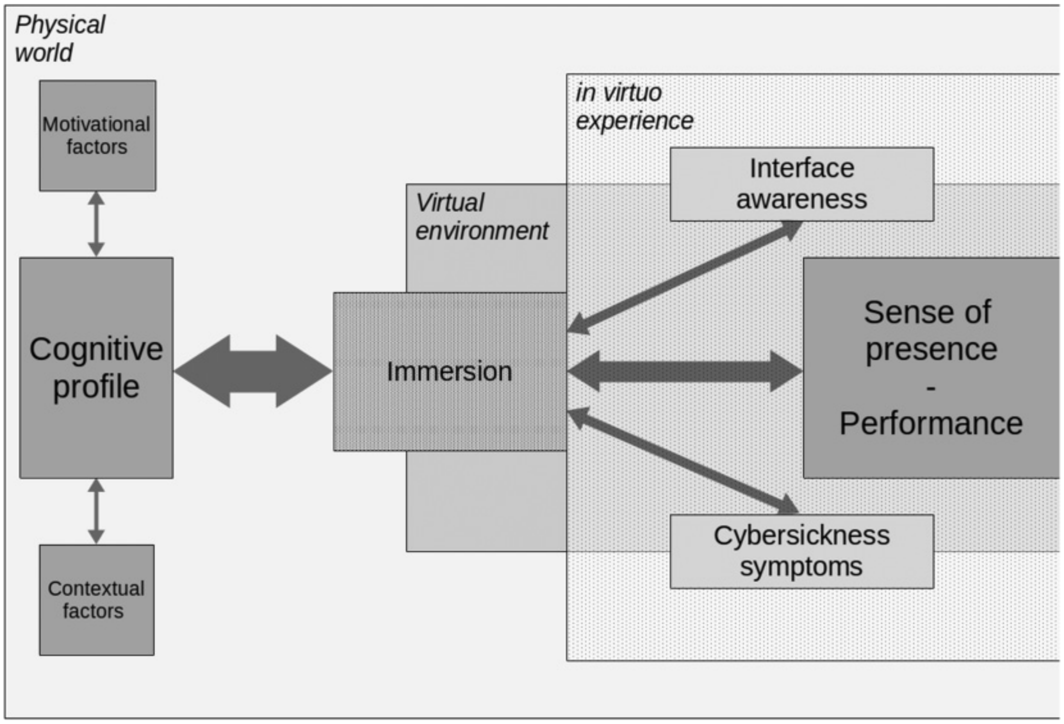

Figure 3. *A graphical representation of the economy of attentional resources in virtual reality based on the constitutive and dynamic interaction between cognitive profile (e.g., video game, experience, susceptibility to perceptive mismatch), motivational-contextual factors (e.g., interest, tiredness) and immersion (e.g., transmission delay, sensorial congruence), modulating the in virtuo experience (e.g., interface awareness, cybersickness symptoms, sense of presence).*

but also more interindividual differences on these same negative effects (Gilbert et al., 2021), depending, for example, on the means of locomotion used (Clifton & Palmisano, 2019; Schuemie et al., 2005; Turchet, 2015). If we consider the sense of presence as a phenomenological psychophysiological construct, it seems odd not to integrate the negative effects of perceptive mismatch or the awareness of the interface.

This global psychophysiological state that we coin the *in virtuo experience* is somewhat close to the ergonomic concept of user experience (IJsselsteijn & Riva, 2003; Marcus, 2013), but with an emphasis on its phenomenology. It can be defined as the subjective and dynamic psychophysiological consequence of the interaction between the user's cognitive profile, immersion, and both contextual factors (tiredness, hunger, or even substance consumption as described by Lorenz et al., 2018)) and motivational factors (the engagement and interest toward the virtual environment). This conceptual apprehension is graphically represented in Figure 3. it is important to note that the relationship between the *cognitive profile* and the *in virtuo experience* is bidirectional, since any *in virtuo experience* will modulate the *cognitive profile* in a constitutive way, for example, by reducing the susceptibility to perceptive mismatch through exposition (Howarth & Hodder, 2008), or by teaching the user how to use the interface, reducing the amount of necessary allocation of attentional resources for interaction. The quality of the *in virtuo experience* affects the economy of attentional resources available in VR in particular, but not exclusively through (i) the appearance of distracting symptoms of cybersickness, (ii) the subject's awareness of the device depending on ergonomics, and, finally, (iii) the emergence and maintenance of the sense of presence. Based on this, the sense of presence can be considered as the amount and quality of attentional resources attributed to the virtual environment and passing the consuming filter of the *in virtuo experience*'s construction.

