SCUOLA DI DOTTORATO
UNIVERSITÀ DEGLI STUDI DI MILANO-BICOCCA

Dipartimento di / Department of

Psychology

Dottorato di Ricerca in / PhD program Psychology, Linguistics, and Cognitive Neurosciences Ciclo / Cycle 38th

# Cognitive Glitches: Prediction Errors and Prior Updates during Immersive Digital Experiences

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**ANNO ACCADEMICO / ACADEMIC YEAR 2024/2025**

# Cognitive Glitches:

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# Abstract

Out-of-the-Ordinary experiences challenge preexisting cognitive schemata and may induce radical schema updates. Virtual Reality (VR) is ideal for generating such experiences: it simulates realistic environments while being free from physical constraints. The present research project investigates cognitive responses to VR scenarios that contradict our fundamental model of space as a Euclidean space. Because previous studies reported individual variability in acknowledging geometrically impossible scenarios as such, we investigated whether this depends on personality traits. We found that Personal Need for Structure (PNS) -measuring mental rigidity- negatively influenced the likelihood of reporting the spatial anomaly (Study 1). To verify that participants who did not report the anomaly were indeed unaware of it, we validated pupil dilation as a marker of surprise in response to expectancy violation during free navigation in VR (Study 2). In Study 3, we partially replicated Study 1: low PNS participants were more likely to report the spatial anomaly, but only in the case of male participants. We capitalized on the findings of study 2 and showed that participants who reported the anomaly displayed distinct pupillary responses compared to those who did not. We hypothesized that the latter tend to suppress high-level prediction errors to avoid cognitive dissonance and cognitive restructuring. Overall, our findings contribute to understanding the predictive processes underlying perception, and suggest the response to the violation of fundamental models is a trade-off between the benefits of an accurate representation and the costs of restructuring. Also, they address individual differences in responding to out-of-the-ordinary experiences. This may inform future studies on the effect of such experiences on creativity, and possibly explain why this effect varies across individuals.

# Chapter 1

## Is Reality Virtual?

Sueña el rey que es rey, y vive
con este engaño mandando.
disponiendo y gobernando;
y este aplauso, que recibe
prestado, en el viento escribe,
y encenizas le convierte
la muerte,¡desdicha fuerte!:
¿que hay quien intente reinar,
viendo que ha de despertar
en el sueño de la muerte?

Sueña el rico en su riqueza
que más cuidados le ofrece;
sueña el pobre que padece
su miseria y su pobreza;
sueña el que a medrar empieza,
sueña el que afana y pretende,
sueña el que agravia y ofende,
y en el mundo, en conclusión,
todos sueñan lo que son,
aunque ninguno lo entiende.

Yo sueño que estoy aquí
destas prisiones cargado,
y soñé que en otro estado
más lisonjero me vi.

¿Qué es la vida?, Un frenesí,
¿Qué es la vida?, una ilusión,
una sombra, una ficción,
y el mayor bien es pequeño;
que toda la vida es sueño,
y los sueños, sueños son.

— Pedro Calderón de la Barca, *La vida es sueño* (1635)

### From the Veil of Māyā to Markov Blanket

The idea that reality could be some illusory construct is certainly not new. In Hinduism, the term *māyā* is used to refer to the deceptive nature of the world as we perceive it, hiding the wholeness of the *Brahaman*, the Absolute (Shastri, 1911). By the same token, Greek philosopher Parmenides of Elea maintained that the multiplicity of objects we experience through our senses is in fact a lie, masking the true wholeness of the Being (Parmenides, 2008). Plato, in the Republic (Plato, 2000), argues that reality as we perceive it is a mere deception. He elaborates his point through the famous "allegory of the cave". In this parable, humans are sitting in a cave, turning their backs to the entrance and facing the wall. They observe the shadows of things passing in front of the cave entrance and believing such shadows to be the only reality.

Centuries later, Renee Descartes questioned whether all we perceive is in fact a dream, or a decoy orchestrated by some evil demon (Descartes, 1996). Similarly, Immanuel Kant realized that we will never know what truly lies beyond our senses, namely the "things themselves" (Kant, 1999). Building upon Kant, idealist philosophers like Georg Wilhelm Friedrich Hegel completely neglected the existence of "things themselves," concluding that our perception and conscious experience is the only reality (Hegel, 2010).

Strikingly enough, contemporary neuroscientists seem to have come to similar conclusions as these philosophers. The theory of Predictive Coding posits that the brain "shapes" the world by applying *a priori* models derived from previous experiences to the stream of information perpetually incoming from the periphery (Clark, 2015; Friston, 2005, 2009; Rao, 2024;

Rao & Ballard, 1999). Such information is the only interface between the brain and the outside world, and is thus a *Markov Blankets* hiding whatever lies beyond it (Kirchhoff et al., 2018): the brain can not know anything about the "things themselves," it merely detects the activation of sensory receptors.

More precisely, the brain can only infers the causes of changes in the physiological activity of sensory organs, from which postulates the existence of objects ("If I see an orange globe in my hand, and smell a citrus scent with my nose, and feel something round with my tactile receptors, it must be because there is an orange in my hand"). The inference process relies on previous experiences and, more specifically, on similarities between the current circumstances and other circumstances we encountered in the past ("Every time I felt these sensations, I had an orange in my hand"). This is just how our conscious experience of the world is thought to arise. This is how our model of reality (i.e., our reality) is constructed.

The extreme consequence is that the distinction between that which is "real" and that which is not "real" blurs. In fact, it would only depend on previous experience: We are convinced that reality is real just because the environment continuously confirms the model of it that we have built throughout our lives (Slater & Sanchez-Vives, 2022).

This point is brilliantly illustrated in "La vida es sueño" by 17th-Century playwright Pedro Calderón de la Barca. The protagonist of the play, Segismundo, has been imprisoned in a tower since he was born and thus ignores the existence of the world outside. At some point, his father frees him and brings him to his palace. Yet, Sigismundo is quickly sent back to prison because of his inappropriate behavior. Once returned to the tower, Sigismundo concludes that the experience he had of the world outside must have been a dream: having experienced nothing but his prison throughout his life, the prison is the only reality to him. So, Sigismundo deems the outside world not to be real.

### Predictive Processing, Constructive Perception

According to the theory of Predictive Coding, the ultimate goal of the brain is to minimize surprise (Friston, 2005, 2009). This allows for efficient responses to environmental changes, which is key for an organism to maintain homeostasis and survive. Therefore, the brain attempts to build the most precise and comprehensive model of the environment, and regularly updates the current one based on new experiences (Friston, 2005, 2009; Rao & Ballard, 1999).

In this framework, the brain constantly makes predictions based on *priors* -i.e., expectations about which occurrence is most likely to occur. These expectations are formed with varying degrees of certainty depending on how often we have experienced a particular situation that shares features with the current one. The more we encounter the same kinds of circumstances, the more stable our expectations about that situation will be.

Such predictions are made throughout the neural pathways of stimulus analysis (Friston, 2005; Rao & Ballard, 1999). Each level encodes expectations with a different degree of specificity, from strictly stimulus-related predictions (e.g., "this orange will look the same in a few moments") to general predictions (e.g., "if I bite this orange, it will taste acidic"). Some predictions are so abstract that they underlie any interaction with the environment (e.g., "I am the cause of my own actions"): they can be considered *core* predictions (Apps & Tsakiris, 2014; Connolly & van Deventer, 2017).

Any stimulus that meets expectations is quickly *explained away*. Yet, expectations are constantly violated: We might notice that a cloud has suddenly covered the sun on a clear summer day; we might reach up for the wallet in our pocket and find out it is not there, even if we are sure that we put it there; we might shockingly discover that our partner is cheating on us.

Such mismatches between priors and sensory inputs result in *prediction errors*. When a prediction error arises at a given level of the predictive system (i.e., the cloud covering the sun, the wallet not being in the pocket, the partner cheating), it is relayed to upper levels to be explained away by taking more factors into account, and by integrating it into a more global picture. For example, the prediction error arising from the missing wallet could be solved by recalling that we put it somewhere else. However, if the wallet is nowhere to be found, we will have to conclude that it was stolen or lost. This requires updating the cognitive model of our wallet. Still, this would be consistent with previous experiences, as we know that wallets are stolen frequently: it would not require an updated of the model of wallets in general. Sometimes, the extent to which expectations are violated is so great that an update at the highest levels is required: this is the case of a revolutionary invention like the airplane, which subverted people's model of transportation.

Friston (2005, 2009) provides an elegant and rigorous conceptualization of predictive coding as a hierarchical process. Given a sensory input (e.g., the acidic gustatory sensation after biting an orange orb), the brain would infer the causes of such input according to Bayesian principles (Slater, 2021). That is, the posterior probabilities of the causes would be computed from the prior probabilities (e.g., the knowledge on the taste of oranges) and from the likelihood that the causes would produce the input.

Friston argues that the prior probabilities are prior in a temporal sense but also in a structural sense: In light of the hierarchical organization of the human cortex, he maintains that the prior probabilities at each neural level stem from inferences at higher levels. That is, the causes explaining a given sensory input are in turn explained by more abstract causes at the higher level. This traces upwards the cortical levels: the highest the level, the more abstract the causes, with core causes at the top.

At each level, a *generative model* specifies the likelihood that candidate causes would produce the observed input. Combined with priors from higher levels, this yields the posterior probabilities that candidate causes are responsible for the input. The unexplained residual propagates upward as a prediction error. At higher levels, it is possible that more abstract causes are inferred so that the error is minimized (“I actually put my wallet here”), but it is also possible that the model needs to be changed so that the observed input would have a higher likelihood under it (“My wallet is lost”).

This theoretical framework leads to a counterintuitive idea: the top-down stream of information would correspond to the “forward” direction of the process through which the brain “generates” the causes of sensory data. Conversely, sensory inputs would correspond to feedback signals for adjusting the generative model. Those which we experience as the cause of our sensations may thus be top-down representations rather than the “true” causes. Ultimately, reality would be a postulate that best explains sensory inputs.

# Chapter 2

## Other Realities

*What is real? How do you define “real”? If you’re talking about what you can feel, what you can smell, what you can taste and see, then “real” is simply electrical signals interpreted by your brain.*

— Morpheus, *The Matrix* (1999)

*The Matrix trilogy* (1999-2003) by the Wachowski sisters can be considered as a modern, sci-fi version of Calderón de la Barca’s "La vida es sueño." The movies cast doubt on whether what we call reality is *truly* real: in fact, it could be a multi-sensory digital simulation. Of course, a digital environment of this kind, indistinguishable from the physical environment, is far from being achievable with current technology (assuming that our word with its technology is not itself a simulation). Yet, over the past decade, Virtual Reality technologies have advanced beyond what once belonged to the domain of science fiction and have now become accessible on the consumer market.