A group of researchers (Draper et al., 1998; Draper & Blair, 1996) consider the sense of presence as the sum of all pools of attentional resources allocated to the virtual environment. However, in our opinion, the attentional resources dedicated to dealing with the ergonomics of the interface, or diverted to dealing with symptoms of cybersickness, do not contribute to the sense of presence, even though they are at least partially allocated to the virtual environment. Here, we defend the idea that all attentional resources consumed in order to build the *in virtuo experience* (allocated to the interface, to the inhibition of irrelevant stimuli from the physical world, or to the resolution of the perceptual conflict) are attentional resource pools that cannot be used for the building of the sense of presence, nor for the execution of task performance (see Figure 3). It is then particularly important to understand the amount of attentional resources required by the interaction between the *cognitive profile* and immersion, in order to determine what is consumed for the building of the *in virtuo experience* and thus available for the presence–performance relationship.

6 Performance and Performance in Virtual Reality

Performance can be defined as the action or process of carrying out or accomplishing a task or function, seen in terms of how successfully it was performed. This action is often an easily and clearly identifiable behavior. For example, when VR is used to assess spatial cognition, performance is indubitably the participant's score on the evaluation, whether measured by navigation time or scaled recognition of spatial orientation cues (Allahyar & Hunt, 2003; Cogné et al., 2017; Maneuvrier et al., 2020). In this framework, performance does not correspond to all of the subject's spatial cognitive processes, but to those that are measured; finding a way to measure precise cognitive processes is one of the major axes of neuropsychology and psychometry. This aspect of measured performance is shared among virtual environments with straightforward behavioral aims, whether it is for diagnostics, rehabilitation, research, or learning. If we ask an immersed participant to catch virtual balls, performance can easily take the shape of a numeric scale counting the number of balls actually caught, and this performance will be the manifestation of visual-motor cognitive processes. If we ask an immersed participant to fix broken parts of a virtual submarine while following a very precise security procedure, performance can be defined as an inverted numeric scale, counting the number of errors or the time needed for the realization. In these cases, performance is similar to the dependent variable of the experimental methodology; it is a measure of the participant's behavior when confronted with a specific task and compared to an expected measure. This consideration of performance is not unique to VR. For example, when a neuropsychologist performs an executive function test on a patient with Parkinson's disease, such as the Wisconsin Card Sorting Test (Lange et al., 2018), it is the patient's performance on this test (when compared to the norm) that will establish the diagnosis based on the functioning state of the evaluated processes (inhibition, mental flexibility, updating). The main question here is to see if the performance measured is altered by the use of virtual reality.

An important methodological problem in exploring this issue lies in the fact that the use of VR currently produces situations where performance takes a much less precise form, for example, when VR is used for exposure therapy to reduce phobias (Botella et al., 2017; Miloff et al., 2019), or to reduce patient pain (Gold et al., 2007; Hoffman et al., 2001). If we imagine a situation where a patient is asked to play a virtual table tennis game in order to alleviate their pain during a particular painful treatment, we can distinguish two types of performance: the subject's performance (e.g., how many points scored during one session or how many balls returned) and the system's performance (the global power of the analgesic effect on the medium- or long-term when compared to other analgesic tools). This distinction, which is reminiscent of the difference between the sense of presence and immersion (Slater &

Wilbur, 1997), also exists in the case of the educational use of VR. Indeed, when a subject is asked to perform a complex and dangerous mechanical procedure, there are again two performances: the performance of the subject, measured by their success in performing the measured and precise tasks of the procedure in the virtual environment, and the performance of the pedagogical environment, which could be measured by the global learning retention. In this essay, we discuss mainly the subject's performance during the VR experience.