Arguably, what makes virtual reality (VR) stand out from “classical” media is its high immersiveness (Brooks, 2005; Jayaram et al., 1997). That is, users of VR applications have their senses stimulated by the digital environment in a way that approximates sensory experiences in the physical world, to the extent that they believe themselves *truly* in the digital world (Brooks, 2005; Sanchez-Vives & Slater, 2005; Slater, 2009). When users wear VR head-mounted displays, a three-dimensional digital scenario is rendered in a way that allows them to see digital objects from different angles depending on the point of view. This is just what happens when we observe physical objects. In many cases, the user can move and manipulate objects within a VR scenario in a way that feels natural (Brooks, 2005). Also, the user can hear sounds coming from specific sources in the digital scenario, as it happens in real life.

The years immediately following the COVID pandemic can be regarded as the heyday of VR. The concept of *metaverse*, in particular, was on everyone’s lips. A *metaverse* is defined as a persistent virtual environment that can be accessed by multiple users at the same time (Mystakidis, 2022). It is, in other words, a VR space for users to interact as if they are in the same location, even if they are physically far apart.

However, VR is not just a digital replica of a physical space. Besides technical limitations, the only constraint to the design of virtual environments is the inventiveness of the designer. This is showcased by many VR scenarios created by artists, such as the Museum of Other Realities (https://www.museumor.com/).

The forecasts for this technology were enthusiastic. In 2021, Bloomberg Intelligence predicted that the *metaverse* was going to be worth almost 800bn dollars by 2024 (Bloomberg Professional Insights, 2022), while Fortune concluded that it represented an opportunity of 8-13tr dollars (Fortune, 2022). KPMG even predicted that the virtual world was going to be as popular as mobile phones by 2030, so that we would be spending most of our waking time in it (KPMG, 2022).

It can be argued that these forecasts were, at most, overly optimistic. Yet, the sudden surge in public interest and the subsequent plummet is well predicted by Gartner Hype Cycle, which models the change in public enthusiasm for new technologies (Fenn & Raskino, 2008). Accordingly, every new technology generates an initial burst of enthusiasm, which then drops as people realize that their expectations were too optimistic. The model also predicts the technology to continue developing out of the spotlight, eventually becoming part of everyday life. Perhaps, this will apply to VR as well.

While the general public has turned its attention away, some applications of VR technologies are still promising. For example, VR is ideal for training purposes (Bliss et al., 1997; Kennedy et al., 2000; Mantovani et al., 2003; Pan et al., 2016). Also, VR was used for exposure therapy and treatment of psychiatric conditions, including: social anxiety (Pertaub et al., 2002), post-traumatic stress disorder (PTSD, Rizzo et al., 2015), acrophobia and other phobias (Freeman et al., 2018; Hoffman et al., 2003; see Bell et al. (2024) for a review).

Above all, VR is an ideal tool for research in the field of experimental psychology (Pan & Hamilton, 2018). It can overcome the problem of poor ecological validity that affects many experimental studies. That is, to keep confounding variables under control, academic research mainly takes place in a laboratory setting. This, however, raises questions about whether the results could be generalized to more complex, real-life situations. VR thus offers the ideal balance between mundane realism and experimental control (Blascovich et al., 2002): it enables researchers to create ecologically valid situations that are nevertheless under their full control.

Also, because VR is unconstrained by the limitations of the physical world, it enables scientists to address research question they can not address otherwise (Slater & Sanchez-Vives, 2022). For example, Seinfeld et al. (2018) made sexual offenders embody women who are being verbally abused in VR: this enhanced their empathy towards women. By the same token, embodying individuals of another ethnic group was shown to reduce racial prejudices (Peck et al., 2013) and increase a sense of complicity with that group (Hasler et al., 2017). Osimo et al. (2015) made participants embody Sigmund Freud to counsel themselves from a second-person perspective. This helped them see problems in a more detached way, leading to addressing their personal problems more effectively.

### Cognitive Aspects

Although one can feel immersed in a movie or in a video game to the extent of forgetting the physical world, only VR can create the impression of being physically in another place. That is, VR can make users feel as if they are in a digital environment (almost) the same way they feel in the physical world every moment. This feeling is called the sense of *presence* (Sanchez-Vives & Slater, 2005; Slater, 2009).

Studies show that participants indeed respond to VR events as they would in the physical environment. For example, participants standing by a precipice in VR show a physiological response that resembles the stress reaction to a real-life situation of this kind (Jordan & Slater, 2009; Zimmons & Panter, 2003). Slater et al. (2008) found that participants respond to a digital arm being hit as if it were their physical arm. Strikingly enough, Wiesing et al. (2025) found that participants confused a VR scene with a real-life scene: after seeing a tablet in a VR office, they expected the tablet to be in the physical counterpart of that office.

The reason why users experience presence VR might be the same reason why we feel present in the physical world (Slater & Sanchez-Vives, 2022). It is, again, a matter of Predictive Coding. If the eyes relay the image of a person moving their lips, while the ears relay the sound of a voice, the most likely explanation for this sensory stimulation is the presence of a person. If no sensory information contradicts this explanation, the brain behaves as if a person were there. This applies to both physical environments and VR environments. It doesn't even matter whether a person is *truly* there, as long as the expectations about a person being there are met, and thus inform an effective behavior. As mentioned earlier, there is no certainty that something is *truly* there even in the case of physical objects: we only interact with things through the Markov blanket of our senses. In sum, the sense of presence (in both a physical and a digital environment) results from coherent multi-sensory inputs that meet the brain's expectations about being in a given place.

A special case of multi-sensory congruence that induces presence in VR are *sensory motor contingencies* (Küçüktütüncü et al., 2025; Slater, 2009). This term refers to proprioception-vision coupling (Girondini et al., 2024; O'Regan & Noë, 2001a, 2001b). For example, if we decide to tilt our head, and thus feel the contraction of neck's muscles, we also expect to see the visual field rotating accordingly. When sensory-motor contingencies occur in VR, presence is reinforced.

Slater and colleagues (Küçüktütüncü et al., 2025; Slater, 2009) propose that presence should be broken down into three facets: *place illusion*: the feeling of being situated within the digital space, which in turn relies on sensory motor contingencies; *familiarity*: the similarity between the VR environment and physical places we have visited before; *plausibility*: the likelihood that the events in VR can truly occur. We speculate that sensory-motor contingencies, familiarity, and plausibility should be considered in the context of Predictive Coding simply as cases of expectations being met at different levels: from a perceptual level (sensory-motor contingencies) to a cognitive level (familiarity and plausibility).

Further factors that can reinforce the sense of presence are body ownership and interactivity. The former refers to the feeling of owning an *avatar* (i.e., the user's digital body) in the same way as we own our physical body (Slater et al., 2010). Again, this is a matter of multi-sensory stimulation (especially visual and proprioceptive) meeting expectations about owning one's body (Sanchez-Vives & Slater, 2005; Slater & Sanchez-Vives, 2022; Slater et al., 2010).

This idea is showcased by the *rubber hand illusion*, which predates VR (Botvinick & Cohen, 1998). Accordingly, participants can be tricked into believing that a manakin arm is in fact their arm. In this paradigm, they see the manakin arm being tickled in synchrony with their true arm, the latter being hidden from their sight. This produces the illusion of owning the fake arm to the extent that they startle if the fake arm is hit with a hammer. Noteworthy, the rubber hand illusion was also replicated in VR (Slater et al., 2008).

Again, sensory-motor contingencies may play a crucial role in the illusion of body ownership. That is, when we decide to reach for an object, and feel the movement of the arm through our proprioceptive receptors, we also expect to see the arm moving with our eyes. If these expectations are met, it creates the illusion of owning the arm, even if it is in fact the arm of a digital avatar.

Concerning interactivity, it can contribute to the sense of presence (Slater & Sanchez-Vives, 2022). When digital objects can be manipulated, and the digital environment reacts to the user's action, the brain's expectations about being in a real environment are met to a greater extent.

Finally, it should be noted that the level of detail and resolution of a digital environment were found to have little impact on the sense of presence (Sanchez-Vives & Slater, 2005; Zimmons & Panter, 2003). As argued by Guardini (2002), VR should be real enough to meet users' expectations about the appearance of a digital environment, yet attempting to maximize realism is often unnecessarily effortful.

### Technological Aspects

The first multisensory, immersive experience was conceived in the 60s: it was the Sensorama, a cinematographic apparatus combining videos with haptic, proprioceptive, and olfactory stimulation (Hamit, 1994). Specifically, a video from the point of view of a biker was paired with a vibrating chair simulating the vibrations of a motorbike, and with a fan mimicking the air stream. Odors were also released to replicate the smells of the environment through which the viewer was supposed to be driving.

The idea behind Sensorama is that the more senses are stimulated realistically and coherently, the more immersed viewers will feel in the fictional environment. If expectations across sensory inputs are met in a fictional scenario, fewer prediction errors would challenge the brain's explanation that the user is truly in that scenario. So, the illusion of presence will arise (Slater & Sanchez-Vives, 2022).

Modern-day VR headsets can be considered the inheritors of the Sensorama. They consist of a display worn like a pair of goggles, hence the name head-mounted display (HMD, (Brooks, 2005)). They provide audiovisual stimulation and can be regarded as the most basic setting for VR (but see Muhanna (2015) for an alternative apparatus: the CAVE). The most obvious difference between current VR experiences and classical video games is indeed in the visual mode.

First, current VR goggles exploit the principles of stereoscopy to recreate the impression of a three-dimensional space (Brooks, 2005; McKenna & Zeltzer, 1992). Accordingly, the brain infers depth in the physical environment by comparing the images relayed by the two eyes: because the eyes are a few centimeters apart, they record images of the same object from a slightly different perspective (Qian, 1997). For example, an object located on the left of the visual field will mainly show its front face to the left eye, while it will show a greater portion of its side face to the right eye. By displaying a slightly different image to each eye, VR goggles produce visual inputs coherent with a three-dimensional environment. In other words, the inputs comply with the brain's expectation about being in a three-dimensional space.

Second, VR headsets can track the position of the participant in the VR space and adjust the images shown on the HMD accordingly, in real-time (Brooks, 2005). This meets the predictions about a shifting point of view while navigating an environment.