Still, it is important to note that the second type of performance (the system's performance) is often considered as associated with the subject's *in virtuo experience*; for example, the analgesic effect of VR seems to be modulated by the participant's sense of presence (Gutierrez-Maldonado et al., 2010; Hoffman et al., 2004), as does the reduction of phobias (Price & Anderson, 2007; Riva et al., 2019) and the transfer effect of educational environments (Levac et al., 2019; Mantovani & Castelnuovo, 2003). Of note, the two types of performance are mutually nourishing and probably correlated. It is even possible to suggest that these effects are covariates of the primary link between the subject's performance and attentional resources; that is, the more attentional resources an individual devotes to the virtual game, the better their performance on it will be, and the more attention will be diverted from their pain, increasing the analgesic effect. This association could be a little more complex in the context of learning, for which making errors and mistakes plays an important role on the learning process (Potts & Shanks, 2014), but this question is out the scope of this work. Finally, and obviously, in order to study performance in a methodological way, it is essential to adapt or weight the difficulty of the task in relation to the participant's level of expertise. In the same way that performance on neuropsychological tests is compared to the reference population, if we want to study virtual performance on table tennis game, the performance of a world champion should not be considered in the same way as that of an individual who has never practiced the sport.

However, and even after considering these two types of performance, a problem remains for those who wish to evaluate and monitor performance in VR: in the examples of the virtual table tennis game or the neuropsychological tests, the researchers have an objective measure of the subject's visuo-manual and cognitive performance (the subject's performance). Whether this performance is linked to the analgesic effect and to the sense of presence is debatable and will be discussed later, but at least it is objectively and empirically measured. However, and as mentioned previously, when a cognitive psychologist uses VR to induce exposure to spiders, the participant's performance is more difficult to measure. One could even argue that no performance is measured, but we think that many forms of performance could be considered as long as they are measured: how long was the participant exposed to the phobic object before removing the headset? How many meters did the participant virtually move away from the phobic object if they had the freedom to do so? How many times did the participant move his gaze away from the phobic object, and for how long? Indeed, it is the measure that turns the behavior into a performance, just as it is the context that makes the difference between running as a sport or running to catch a bus, even though the behavior is roughly the same. Here, we argue for the identification and measurement of both types of performance in VR so that comparisons can be made between subjects and between studies. This should lead to a more rigorous methodological development of the tool; performance (both subject's performance and system's performance) is almost always the primary purpose and reason for using the tool, so it must be understood and controlled precisely. Whether the participant is running on a treadmill to catch a virtual bus or to outrun a virtual avatar, VR allows the standardized measurement of performance, that is, the distance covered in a specific time. For our purposes, this measurable performance of the participant (and the system's performance) should be included in the framework of VR and be linked to the *in virtuo experience* and the *cognitive profile*, in order to allow large-scale comparisons. This would allow in the future to dissociate the real performance of the subject (the participant's ability to run) from the parasitic effects induced by the use of virtual reality.