Third, HMDs differ from traditional screens as the digital environment surrounds the users: the field of view of most VR headsets is normally 90-110 degrees in the horizontal dimension and 70-90 degrees in the vertical dimension (Brooks, 2005) - but still smaller than the field of view of the human eye (Nakano et al., 2021).

The auditory component can also play a role in creating the feeling of a three-dimensional space (Brooks, 2005; Hendrix & Barfield, 1996; Sanchez-Vives & Slater, 2005). Normally, the brain can localize a sound source based on the delay between the stimulation of the ears (Edmonds et al., 2013). For example, the sound waves produced by an object on the right of the body reach the right ear first. By exploiting this principle, the HDM's headphones can produce a pattern of auditory stimulation that the brain interprets as the sound of an object located at a specific position in the VR scenario. Together with volume differences and echo manipulation, this creates spatialized auditory experiences (Brooks, 2005).

Like the Sensorama, other senses can be implemented in VR: Suits worn by the VR users can replicate tactile sensations through electrical stimulation of the skin (Jones et al., 2004; Konishi et al., 2016); olfactometers can release scents in the air to recreate the smell of a specific environment (Archer et al., 2022); gloves can simulate the mass of a manipulated object by preventing the fingers from closing beyond the virtual volume of the object (Choi et al., 2017); a fan on the HMD can produce the sensation of air flow as in the Sensorama (Ranasinghe et al., 2017).

Noteworthy, a mismatch between sensory input not only diminishes the sense of presence, but it can also cause physical sickness (Dużmańska et al., 2018; Kennedy et al., 1993). When the body navigates a physical space, the movements of the visual fields match proprioceptive inputs signaling the movement of muscles. However, when navigating the VR space through the HMD's joysticks, leg stillness does not meet the brain's expectations. Sometimes, such a movement of the visual field in the absence of leg movements is interpreted by the brain as symptoms of poisoning, so vomiting is triggered in response (Treisman, 1977). This adverse effect, akin to other forms of motion sickness, is termed *cybersickness* (Dużmańska et al., 2018).

VR experiences and applications should be carefully designed to avoid cybersickness. This requires producing a pattern of proprioceptive stimulation cohering with the movement of the visual field during navigation. The ideal solution would be using VR in an area that is large enough for the user to move naturally. However, this is often unfeasible. The *Virtualizer* offers a clever alternative (Cakmak & Hager, 2014). It consists of a platform allowing for leg movements while the user is anchored to the spot through a harness. A more trivial solution, however, is to avoid the continuous movement of the visual field by letting users navigate the VR environment through teleportation.

In sum, VR can "trick" the brain into responding to a digital environment in the same way it would respond to a physical environment. It does so by producing a pattern of sensory stimulation consistent with previous experiences with the physical environment. This induces the brain to have expectations about a digital environment similar to those about a physical environment. However, VR also allows researchers to subvert such expectations in a way that would be impossible in the physical world. This can both help elucidate the predictive mechanisms underlying perception and have practical applications.

# Chapter 3

## Doing the Impossible

In line with Predictive Coding, the brain deems a given event impossible "simply" because its occurrence would contrast with all previous experience (Slater & Sanchez-Vives, 2022). If an impossible event were to occur nevertheless, it would require a dramatic update of predictive priors, and perhaps call into question so-called *core* predictive models (Apps & Tsakiris, 2014; Connolly & van Deventer, 2017). By inducing this, researchers would have the opportunity to test the predictive apparatus of the brain in extreme conditions, and clarify how the experience of reality is constructed.

However, most impossible scenarios one can conceive are, tautologically, impossible to create in the physical world. Yet, experiencing something forbidden by the laws of our universe might not be necessary for the purpose of challenging foundational cognitive models. What matters is to contradict everything experienced so far. Indeed, physical impossibility does not imply expectancy violation: a fantastic event in a fantasy novel is, in fact, perfectly in line with all previous experiences with this literary genre. Conversely, it would be necessary to violate expectations that apply not only to real life but also to fiction. Or to make fiction experienced as real life. VR is arguably the best candidate to achieve this.

Various authors showcased how VR can be used to create situations that would be impossible in the physical world. For example, Rosenberg et al. (2013) developed a virtual experience in which participants were able to fly. Friedman et al. (2014) enabled participants to go back in time and change past events. Steptoe et al. (2013) made participants embody humanoid characters with a tail. Ritter et al. (2012) designed three virtual environments that violated the laws of physics: in the first scenario, objects became smaller -rather than bigger- when approached; in the second scenario, participants' steps made them move faster than they would in the physical world; in the last scenario, gravity pointed upwards. In sum, VR seems ideal for creating impossible scenarios (Chirico et al., 2022; Gaggioli et al., 2016; Slater & Sanchez-Vives, 2022; Wiseman & Watt, 2022).

As mentioned earlier, however, designing unexpected VR scenarios requires a nuanced understanding of people's expectations, which might not be so obvious. This point is highlighted by Slater and colleagues: on the one hand, medical practitioners who were tasked to counsel digital patients in VR complained about not having a functioning computer on their desk (Pan et al., 2016); on the other hand, participants were not so shocked by seeing a floating whale in a VR mall (Freeman et al., 2018).

The explanation could be that expectations about a given situation in VR include both lower-level expectations about the situation itself and higher-level expectations about being in a VR scenario (Slater & Sanchez-Vives, 2022). Therefore, VR users do expect to experience situations that they would never experience in the physical world: after all, users know that VR scenarios are developed by humans (Slater & Sanchez-Vives, 2022). Because movies and video games have exposed people to the possibility of fantastic events occurring in fictional worlds, such events in VR might be perceived as both plausible and familiar.

Again, the key would be to violate expectations so fundamental that they apply to VR as well. For instance, doctors might still expect to use a computer while consulting with a patient in VR, even if the patient looked like an alien creature. More generally, it can be speculated that people expect some laws of our universe to hold even in a fantasy scenario. For example, they may expect the geometry of a digital space to reflect the Euclidean geometry of the physical space. Yet, spaces with a different type of geometry are theoretically possible and can be created in VR.

## non-Euclidean Geometry in VR

The geometry of our living space accords with Euclid's postulates. In particular, Euclid's 5th postulate predicts that, given a straight line and a point not on it, only one line parallel to the given line can be drawn through the given point (Playfair, 1846). The common-knowledge assumption that parallel lines never meet follows from this. Nonetheless, mathematicians have theorized spaces that violate the 5th postulate: In *hyperbolic* geometries, parallel lines diverge (Fenchel, 1989; Sommerville, 1914); in *elliptic* geometries, parallel lines converge (Sommerville, 1914).

Some authors succeeded in creating these impossible geometries in VR. For example, Hart et al. (2017) simulated hyperbolic geometries. Also, Strickrodt et al. (2018) and Warren et al. (2017) developed non-Euclidean mazes with impossible shortcuts. The latter studies aimed to highlight that our cognitive maps are geometrically inconsistent. In one case (Warren et al., 2017), none of the participants acknowledged the presence of wormholes, while in the other case (Strickrodt et al., 2018), only half did.

To overcome the limitations of exploring a VR environment from a small physical space, Suma et al. (2012) created non-Euclidean rooms that overlapped to different extents. Participants, who had been previously informed of this, were asked to report whether they had noticed the overlap. Similarly, Auda et al. (2022) tested non-Euclidean VR rooms with different levels of overlap. Participants were asked to perform a task in VR without being informed of the spatial incongruence. Subsequently, participants were interviewed to reveal whether and at which level they had noticed the anomaly. Out of twelve participants, eight reported that the VR environment was impossible.

The awareness of non-Euclidean, overlapping rooms was also investigated by Robb and Barwulor (2021). Although not discussed explicitly, their results have interesting implications. When participants had to estimate the size of the two overlapping rooms separately (i.e., using a different graphic interface for each room), their estimations were similar to those of the participants who navigated an area consisting of two rooms on different floors. However, when the participants had to estimate the dimensions of the two rooms simultaneously (i.e., using the same interface for both rooms), they estimated them as significantly smaller than the control participants. This suggests that participants made the rooms smaller to prevent the impossible overlap - even though the interface did allow the rooms to overlap. Perhaps, participants were aware of the real dimensions of the rooms (as can be inferred from the estimations with separate interfaces), yet the dimensions were adjusted to be consistent with Euclidean geometry.

At the end of the session, only two participants spontaneously reported that the space was impossible. However, as soon as participants were informed of it, many recalled having the impression of something odd (Robb & Barwulor, 2021).

The variability in reporting the non-Euclidean anomalies suggests that individuals differ in their tendency to update fundamental cognitive models, and cognitive models in general. This may uncover the opportunistic nature of the brain's model of reality, so that a parsimonious representation is preferred over an accurate representation if the former still allows for an efficient response (Friston, 2005, 2009; Kaaronen, 2018).

Notably, studying the different responses to impossible scenarios can not only clarify the mechanisms of predictive processing in the brain but also has practical applications. Indeed, it can help understand the impact of out-of-the-ordinary experiences on creativity.

## Cognitive Update and Creativity

The term *diversifying experience* (DXs) refers to experiences that contradict previous expectations, preconceptions, and cognitive models; it was introduced in the context of creativity research because such out-of-the-ordinary experiences were found to promote creativity (Gocłowska et al., 2018; Ritter et al., 2012).

In turn, creativity can be defined as the ability to produce new conceptual combinations that are useful or meet specific requirements (Runco & Jaeger, 2012). While laypeople may associate it with the arts, creativity is in fact crucial to solve all kinds of *ill-defined* problem, namely problems to which no heuristic applies (Newell & Simon, 1972; Nijstad et al., 2010; Pisapia & Rastelli, 2022).

Highly creative people often faced disruptive events and had turbulent personal backgrounds (Martindale, 1972; Simonton, 1999). For example, Martindale (1972) reports that 30% of poets had absent fathers. Similarly, first or second generation immigrants, who were thus fostered in a multicultural and diverse environment, show high creativity (Simonton, 1999).

Moreover, Maddux and colleagues found that students who had multicultural experiences were more creative than students who did not, especially when students actively engaged in the foreign culture (Maddux & Galinsky, 2009; Maddux et al., 2010). Multiculturalism may benefit creativity by promoting the integration of seemingly contradictory elements, and cultural shock may force foreigners to challenge their cultural norms and assumptions, integrating new elements into a more complex worldview (Chirico et al., 2022; Leung & Chiu, 2008, 2010; Maddux & Galinsky, 2009; Maddux et al., 2010).

By the same token, acknowledging the narrowness of one's mental frames, manifesting the need to accommodate radically new information and experiences, can increase creativity (Beghetto, 2021; Chirico et al., 2018, 2020). This often occurs when facing the vastness of the world both physically and conceptually (Chirico et al., 2016). Such experiences range from zero gravity in space to the birth of a child, and are often associated with a sense of awe.

In general, it can be hypothesized that DXs affect creativity because they let individuals discover unprecedented connections between ideas, and prompt a cognitive restructuring to resolve the violation of the prior schemata (Chirico et al., 2022; Leung & Chiu, 2010; Maddux & Galinsky, 2009; Maddux et al., 2010).

In line with this, Bieth et al. (2024) provide evidence of the relationship between knowledge restructuring and creative problem solving. The authors asked participants to solve riddles that required bridging seemingly unrelated concepts. After the riddles were solved, the authors found a reorganization of the semantic associations between the riddle's elements. Also, knowledge restructuring is crucial for overcoming a creative *impasse* (Tulver et al., 2023). Indeed, an insight occurs after the problem is re-framed such that, for example, new connections are created between its elements (Tulver et al., 2023).

However, if DXs do induce knowledge reorganization, it is worth wondering whether the effect only pertains to the elements of the experience itself or a broader set of elements: does experiencing zero gravity enhance creativity just in the domain of physics?

Experimental evidence suggests that integrating distant information affects creativity broadly and non-specifically. For example, creativity exercises that require connecting incompatible elements produce a generalized creativity boost (Ma, 2006; Miron-Spektor et al., 2011; Wan & Chiu, 2002). Also, incongruous pictures increase the score at standardized creativity tests (Gocłowska et al., 2014), while task-unrelated images can help designers produce more creative outputs (Brun et al., 2019). These findings suggest that cognitive model violations can increase creative thinking in general, so that the effect of DXs may underlie mechanisms beyond the mere acquisition and integration of new information.

In light of this, it might be tempting to speculate that DXs produce a generalized restructuring of semantic networks, which would improve the ability to produce new remote associations in general (Hills & Kenett, 2022; Kenett & Faust, 2019). Nevertheless, evidence that novel associations between elements trigger a general semantic reorganization is wanting. Bieth et al. (2024) found that solving riddles did not affect connections between elements that were irrelevant to the riddle, which suggests that knowledge reorganization in a given domain does not necessarily extend to other domains.

An alternative explanation is rooted in the flexibility-persistence dichotomy, whose interplay is thought to play a pivotal role in creative processes (Boot et al., 2017; Jauk, 2019; Nijstad et al., 2010). On the one hand, flexibility refers to the exploration of many possible solutions by switching between different conceptual categories. On the other hand, persistence refers to the attentive and thorough exploration of solutions within a given conceptual category. This dichotomy, in turn, relates to a broader theory of cognition as a trade-off between exploratory and exploitative states of mind (Herz et al., 2020; Ivancovsky et al., 2024).

Accordingly, cognition is hypothesized to shift between exploration and exploitation to adapt to the demands of current circumstances (Ivancovsky et al., 2024). Predictable environments and task engagement would favor an exploitative mode, characterized by low distractability, focused attention, and reliance on previous knowledge. Instead, novel environments and task disengagement would favor an exploratory behavior, which entails environmental monitoring, broad attention, and information update.

When focusing on a well-known task, it is more advantageous to stick to a validated strategy and avoid distractors. In this case, persistence is favored. In a novel or volatile environment, instead, it would be advantageous to consider various behavioral strategies and update behavior continuously. In this case, flexibility is preferable.

By uncovering the narrowness of one's cognitive models and behavioral repertoire, DXs manifest the need for a cognitive update and new behavioral strategies, encouraging the exploration of novel possibilities to solve unexpected challenges. This, in turn, may bias cognition in the direction of flexibility (Boot et al., 2017; Ivancovsky et al., 2024; Jauk, 2019): it may broaden the scope of attention and reduce latent inhibition of seemingly unrelated ideas, so that more ideas can be considered and integrated. This helps resolve apparent contradictions and informs new behavioral strategies. According to Beghetto (2021), facing uncertainty is actually the primary cause of creative behaviors.

While past research on DXs focused on multicultural experience (Leung & Chiu, 2010; Maddux & Galinsky, 2009; Maddux et al., 2010), the epitome of a DX would be witnessing an event that was believed impossible, which can be achieved through VR (Chirico et al., 2022; Gaggioli et al., 2016; Wiseman & Watt, 2022).

Indeed, Ritter et al. (2012) found that physically impossible experiences in VR positively affect creative thinking. The authors report a significant difference in creativity between the impossible scenarios and control VR scenarios - where no expectations were violated. While providing promising evidence, Ritter et al. (2012) did not compare the post-VR score with baseline scores. Thus, direct evidence for an increase in participants' creativity was not provided. Also, and perhaps more importantly, the cognitive mechanisms underlying the creativity boosting effect of DXs was not investigated explicitly. A causal relationship between expectancy violations and creativity is assumed, yet awaits experimental validation (Wiseman & Watt, 2022).

Given that psychedelic substances are purported to enhance creativity (Gandy et al., 2022; Girn et al., 2020; Sessa, 2008). Riva and coworkers (Brivio et al., 2020; Brizzi et al., 2025; Greco et al., 2025) produced psychedelic-like VR experiences and tested whether they had this effect. The VR experience was developed by feeding an immersive video clip to a modified convolutional neural network that simulates visual hallucinations (Suzuki et al., 2024). The authors found that the hallucinatory video enhanced creativity when they used a within-subject design (Brizzi et al., 2025; Greco et al., 2025) but not a mixed design (Brivio et al., 2020).

Importantly, while Riva and colleagues aimed at mimicking the putative effects of psychedelics on creativity, such substances act by reducing the strength of predictive priors that constrain sensory information (Girn et al., 2020), whereas the hallucinatory immersive videos was speculated to do just the opposite (Greco et al., 2021): the unexpected pattern of sensory stimulation produced by the video increased the prediction error signal. In other words, viewing hallucinatory videos in VR might be more similar to having DXs than genuine psychedelic experiences. Because such videos were developed specifically as a simulation of the psychedelic phenomenology, they do not allow conclusions to be drawn about the effect of DXs in general.

In sum, although odd or even impossible experiences in VR were found to positively affect creativity, the cognitive mechanisms underlying this effect is unclear. To address this, it would be first of all necessary to dissect how the brain responds when fundamental predictive models are violated, and elucidate the mechanisms driving the update of such models.

## Personality Traits, Model Updating, and Creativity

Assuming that the need for a cognitive update underlies the effects of DXs on creativity (either by inducing semantic network reorganization or an exploratory state of mind), the fact that people may resist cognitive updates to different extents implies that the effect of DXs may vary (Gocłowska et al., 2014, 2017; Kaaronen, 2018).

Indeed, schema violations have different effects on different individuals: they may favor creativity in some cases, but they might be detrimental in other cases (Gocłowska et al., 2014, 2017). This seems to depend on personality traits, such that more open-minded individuals would benefit from schema violations, while narrow-minded individuals would not (Leung & Chiu, 2008, 2010; Wiseman & Watt, 2022).

For example, Gocłowska et al. (2014) argue that the effect of schema violations on creativity is influenced by Personal Need for Structure (PNS). This trait captures how strongly individuals prefer clear, consistent mental frameworks and predictable situations, and dislike when expectations are disrupted (Thompson et al., 2013). Gocłowska et al. (2014) found that schema violations enhance creativity when PNS is low but diminish creativity when PNS is high.

Note that Gocłowska et al. (2014) manipulated schema violation by showing participants incongruous pictures (e.g., an Eskimo in a desert background): While their results are revealing, the authors did not assess whether personality modulates the effect of DXs - a picture can hardly be considered as such.

Instead, Leung and Chiu addressed the effect of personality traits specifically on DXs (Leung & Chiu, 2008, 2010). For example, they investigated the effects of Need for Cognitive Closure. This trait refers to the preference for firm answers and the dislike for ambiguity, and can be considered akin to PNS (Thompson et al., 2013). They found that high Need for Cognitive Closure reduced the effect of multicultural experiences on creativity (Leung & Chiu, 2010). If the creativity boost requires challenging preexisting schemata, the difference may indeed depend on a higher or lower tendency to do so.

On the contrary, Leung and Chiu found that multicultural experiences enhance creativity to a greater extent in students with higher Openness to Experience (OE; Leung and Chiu, 2008). High OE scorers are curious, attracted to unconventional ideas and people, and actively engage with novel experiences (John et al., 1991). Accordingly, Gocłowska et al. (2017) found that participants with high OE enjoy expectancy violations.

Also, it should be noted that the exploratory tendency mentioned earlier is not only a state but also a trait: the latter is the case of high OE scorers (Ivancovsky et al., 2024). It implies a flexible cognitive mode and malleable mental frameworks, which can be easily updated to accommodate novel information. This could, theoretically, explain why high OE individuals benefit from DXs to a greater extent.

In general, when confronted with a violation of their preexisting models, some individuals might attempt to solve the cognitive dissonance by updating the models, while others may avoid the dissonance by suppressing the prediction error (Kaaronen, 2018). If the creativity boost results from challenging preexisting models and acknowledging the need for cognitive restructuring, whether or not the prediction error is suppressed might be crucial.

## Overview of the Present Research Project

The studies described in the following sections elucidate the cognitive response to DXs. We believe that Virtual Reality (VR) is the ideal tool to recreate and study these experiences. Specifically, We designed a VR experience that violates such a foundational expectation as the geometry of space: a non-Euclidean VR scenario.

Previous studies that employed this kind of scenarios for various reasons report that some participants did not notice the incongruous geometrical layout. The lack of awareness of the spatial incongruence might, in turn, underlie a suppression of the prediction error which is caused by the mismatch between the scenario and the cognitive model of space. So, we decided to focus on clarifying how individual differences make participants more or less likely to acknowledge a violation of a foundational predictive model. This matter had not been adequately addressed before.

The line of research begins with an assessment of the role of individual differences in reporting the expectancy violation (Study 1), continues with the development of objective physiological measures of such violation (Study 2), and concludes with a cross-validation between explicit and implicit measures (Study 3).

More specifically, Study 1 preliminarily explores how individual differences influence the likelihood of reporting the incongruous geometry of a non-Euclidean VR environment (Serrao et al., 2025). The research question can be formulated as follows: Do personality traits make people more or less inclined to challenge and update fundamental cognitive models, such as the geometry of space?