7 Performance, Sense of Presence, and Attention

Speaking of running, there is a saying in French commonly used to talk about task and notably sport performance: *"il/elle n'était pas dedans,"* which could be translated as "he/she was not being there," used to rationalize a poor performance because *"il/elle était ailleurs"* ("he/she was being elsewhere," similar to the expression "absent minded"), where this other place is the wandering of the person's mind. The point of this linguistic digression is that in the physical world, since the sense of presence is perceptually invisible, we consider the relationship between paying attention and performance, rather than the sense of presence and performance. Why should this be different in VR? Is the sense of presence in VR not just attention focused on the virtual environment, and then just a different semantic taxonomy of attentional resources which, for sure, favor performance? In the same vein, many authors link the sense of presence to the concept of flow (Bian et al., 2020; Draper & Blair, 1996; Lackey et al., 2016; Park & Hwang, 2009; Redaelli & Riva, 2011), which is a state of consciousness favorable to performance defined by intense and focused concentration (Csikszentmihalyi, 1975; Nakamura & Csikszentmihalyi, 2009). Should we simply consider sense of presence in VR as flow in the virtual environment? If this were the case, sense of presence would indubitably favor performance. This logical assumption, however, does not stand the analysis of attentional resources (Draper et al., 1998; Draper & Blair, 1996). In their paper, Draper et al. (1998) note that if we consider the sense of presence as the amount and quality of pools of attentional resources devoted to the virtual environment, this allocation does not always align with the amount and quality of pools of attentional resources devoted to the task. Indeed, an individual can allocate many resources to virtual stimuli not related to the task, for example, distracting stimuli, building a strong sense of presence without enhancing performance. For example, if you ask participants to play a virtual game of basketball, some could decide to take a little break and explore the virtual stadium that they find particularly well designed. This behavior should increase the sense of presence in the virtual stadium, but reduce the performance, which is to put the ball in the basket. On the other hand, if the task is to find a lost object in the stadium, then this exploration will increase both the sense of presence and the performance, showing a positive association between the two. In both cases, the participant can reach a state of flow in relation to the task at hand; the question is whether the activity that the individual is focusing on is the one measured for performance.

An even more extreme possibility is to consider a situation where participants are, while immersed, asked to perform tasks completely outside the virtual environment, with sensorimotor processes that are not supported by the latter. For example, during the virtual basketball game, the participant must try to aim the ball in a basket located in the physical world as instructed by the experimenter before the immersion. On this matter, a study by Slater et al. (1995) interestingly used this kind of task in order to behaviorally measure the sense of presence. In this experiment, the authors used two radios, one virtual and one real, which they spatially superimposed at the beginning of the experiment and dissociated during immersion. At one point, they asked the participant to point to the location of the radio, the presupposition being that a more present individual will point in the direction of the virtual radio while a less present participant will know the location of the real radio. The point of this is that the allocation of attentional resources for the constitution of the sense of presence does not necessarily superpose with that of the measured performance, and that sense of presence is not a global state of flow in a virtual environment. Here, Riva et al.'s (2015) conceptualization of the sense of presence can shed some light: the sense of presence can be considered as a phenomenological base halfway between cognition, volution, and action that allows the individual to extract affordances from their environment. Following their actions and choices of actions, thus made possible by the sense of presence, the subject will then manifest (or not) the expected performance, developing (or not) a state of flow along the way. With all this in mind, and considering the particularities of the sense of presence in VR mentioned previously, this phenomenological state must be considered as the particularity that it is.

8 Sense of Presence, Task Integration, and Performance

The common heuristic idea regarding the presence–performance relationship is that of a positive correlation, or even causality. Indeed, when considering the close links between the sense of presence and attention mentioned previously, it seems natural to think that the more present a subject is in the virtual environment the stronger their performance will be in that same environment (Nash et al., 2000; Sheridan, 1992; Witmer & Singer, 1998). However, as Welch (1999) notes: "Despite the popularity of this notion, there is no solid evidence to support it." In this report, Welch (1999) mentions the automatic aspect of some tasks (like driving a car) which do not require a strong sense of presence and can be executed properly "while our minds are elsewhere." While this assertion is true, this does not prove anything regarding the presence–performance relationship; nobody would argue that focusing on the road would fail to improve driving performance. However, it is true that empirical studies have difficulties proving an association between the two phenomena (Ma & Kaber, 2006; Pallamin & Bossard, 2016). Still, some studies have found significant (but often weak) associations (Cooper et al., 2018; Grassini et al., 2020; Pausch et al., 1997; Sadowski & Stanney, 2002; Slater et al., 1996; Stevens & Kincaid, 2015; Witmer & Singer, 1998; Youngblut & Huie, 2003), from which the inference of causality is difficult, if not impossible.

As pointed out by Nash et al. (2000) and Welch (1999), a fundamental problem lies in the fact that even when empirical data show an association, it is hard to tell if presence improves performance, or if performance improves presence. To use the example of catching balls in a virtual basketball environment, does feeling present in the environment help to catch the balls, or does catching a ball, and thus adding tactile feedback via sensorymotor loops and feeling of accomplishment via rewarding loops to the experience, help to feel more present? In a recent study evaluating the sense of presence during a virtual spatial cognition evaluation, sense of presence was found to be a significant predictor of performance, with approximately 15% of variance explained by sense of presence alone, while 25% of total performance was predicted by adding the symptoms of cybersickness to the model (Maneuvrier et al., 2020). In this study, spatial cognition performance was evaluated post-hoc through spatial cognition and navigation memory tests performed in the virtual environment. It is thus unlikely that performance (or at least self-evaluation of performance) improved the sense of presence, since participants did not know their performance or the way they would be evaluated. Therefore, inferring causality based on the empirical data is in this study is rather parsimonious, but does not explain why such a strong association between performance and the sense presence is not systematic in the literature.

As mentioned previously, one probable answer is that this relationship depends on the nature of the performance and its relationship with the virtual environment (Nash et al., 2000), or more precisely its integration in the virtual environment; that is, are the processes required for the task supported by ecological behaviors (Lobo et al., 2018; Parsons, 2015)? Is the behavioral task for which performance is measured enrooted in the virtual environment interaction on a perceptual, cognitive, and motor dimension? This degree of task integration in the virtual environment can be considered as a continuum, with a detached task on one hand ("Throw the ball to the physical location of the experimenter" while the participant is playing virtual basketball), and on the other end an integrated task ("Put the ball in the virtual basket" while the participant is exploring the same environment). One important thing to note is that instructions alone are not sufficient to understand the degree of task integration in the virtual environment; the means of interaction with the world, which some would call affordances (Gibson, 1966), play a crucial role. The same task ("Put the ball in the virtual basket") will be integrated in the virtual environment if the participants are using fully tracked interaction (haptic gloves) and locomotion devices to interact with the 3D space, and less integrated if they are seated and using a joystick to perform the same task. Indeed, the use of a joystick and the lack of locomotion adds a larger layer or gap between the environment and the behavioral task, reducing its ecological dimension (altering the "throwing a ball" affordance), and, for our purposes, the integration of the task in the virtual environment. The degree of task integration in the virtual environment can thus be considered as the ecological validity of the performance measured.

Since attentional resources are not infinite and one allocation (the building and maintenance of the sense of presence) drives away resources of other potentially concurrent (the subject's performance) allocations, the two phenomena have to be considered together inside the *in virtuo experience* framework because their whole relationship depends on how well these two attentional vectors align in VR. Indeed, since we have seen that the sense of presence is the phenomenological basis allowing action on the environment, the more the measured action (the performance) will be anchored in the virtual environment, the more the sense of presence will support this action. In other words, the strength of the association between the sense of presence and a subject's performance varies depending on the integration of the measured task in the virtual environment, that is, its ecological validity. If the two vectors are sufficiently associated, the attentional resources used for the constitution of the sense of presence will make it possible to offer a much more solid phenomenological basis for action (and/or enaction) for the realization of the performance. A mutually nourishing effect can also be envisaged: the realization of the performance, if it is supported by the sense of presence, will consolidate this base, whether it is by adding sensory stimuli or volitional commitment.

We will consider one last example. It is arguable that a fully tracked spatial cognition evaluation is one of the most integrated tasks possible in a virtual environment because spatial information supports both the processing of the sense of presence (sometimes called "spatial presence") and the ability to navigate in the environment (Wirth et al., 2007). For this reason, it is not surprising that VR has been widely used for spatial cognition research and diagnostics, where paper-and-pencil tests show a weak ecological validity (Allahyar & Hunt, 2003; Allison & Redhead, 2017; Byagowi & Moussavi, 2012; Cogné et al., 2017; Cohen, 2013; Cushman et al., 2008; Diersch & Wolbers, 2019; Ijaz et al., 2019; Kim & Bock, 2020; Kim et al., 2019; Maneuvrier et al., 2020; Zhou et al., 2020). In the case of spatial exploration, task performance and the sense of presence vectors are well aligned, resulting in a strong association between the two, which is empirically observable in Maneuvrier et al. (2020) In this case of spatial cognition, the resources attributed to the constitution of the phenomenological basis of the sense of presence align with the processes measured by the performance. The task being well integrated in the virtual environment, the phenomenological base that is the sense of presence truly supports the measured performance, making the relationship between the two positive and even mutually nourishing. We think this conceptualization, coined the Phi Angle, helps modeling the VR equation, as illustrated in Figure 4. In this model, we suggest the conceptualization of the presence–performance relationship as two vectors that have the same origin (attentional resources), but whose angle (association) depends on the integration of the task in the virtual environment.