To address the limitations of subjective reports, we performed study 2 in order to validate a reliable, quantitative, and real-time measure of prediction errors and expectancy violations in a naturalistic VR environment. We wondered: Is it possible to objectively detect prediction errors in VR using physiological biomarkers such as pupillometry?

Building upon that, study 3 sought to replicate the findings of study 1. Critically, we used pupillometry to confirm that participants who did not report the anomaly were indeed unaware of it. We asked: How do subjective and physiological measures converge in detecting expectancy violations and cognitive updating, and how do individual differences modulate this process?

Future directions of research are discussed. We outline an experimental paradigm to directly test the effect of model updates during DXs on creativity performance, and the role of personality traits in modulating the effect.

# Chapter 4

# Qualitative Assessment of Individual Differences in Processing non-Euclidean Geometry in VR (Study 1)

The expectation that our surrounding space is Euclidean has been confirmed throughout our lives. So, a non-Euclidean environment allows for testing the likelihood of challenging a foundational cognitive model of reality. We assumed that participants' omission of any reference to the spatial incongruence indicated that they had not noticed it. This, in turn, can be interpreted as a resistance to questioning the long-standing model of space as Euclidean. The limitations of this approach are addressed in the discussion and in study 3.

We hypothesized that a more rigid mindset correlates with a lower tendency to become aware that the environment is impossible. Indeed, Bressan et al. (2008) found that people with stronger religious beliefs tend to neglect violations of their expectations. On the other hand, we expected that participants with an exploratory disposition would have been more likely to acknowledge the spatial incongruence (Gocłowska et al., 2017).

Additionally, we hypothesized that participants process the elements of the incongruous environment even when they do not integrate such elements into an incongruous whole, as found by (Robb & Barwulor, 2021). If this is the case, it will suggest that the absence of acknowledgment of the anomaly does not stem from participants failing to perceive the contradictory elements, but rather from the suppression of a prediction error that would otherwise conflict with a core predictive model.

## Methods

### *Experimental Design*

We employed a between-subject design. We planned to compare two groups: one experiencing a non-Euclidean scenario and the other group experiencing a Euclidean version of the same scenario. However, given the exploratory nature of the study, we developed two different non-Euclidean scenarios -hyperbolic and elliptic- with the respective Euclidean counterparts. Note that each non-Euclidean scenario was only tested against the respective Euclidean scenario. In other words, we carried out two tests separately and in parallel: hyperbolic vs the matching control, and elliptic vs the matching control.

### *Participants*

The study was conducted in compliance with the principles of the Declaration of Helsinki (World Medical Association, 2013) after the favorable opinion of the ethics committee at the University of Milano Bicocca. Because the study was conceived as a pilot, we did not perform a power analysis. Instead, we aimed to recruit as many participants as possible. Participants were Psychology students at University of Milan Biccoca and applied spontaneously through an online recruiting platform in exchange for university credits.

We had previously observed that senior participants often have trouble with the VR control system and with the VR apparatus in general. So, we recruited participants between 18 to 35 years old. Potential participants currently suffering from epilepsy were not eligible. Also, before enrolling in the study, participants were asked to fill out the Cybersickness Susceptibility Questionnaire (CSSQ, 18 items, Cronbach's $\alpha$ = 0.87; Freiwald et al. (2020)) to assess whether they had experienced motion sickness in their childhood. Participants with a total score higher than 10 were not enrolled as they have a higher tendency to experience cybersickness (Treleaven et al., 2015).

We initially recruited 20 participants who were randomly assigned to either the hyperbolic scenario or its Euclidean counterpart, and 20 participants who were assigned to either the elliptic scenario or its Euclidean analogue. However, several issues arose with the elliptic scenario, so we decided to drop it together with its Euclidean counterpart. After that, we kept recruiting participants for the hyperbolic scenario and its control, so that further 15 participants were enrolled for the latter conditions. In sum, we ended with 20 participants ($M_{Age}$=21.60; Female = 18, Male = 2) assigned to the elliptic condition and to the respective control condition, and 35 participants ($M_{Age}$ = 24.32; Female = 23, Male = 12) assigned to the hyperbolic condition and to the respective control condition.

### *VR Scenarios*

The two non-Euclidean VR scenarios and their two Euclidean counterparts were developed with Unity engine (version 2020.3.27f1). In all four cases, the virtual area consists of a main rectangular room from which two parallel corridors can be accessed (Figure 1). These corridors are connected through a transverse corridor on the other end, resulting in a rectangular path.

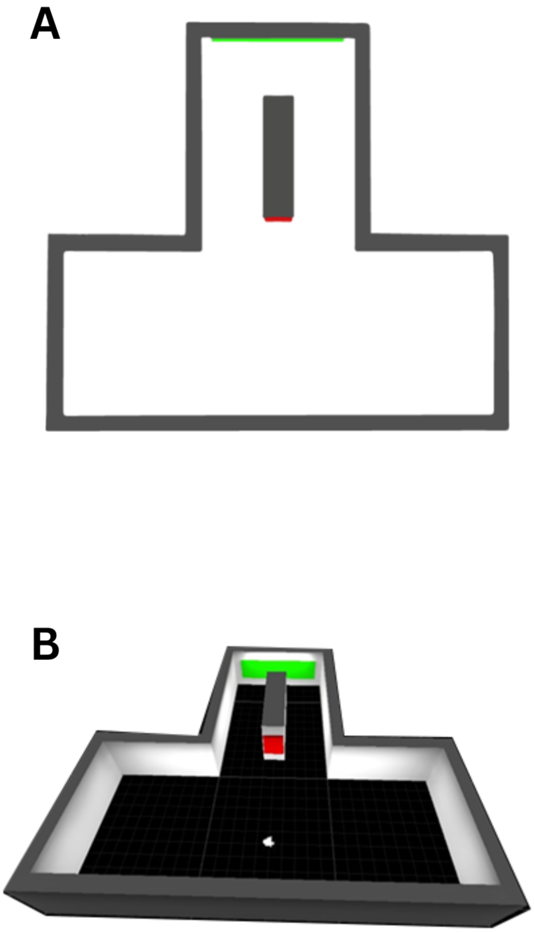


**Figure 1.** Map of the virtual area in the Control condition (A), featuring the position of the red and green panels, and 3D view of the Control environment (B).

In the two non-Euclidean conditions, the parallel corridors are not perpendicular to the transverse corridor: in fact, they form so-called Saccheri quadrilaterals (Saccheri, 1920) with divergent parallel sides (hyperbolic experimental condition, Figure 2) or convergent parallel sides (elliptic experimental condition, Figure S1).

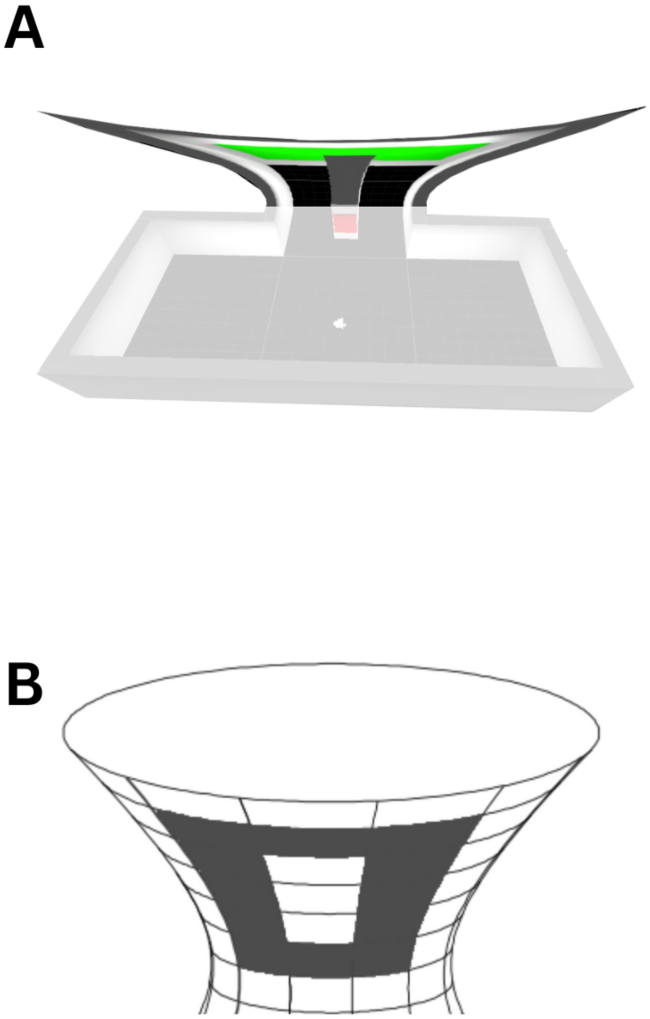


**Figure 2.** Attempt to describe the participant's experience of the hyperbolic environment (A): the longitudinal corridors are both parallel and divergent. They violate Euclid's 5th postulate, forming a non-Euclidean shape called the acute Saccheri quadrilateral (B). Please note that this is not the true map of the 3D scenario, since a non-Euclidean environment cannot be depicted in 3D.

When looking through the parallel corridors from the main room, participants would expect that the length of the hidden portion of the transverse corridor equals the width of the structural element hiding it (i.e, the block bearing the red panel, Figure 1). This belief is reinforced by the two ends of a green panel on the partially-hidden wall of the transverse corridor: in line with the Gestalt principle of good continuity (Palmer, 2003), participants expect the two green ends to be part of a single, rectangular panel. These expectations apply to all conditions, yet they are violated in the non-Euclidean conditions: when participants turn the corner and enter the transverse corridor from either parallel corridor, they find that the transverse corridor is four times longer than expected (hyperbolic condition, Figure 3), or four times shorter than expected (elliptic condition, Figure S1). In the corresponding control conditions, the transverse corridor is as long as it can be expected from the outside.

Note that the overall VR area in the elliptic condition (and, consequently, in the corresponding control condition) is bigger than in the hyperbolic condition: This was done because, otherwise, the convergent parallel corridors would have converged into each other, leaving no room for the transverse corridor.