9 Model Testing and Limits

The elements making up the *cognitive profile* are perhaps the best known in the literature; they correspond to the various human factors impacting the processing of immersion and mentioned earlier. However, to be truly tested empirically in the *cognitive profile* framework, all of these variables must be studied concurrently, but also in relation to the *in virtuo* experience. To do this, tools like principal component analysis or cluster analysis (K-means, nearest neighbor forest) could be useful to understand the contribution of each human factor on the *cognitive profile*, but also on the *in virtuo experience*. The K-means clustering was used previously by Maneuvrier et al. (2021) in order to perform the analyses on only one phenomenological psychophysiological dimension (sense of presence and cybersickness)

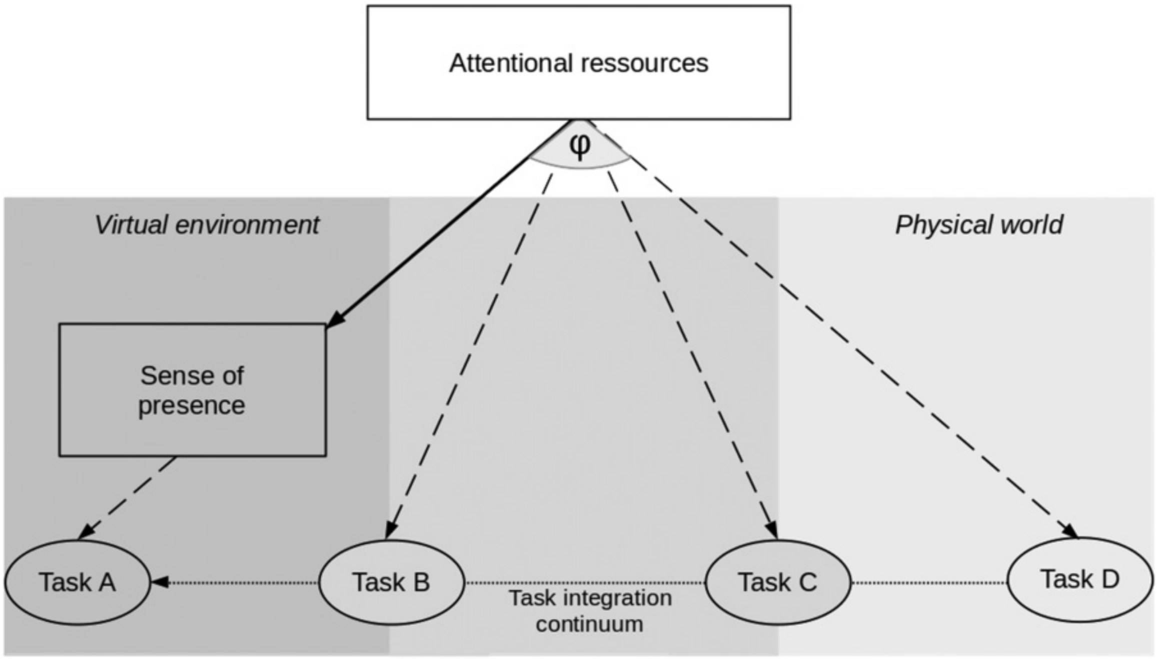

Figure 4. *A graphical representation of the presence–performance relationship considered as attentional resources vectors with a common origin. The angle between the two vectors (Angle Phi φ) depends on the degree of task integration in the virtual environment. Task A corresponds to a theoretically fully integrated task where presence and performance perfectly align and each allocation of attentional resources to one of the vectors enhances the other ($\varphi = 0°$, e.g., catching balls in a futuristic invisible virtual reality system). Task B corresponds to a strongly integrated virtual task ($\varphi \sim 25°$, e.g., a greatly immersive spatial cognition evaluation). Task C corresponds to a partially integrated virtual task ($\varphi \sim 60°$, e.g., a poorly immersive training simulator), and Task D corresponds to a nonvirtual task in which the allocation of attentional resources to the sense of presence deteriorates task performance and vice versa ($\varphi > 90°$, e.g., answering mathematical problems enunciated orally while catching virtual balls).*

rather than on two dimensions. Within this framework, it would be defensible to carry out similar analyses on a larger number of variables: on the one hand, on the *cognitive profile* (experience of video games, field dependence, sensitivity to cybersickness) and on the other hand, on the *in virtuo experience* (sense of presence, cybersickness, flow). Clearly, system factors, overlooked in this model, should also be considered. In order to take into account the system factors, it would be possible to draw up a list of technical elements (resolution, latency, means of locomotion, duration of immersion) and to evaluate their respective contribution to the quality of the immersion via principal component analyses or unsupervised learning. If the constituent elements of these three components (*cognitive profile*, immersion, and *in virtuo experience*) as well as the relationships between these three dimensions could be determined with sufficient empirical data, the standardization of VR protocols would be greatly facilitated, and the understanding of the psychophysiology of VR taken further.

Concerning the Phi Angle model, and although its primary purpose is theoretical in order to help conceptualize the presence–performance relationship, we hypothesize that it can be explored and validated empirically. Indeed, the Phi Angle corresponds to the strength of the association between the sense of presence and performance. Consequently, we already have three potentially empirical values here: the sense of presence, performance, and the association (Pearsons R, for example) between these two. In order to demonstrate the validity of this conceptualization, and since we propose that the value of the Phi Angle depends on the integration of the task in the virtual environment (also called ecological validity of the performance), it is the latter that needs to be manipulated and measured. The first idea that comes to mind, the simplest one, would be to play on the degree of immersion within the same environment measuring the same performance. For example, ask a group of participants to perform a navigation and spatial orientation task in a virtual environment by modifying the means of locomotion and interaction: natural linear locomotion tracked in VR, artificial locomotion using tracked controllers VR, and artificial locomotion using a joystick on a 3D screen. Different levels of task integration should empirically lead to different associations between the sense of presence and performance. A problem immediately raised is that these different system factors will result in different levels of *in virtuo experience*, especially in terms of cybersickness known to impact cognitive performance (Gresty et al., 2008; Gresty & Golding, 2009). This problem could be neutralized by properly measuring the various human and system factors and weighting the measured performance according to them, but it is still possible that too low immersion levels would result in too low sense of presence levels to make comparisons. A similar example could be to vary only the means of interaction by playing on the quality of affordances and thus the ecological validity of the performance. This could take the form, in a visual–manual VR shooting task, of comparing several ways of shooting with a virtual pistol: either by pulling the trigger of a tracked controller while physically aiming at the target, or only by pointing the pistol for a certain time towards the target without activating the trigger, or by aiming at the target with the virtual pistol for a certain time towards the target but pulling the trigger with the opposite hand. By comparing the association between the sense of presence and performance within these experimental conditions presenting different degrees of task integration in the environment, it should be possible to empirically test the Phi Angle. Obviously, the firing latency would decrease the performance, which should be compensated by adding a similar delay in the first condition.