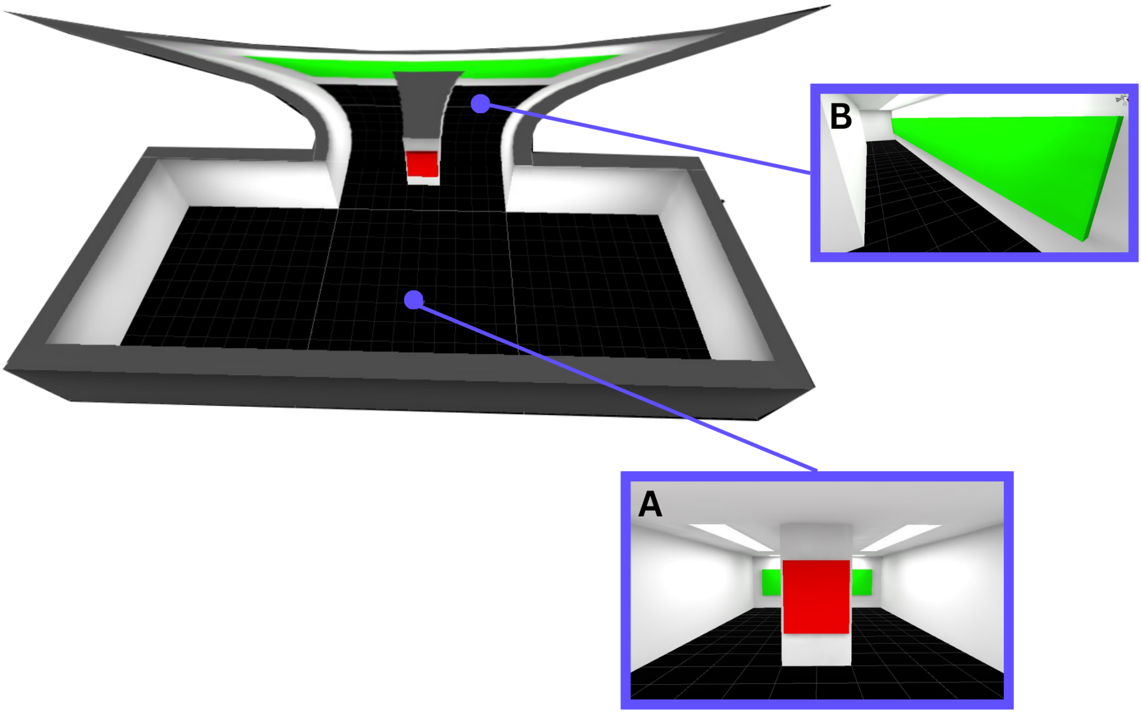


**Figure 3.** View of the green panel from both the main room (A) and from the inside of the transverse corridor (B).

### *Assessment of Spatial Perception and Awareness*

We tested participants' perception of the spatial elements of the VR scenario. Specifically, we wanted to assess participants' perception of the length of the transverse corridor, whose true dimensions are incompatible with Euclidean geometry. We did so indirectly, by asking participants to evaluate the size of the green panel located on the wall of transverse corridor (Figure 1). This panel is, indeed, proportional to the transverse corridor, which, in turn, is larger than expected in the hyperbolic condition (Figure 3), and shorter than expected in the elliptic condition (Figure S1). Consequently, the width of the green panel differs between each non-Euclidean scenario and its Euclidean counterpart.

As a control, we also asked participants to estimate the width of the red panel, which is located in the main room and is consistent between each non-Euclidean scenario and its control conditions (Figure 1). This method was inspired by Robb and Barwulor (2021), who asked participants to estimate the size of the overlapping rooms and compared the estimates between a non-Euclidean condition and a control condition.

We also assessed the awareness that the scenario is impossible in a qualitative way. That is, we asked participants to sketch a map of the scenario on paper. This task was mainly meant to prompt a reflection and discussion on the geometry of the virtual area, giving those who had noticed the incongruence the opportunity to report it.

Yet, we also analyzed the sketches themselves and their proportions. Specifically, we were interested in the proportions and angles of the transverse corridor with respect to the rest of the map. Because it is impossible to represent the real proportions of the non-Euclidean area, we expected those who would have noticed the incongruence to draw divergent or convergent parallel corridors on the map. Therefore, we expected the presence of non-right angles on the map to reflect the awareness of the incongruence.

### *Procedure*

Participants entered the VR environment through an Oculus Meta Quest 2 HMD. First, they found themselves in a training VR room on a Segway scooter, and learned how to navigate the area on it. The use of a vehicle was meant to minimize the likelihood of cybersickness as it helps the brain explain the movements of the visual field in the absence of body movements.

Note that we could not let participants move through teleportation, as the correct assessment of distances was deemed to be crucial for noticing the spatial incongruence.

After the training, participants entered the experimental area and found themselves in the main room. They were instructed to navigate the digital space to collect 6 sets of 7 numbered tokens located at pseudo-random positions - the tokens were positioned to guide the exploration of the area. The performance of the participant was not monitored: the task was merely instrumental to prompt navigation.

At the end of the task, participants were asked to estimate the width of the red and green panels located in the virtual area they had just left (Figure 1). Each estimation was performed in a separate VR room: participants were asked to replicate the correct size of the target panel by enlarging or shrinking a panel of the same color.

Then, they removed the HMD and completed three questionnaires on the Qualtrics online platform (https://www.qualtrics.com). We first assessed whether and to what extent participants experienced cybersickness during the VR experience through the Italian version of the Simulator Sickness Questionnaire (SSQ, Kennedy et al. (1993)). In this questionnaire, participants are asked to indicate the severity of 16 cybersickness symptoms (e.g, “nausea”) on a 4-point Likert scale (0 =*Not at all*, 3 = *Severe*), with a maximum possible score of 235.62.

Then, we assessed personality traits of the participants using two questionnaires. The Personal Need for Structure questionnaire (PNS, Cronbach’s $\alpha$=0.84; Thompson et al. (2013)) quantifies the rigidity of mental schemata, the preference for predictability, and the dislike for expectancy violations. Participants are asked to express the extent to which each of the 12 items (e.g, “It upsets me to go into a situation without knowing what I can expect from”) applies to their personality on a 6-point Likert scale ( 1 = *Strongly Disagree*, 6 = *Strongly Agree*). The maximum score is 72. This test was administered in Italian (Vannucci et al., 2011).

We also assessed Sensation Seeking (SS), namely the tendency to seek unusual and intense experiences (Zuckerman et al., 1993). We administered the abbreviated version of the SS Scale (8 items, Cronbach’s $\alpha$=0.73; Zuckerman, 2014). Participants were required to mark the extent of their agreement with each of the 8 items (e.g, “I like wild parties”) on a 5-point Likert scale ( 1 = *Strongly Disagree*, 5 = *Strongly Agree*). The maximum score is 40. We assessed SS in Italian (Primi et al., 2011).

Note that we initially preferred to quantify the enjoyment of novel experiences and the exploratory disposition through SS instead of OE. Indeed, the latter is considered a rather broad psychological construct: it captures not only preferences for novelties and schema violations but also, for example, aesthetic sensitivity, intellectual curiosity, and emotional depth (Gocłowska et al., 2017). SS, on the other hand, was deemed more suitable for capturing the tendency towards exploration, which, in turn, may entail cognitive flexibility and a greater likelihood to challenge preconceptions (Ivancovsky et al., 2024).

Finally, participants were asked to sketch a map of the experimental area on a sheet of graph paper. This type of paper was meant to aid participants in drawing the map with the intended proportions, and also facilitate the measurement of the angles' amplitude.

## Results

### *Hyperbolic scenario*

Participants who were assigned to the hyperbolic non-Euclidean condition and its Euclidean counterpart experienced relatively low levels of cybersickness ($M_{S}SQ$ = 35.16, $SD_{S}SQ$ = 30.03). Among those in the non-Euclidean group (*N* = 17), four verbally acknowledged that the transverse corridor was longer than it could be in the physical world. Two of these participants drew maps with divergent parallel corridors (Figure 4A,B), one drew divergent parallel corridors and a long transverse corridor that overlaps a smaller corridor (Figure 4C), and one sketched a transverse corridor with a missing segment (Figure 4D). In sum, we realized that drawing divergent corridors was not the only way to represent the hyperbolic environment. So, the amplitude of the angles was ineffective in capturing the awareness of the geometric incongruence. A further participant drew a puzzling map (Figure 4E). Because he was not fluent in any of the languages spoken by the experimenters, it was unclear whether he had noticed the incongruence. Therefore, this participant was excluded.

The remaining 13 participants who had been assigned to the non-Euclidean hyperbolic condition did not report the geometric incongruence. They sketched maps that represented the Euclidean counterpart of the scenario and, indeed, their sketches were indistinguishable from those of the control group (e.g., Figure 4F).

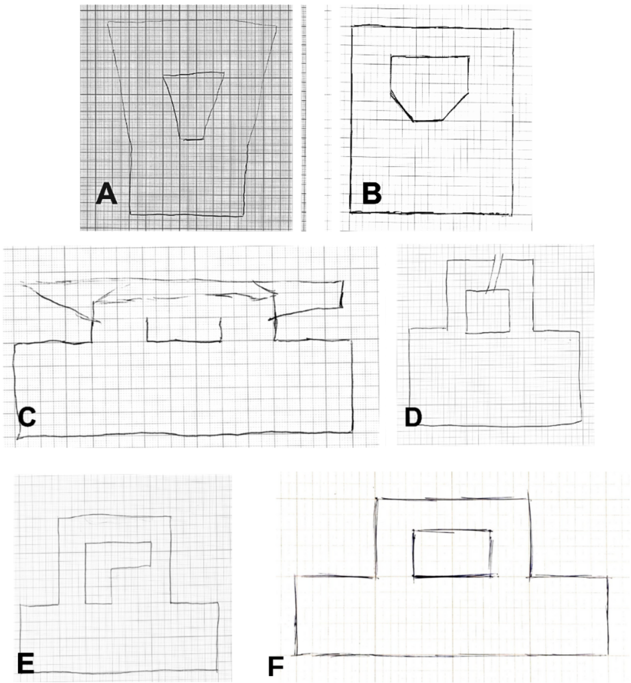


**Figure 4.** Participants who reported the spatial anomaly represented it in different ways. Three of them (A, B, C) drew divergent parallel corridors, resembling a Saccheri quadrilateral. One (D) drew the transverse corridor with a missing segment. Finally, one participant drew a puzzling map (E). Participants in the non-Euclidean condition who did not report the incongruence, as well as participants in the Control condition, drew maps that mirror the layout of the environment in the Control condition (F).

First, we investigated whether the individual differences among participants in the non-Euclidean hyperbolic condition, correlated with awareness of the incongruence (0 = not reported, 1 = reported). Despite only 4 participants noticing the geometric anomaly, we found that those who acknowledged it had significantly lower PNS ($\chi^2(1) = 5.93$, $p$ =.015, $OR$ = 0.089, Figure 5). On the other hand, no relationship with SS emerged ($\chi^2(1) = 1.46$, $p$ = .227, $OR$ = 1.153).

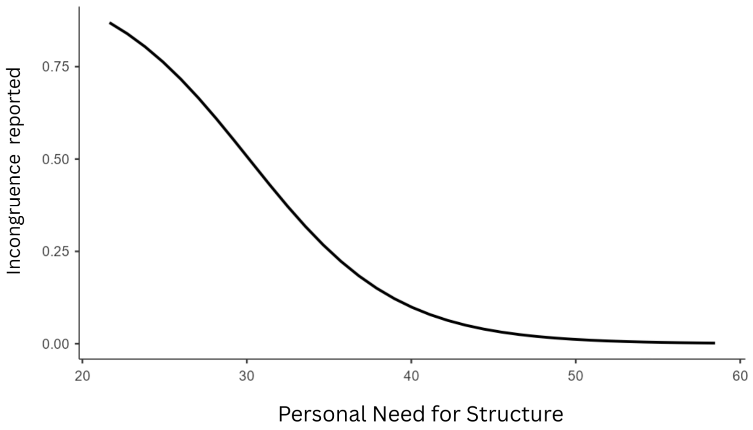


**Figure 5.** Probability of not reporting the spatial anomaly as a function of Personal Need for Structure

Also, we noticed that all participants who reported the incongruence were males, and we wondered whether gender played a role in the probability of reporting it. Indeed, we found a significant effect, such that males were significantly more likely to report than females ($\chi^2(1) = 7.53$, $p = .006$).

Then, we investigated how the hyperbolic space had been processed in the absence of awareness of its anomalous geometric features. For this analysis, we considered both the non-Euclidean hyperbolic group and the matching control group ($N = 35$). Yet, we obviously excluded the four participants who reported the incongruence, and the one who might or might not have noticed it (see above).

Because the green panel was bigger in the hyperbolic condition compared to the Euclidean counterpart, we assessed whether participants in the hyperbolic condition who did not report the anomaly still estimated the green panel as larger than the control group did. Note that the real size of the green panel in the non-Euclidean hyperbolic condition is incompatible with a Euclidean space (Figure 2). As a control, we also compared the estimation of the red panel across the two groups.

In addition to the participants who reported of the incongruence, two more participants were excluded from this analysis since they estimated the green panel as smaller than the red panel: Because the green panel is bigger than the red panel both in the hyperbolic condition (from any perspective) and in the control condition, it was unclear whether they had confused the two panels or estimated at random. Without these two participants, we were left with a final sample of $N = 28$.

We performed an independent sample t test with Welch correction. The estimation of the green panel's width in the hyperbolic condition was significantly larger compared to the Euclidean counterpart ($t(14.4) = 2.17$, $p = .047$, *Cohen's d* = .846, Figure 6A). On the contrary, we found no difference between the two groups in estimating the width of the red panel ($t(12.7) = .878$, $p = .396$, *Cohen's d* =.344, Figure 6B).

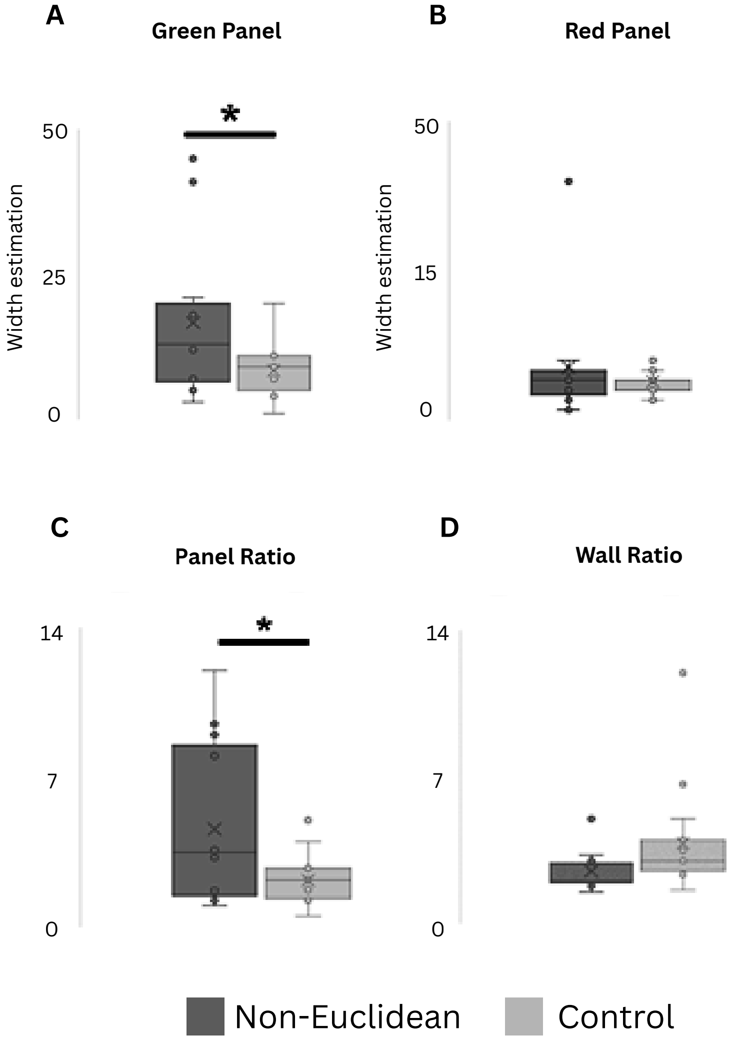


**Figure 6.** The estimate of the green panel by the group who experienced the non-Euclidean hyperbolic environment (without reporting the incongruence) is significantly different from the estimate of the green panel by the group who experienced the control environment (A). Yet, there was no difference between the two groups in estimating the width of the red panel (B). Also, while the ratio between the estimated width of the two panels differs between the non-Euclidean and the control group (C), there was no significant difference in the ratio between the corresponding walls as they were represented by the two groups on the maps (D).

We also assessed the proportion of maps of the VR area sketched by the participants, and focused on the representations of two walls on which the red and green panels were located in VR (Figure 1). More specifically, we compared the ratio between the representations of these two walls across conditions. This was done to confirm that the maps by participants who experienced the non-Euclidean hyperbolic scenario (and did not report the incongruence) had the same proportions as the maps sketched by participants who experienced the control scenario. As a reference, we also compared the ratio between the estimated width of the two panels -red and green - across conditions.

We found no difference in the ratio between the representation of the two walls across conditions ($t(18) = -1.89$, $p = .075$, *Cohen's d* = -.695, Figure 6D). On the contrary, the ratio between the two panels differed significantly across conditions ($t(14) = 2.23$, $p = .043$, *Cohen's d* = .869, Figure 6C), reflecting the difference in the estimates of the green panel.

### *Elliptic scenario*

Those who experienced the elliptic non-Euclidean condition and its Euclidean counterpart reported comparatively low cybersickness ($M_{SSQ}$ = 31.79, $SD_{SSQ}$ = 19.51, Bimberg et al. (2020)). Participants in both groups drew puzzling maps (Figure S2): it is often not possible to tell which element on the map corresponds to which element in the virtual area. So, it is unclear how to interpret these maps. Also, none of the participants in the non-Euclidean elliptic condition reported the impossible geometry of the virtual area. Therefore, the non-Euclidean elliptic environment proved ineffective in addressing awareness of the geometric incongruence.

We assessed the difference in the estimates of the panels between the two conditions with an independent sample t test. We applied a Welch correction for unequal variance. The estimates of the green panel were different between the elliptic group and the matching control group ($t(9.75) = -3.18$, $p = .010$, *Cohen's d* = -1.42). Yet, the two groups also differed in their estimates of the red panel ($t(12.5) = -2.20$, $p = .048$, *Cohen's d* = -0.982), which in fact had the same width across the two conditions. The purpose of estimating the red panel was to rule out that the overall representation of the area differed between the non-Euclidean and the control group. This seems to be the case here, even though the only real difference was in the transverse corridor. It is tempting to speculate that participants in the elliptic conditions have adjusted their memory of the overall area to accommodate the incongruence. Yet, the elliptic condition did not seem to serve the purpose of addressing the research questions: We could not tell those who noticed the incongruence apart.

## Discussion

In this study, we tested the effect of personality traits on challenging such a core cognitive model as the geometry of space. We hypothesized that an exploratory disposition - operationalized here as SS - increases the likelihood of reporting the incongruous geometry. On the contrary, we hypothesized that mental rigidity - operationalized as PNS - decreases the probability of reporting it. We also hypothesized that failing to acknowledge the incongruence does not stem from not seeing the contradictory elements but rather from failing to integrate them.

We tested two pairs of conditions: in each pair, one group performed a task in a VR environment with an ordinary (i.e., Euclidean) geometry, while the other group performed the same task in an environment with an anomalous (i.e., non-Euclidean) geometry. However, we decided to drop one pair of conditions halfway (the elliptic scenario and its Euclidean counterpart) and focused on the other pair (the hyperbolic scenario and its Euclidean counterpart).

Among those who experienced the hyperbolic scenario, the majority did not report the spatial incongruence. These participants sketched maps of the non-Euclidean VR area that were visually indistinguishable from the maps drawn by those who experienced the control scenario. This may suggest that participants in the hyperbolic group did not notice the incongruence.

Nevertheless, when these participants were asked to estimate the width of the green panel located in the incongruous portion of the scenario, their estimations were bigger compared to the estimations of the same panel by participants in the control group did. Because the green panel was bigger in the non-Euclidean hyperbolic condition, this suggests that participants in the hyperbolic condition who did not report the geometric incongruence still perceived the true width of the green panel. Also, these participants represented the non-Euclidean environment as an ordinary space, even if the estimated green panel would not fit in a space with such proportions. We interpret this as a failure to integrate the local information on the panel size with the overall spatial representation of the VR environment. They apparently dismissed the incompatibility, in line with the findings of (Robb & Barwulor, 2021).

More importantly, we found that the acknowledgement of the spatial anomaly correlates with lower PNS. If the lack of acknowledgement of the spatial incongruence reflects a failure to challenge the cognitive model of space, it would be reasonable to expect that people with higher PNS are more reluctant to do so. Indeed, high PNS indicates an over-reliance on mental schemata (Gocłowska et al., 2014).