The fact that modifying the integration of the task in the environment will irrevocably modify the sense of presence constitutes one of the two major limits to the empirical validation of this model. However, we have seen that this limitation can be overcome, or at least controlled. Another major limitation is, however, more difficult to control and remains common to all VR researchers: how to measure the sense of presence. The Presence Questionnaire (Witmer et al., 2005; Witmer & Singer, 1998), by emphasizing system factors and in particular the means of interaction, may indeed make the first limitation mentioned above even more salient. It would therefore seem questionable to use the latter, especially when one has a phenomenological conception of the sense of presence. However, since the Presence Questionnaire is the most widely used in the literature, it allows comparison between the maximum number of empirical studies (Grassini & Laumann, 2020). In addition, its success makes it the only questionnaire translated and validated with a standardized reference population in different languages, for example, in French (Robillard et al., 2002). Moreover, the direct questions about the sense of presence of the SUS (Usoh et al., 2000) or the IPQ (Schubert, 2003) questionnaire may cause, in our opinion, a response bias: "where a questionnaire poses queries about presence directly or indirectly, it may possibly load an answer that would not otherwise have reached the participants' conscious level" (Grassini & Laumann, 2020; Slater, 2004; Szczurowski & Smith, 2017). Physiological and behavioral measures such as heart rate or skin temperature are also complex to use since they measure the participant's physiological arousal, which can be caused by hundreds of other variables besides the feeling of presence, notably cybersickness (Weech et al., 2019). They are also generally more restrictive and costly (Grassini & Laumann, 2020). The methodological problem of measuring the sense of presence could find solutions in the standardization of automatic tools. Indeed, many variables could be used and generalized in order to measure the phenomenon dynamically (Kim et al., 2021; Ochs et al., 2018). The numerous datapoints generated by the behavior in VR (movement, posture, ocular reaction, association of physiological data) could indeed give rise to unsupervised machine learning analyses that could dynamically detect patterns of the sense of presence, in association with subjective measures. Similar methods could be used and aggregated in order to dynamically measure cybersickness (Arcioni et al., 2019; Chardonnet et al., 2017; Fulvio et al., 2021; Kim et al., 2021; Palmisano et al., 2018; Teaford et al., 2020; Weech et al., 2018), and thus more globally measure the *in virtuo experience* described above. Again, this question would deserve the pooling of many data and the standardization of tools in order to make empirical studies easily comparable (Gilbert et al., 2021; Lombard et al., 2000; Stanney, Lawson, et al., 2020).

10 Conclusion

The conclusion of this work is that the sense of presence is a psychophysiological phenomenological base supporting the interaction with the environment. In the case of virtual reality, this sense of presence relies on information from immersion, but it remains to some degree layered on information from the physical world. This layering induces large interindividual differences of *in virtuo experience* (cybersickness, awareness of the interface) caused by the interaction between the participant's *cognitive profile (*video game experience, field dependence) and the immersion. The relationship between the *in virtuo experience* and the *cognitive profile* is constitutive, as both are constantly modulating and defining each other. The quality of the *in virtuo experience* modulates the attentional resources available in VR, especially for the sense of presence–performance relationship. Indeed, we suggest that the relationship between the sense of presence and performance in VR be conceptualized as two independent vectors of attentional resources sharing a common origin. In this model, the angle between the two vectors (the Phi Angle) varies depending on the degree of integration of the task in the virtual environment. If the task is sufficiently integrated in the virtual environment and the Phi Angle small, the attentional resources used for the building and maintenance of the sense of presence will offer a much more solid phenomenological basis for action for the realization of the performance. In this case, the sense of presence and performance will be positively associated, and even mutually nourishing.

This approach has several advantages. First, it explains the apparent inconsistencies found in the empirical data in the literature, as some tasks are more integrated in the virtual environment than others, which is rarely taken into account when discussing the presence–performance relationship. In addition, the Phi Angle (i.e., the strength of the association) could also be considered as a means of measuring the ecological fidelity of a VR study; the lesser the angle between presence and performance, the stronger the ecological dimension of the behavioral task (Coleman et al., 2019; Parsons, 2015). Furthermore, apprehending the *cognitive profile* in interaction with the immersion could (i) help a priori predicting a participant's *in virtuo* experience and thus the amount of attentional resources available in VR in order to determine how well the tool would work for the participant and (ii) a posteriori reweighing performance based on what is known about the participant's and the system's properties in order to neutralize the parasite effects of human factors on the *in virtuo experience* and thus on performance. Similarly to what is usually done with the Z-scores in neuropsychology in order to compare an individual to its reference population, future investigations described in this work and based on standardized paradigms could lead to a more robust methodology of VR. Of course, future works outlined in this essay are needed in order to empirically determine if the Phi Angle can be, as we defend, the condition for the sense of presence to be "a benefit or a detriment to performance" (Barfield et al., 1995).

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