This is consistent with findings by Bressan et al. (2008). The authors report that participants with a more conservative mindset were less likely to notice a deviant visual stimulus after a series of coherent stimuli, suggesting they might be more reluctant to update their cognitive priors.

The resistance to challenge a core cognitive model can be a protective mechanism against cognitive dissonance, which would otherwise call for a radical reweighting of predictive priors (Friston, 2009; Kaaronen, 2018)). A restructuring of this kind is highly costly, and might be unnecessary and even disadvantageous if the previous model proved effective in countless situations (Constant et al., 2024; Friston, 2009; Kaaronen, 2018). Thus, dismissing the violations of a validated model as noise is often an advantageous strategy, especially in a stable environment (Beghetto, 2021; Constant et al., 2024; Kaaronen, 2018).

The lower tendency to challenge cognitive models can be the reason why participants with high PNS do not benefit from DXs in terms of creativity (Gocłowska et al., 2014; Leung & Chiu, 2010). Gocłowska et al. (2014) explain this finding by pointing out that people with high PNS prefer a persistence-driven approach over a flexibility-driven approach to ill-defined problems (Rietzschel et al., 2007), whereas schema violations favor flexibility. However, the authors do not clarify how and why schema violation induces flexibility. We propose to fill this gap by considering that only low PNS scorers respond to an expectancy violation with a cognitive update, which in turn favors an exploratory state of mind and a flexibility-driven approach (Ivancovsky et al., 2024; Nijstad et al., 2010, see Integrative Discussion).

We did not find any correlation with SS. We had preferred SS over OE because the latter is a much broader construct (Doshi & Hauser, 2024; Gocłowska et al., 2017, 2019). Yet, SS does not completely overlap with OE (Zuckerman et al., 1993). As SS had no effect, we opted for testing OE in subsequent studies.

Finally, male participants were found to be more likely to notice the incongruence. This might be due to gender differences in spatial navigation, visuo-spatial processing, and spatial cognition in general (Hugdahl et al., 2006; Lauer et al., 2019; Nazareth et al., 2019). Alternatively, this can be due to male participants having more experience with action video games (Association, 2024; Gottfried & Sidoti, 2024), which might have refined their ability to map digital spaces, and their spatial cognition in general (Feng et al., 2007).

## Limitations

The study has obvious limitations. First, the sample size was small, and only four out of eighteen participants acknowledged the incongruence. This prevented us from drawing robust conclusions. If gender does play a role, a more balanced sample might result in more participants reporting the incongruence, yielding more reliable results.

Second, while only four participants explicitly reported the incongruence, it cannot be ruled out that more participants noticed it without reporting it, and that they drew classical Euclidean maps because they could conceive no way of representing the impossible space. With that in mind, we decided to introduce a physiological measurement that can provide a more reliable, quantitative assessment of incongruence awareness in real-time. Still, it should be noted that participants who did not report the incongruence expressed surprise when it was eventually pointed out to them by the experimenters.

# Chapter 5

## Pupillometry as a Measure of Expectancy Violation in a Naturalistic VR Scenario (Study 2)

To study cognitive processes such as prediction errors and cognitive updates, it is crucial to confirm the reliability of explicit assessments by pairing them with implicit measures (Perugini et al., 2010). This requires tools capable of detecting the biological correlates of such processes. In our case, we sought a methodology to assess prediction error that could be paired with the experimental paradigm of study 1. In other words, it had to be compatible with the VR apparatus, standing position, and body movements.

Electroencephalography (EEG) is well-suited for the purpose of measuring prediction due to its high temporal resolution (Hsu et al., 2015; Kamp & Donchin, 2015; Silvetti et al., 2014). However, EEG comes with certain drawbacks: it involves lengthy setup procedures, can be uncomfortable for participants, and is highly susceptible to movement artifacts. Functional Magnetic Resonance Imaging (fMRI) is also applied to investigate this cognitive process (Colas et al., 2017; Silvetti et al., 2013; Volz et al., 2003). Yet, the costs for using this technique are high, and the participant must lie down in a tube, making it incompatible with our research procedure.

Electro-dermal activity (EDA) can be used to detect violations of expectations, confusion, and surprise (Stemerding et al., 2022). This technique requires placing electrodes on participants' hands, which was unfeasible in our case: Participants needed both hands to navigate the VR area with the controllers, and the movements of the fingers would have caused artifacts. Although we tried to change the control system so that participants could navigate with one joystick, this setup was deemed impractical.

Pupillometry offers a valid contactless alternative to EEG, fMRI, and EDA as a technique to detect prediction errors (Grujic et al., 2024; Stemerding et al., 2022). It is particularly suitable for VR, as some HMDs have integrated eye-trackers that can measure pupil size. While pupil dilation was found to be associated with expectancy violations in a VR study (Harris et al., 2022), it was unclear whether this association can still be detected in a complex, multi-sensory

VR experience. The second study was designed to address this point.

Normal pupil size shows a general range between 2 and 8 mm, according to light intensity (MacLachlan & Howland, 2002). The main function of pupil size fluctuations is indeed to modify the amount of light that enters the eye based on environmental illumination levels. This is known as the Pupillary Light Reflex (Ellis, 1981). Apart from that, pupil dilation has been historically regarded as an indicator of *arousal*.

According to the well-known valence-arousal model from Mehrabian and Russell (1974), and also to more recent research (Bakker et al., 2014), arousal is defined as "a mental activity describing the state of feeling along a single dimension ranging from sleep to frantic excitement and linked to adjectives such as stimulated-relaxed, excited-calm and wide awake-sleepy". In this model, arousal mainly refers to the intensity of emotional reactions, whereas *valence* represents the hedonic quality - the extent to which the emotional reaction is positive, neutral, or negative. However, because the term arousal has been applied to disparate contexts, its meaning is extremely vague (Grujic et al., 2024). A common denominator is the underlying activity of the Autonomic Nervous System (ANS, McCorry, 2007).

The ANS is composed of two branches: the sympathetic nervous system, which triggers the so-called *fight-flight* responses, preparing the body for a prompt and strong physical activity; the parasympathetic system, which regulates *rest-digest* functions, enrolling basic bodily functions while relaxing or slowing down metabolic activities (McCorry, 2007). Pupillary responses are indeed regulated by the ANS, which controls the activity of two smooth iris muscles: While the sympathetic nervous system excites the *dilator pupillae* and induces pupil dilation, the parasympathetic nervous system innervates the *sphincter pupillae* and regulates pupillary constriction (Beatty & Lucero-Wagoner, 2000). In light of this, it seems more appropriate to consider pupil dilation as a correlate of ANS activation (Beatty & Lucero-Wagoner, 2000; Lanatà et al., 2011).

In addition to that, a body of evidence suggests that changes in pupil size reflect a balance between exploitative and exploratory behavioral states, which are mediated by noradrenaline and regulated by the *locus coeruleus* in the brain stem. Tonic activity of this nucleus would trigger an exploratory state of mind, while phasic activity of this nucleus would induce an exploitative state (Gilzenrat et al., 2010; Kamp & Donchin, 2015; Preuschoff et al., 2011). In the former case, the brain is more likely to update preexisting information, while it is more reliant on prior knowledge in the latter case (Ivancovsky et al., 2024). A larger pupil may thus facilitate broader environmental monitoring during periods of exploration and task disengagement (Ebitz & Moore, 2019; Grujic et al., 2024). Instead, a small pupil would be advantageous when focusing on a specific objective, as it favors the discrimination of relevant elements. This is due to higher spatial frequencies being more easily discriminated with a smaller pupil and vice versa (Ebitz & Moore, 2019).

In this framework, a difference should be drawn between pupil dilation in a novel or volatile environment and dilation after a surprising event (Becker et al., 2024; De Berker et al., 2016; Stemerding et al., 2022). The difference is in the time course of the response, and reflects the underlying activity of the locus coeruleus: the pupil is tonically dilated during the exploration of a novel environment and information update, but it shows phasic dilation in response to an unexpected event, especially during the performance of a task (Gilzenrat et al., 2010; Grujic et al., 2024).

There is also evidence that pupil dilation occurs in response to a change that is relevant to the task and requires a strategy update, while the same response is not detected when the change does not affect task performance (Dragone et al., 2018; Gilzenrat et al., 2010; Kamp & Donchin, 2015; Umemuro & Yamashita, 2003). Umemuro and Yamashita (2003) showcased this point in a visual memory task. They found that pupil dilates when more than one answer or none of them was correct, while they detected no dilation in response to task-irrelevant visual changes in the graphic interface - such as the color or the position of the answers.

In general, it can be speculated that pupil dilation reflects both the need for a behavioral update after a task-relevant change and the need for behavioral flexibility in a novel or volatile environment (Grujic et al., 2024).

Many studies assessed pupil size during a repeated task or the presentation of a sequence of stimuli. For example, Proulx et al. (2017) found that upside-down faces induce an increase in pupil size compared to neutral faces. Kloosterman et al. (2015) found that participants' pupil dilates at the disappearance and reappearance of a target element, and that the dilation is greater when the timing of the disappearance is more unpredictable. Stemerding et al. (2022) showed participants different geometric shapes that could predict an electric shock with a different probability. They found that the uncertainty correlates with pupil dilation before the shock. Also, they found that pupil dilation is higher in the most uncertain condition when the shock does occur, but not when the shock is omitted. Similarly, Becker et al. (2024) showed participants pictures of faces, each of which predicted a subsequent vowel sound with a different probability. They report that pupil size correlates with uncertainty before the sound, and unexpectedness after the sound.

In order to minimize the effect of confounding factors in the visual domain (e.g., changes in luminance) several studies employed auditory stimuli. For example, Preuschoff et al. (2011) found that pupil size increases during an auditory gambling game when the outcome is unexpected. Also, Scheepers et al. (2013) found that pupils dilate in response to the variation in the rhyme pattern of a poem, and Liao et al. (2018) report that pupil dilation occurs when the structure of a piece of music violates expectations.

While these paradigms are ideal for minimizing confounders, it is unclear whether pupil size can still be used as a proxy of unpredictability and expectancy violations in more naturalistic scenarios (Feuerriegel et al., 2021). Antony et al. (2021) attempted to fill this gap by assessing pupil size while participants watched a basketball match. They found a correlation between pupil dilation and surprise. Similarly, Reisenzein et al. (2006) found a 2.5 *SD* increase in pupil size when a computer crashed during a reading task, while Raisig et al. (2010) reported pupil dilation when a script describes a sequence of events in the wrong order. Yet, in both studies, participants were still merely attending to a screen.

In sum, the aforementioned studies found that pupil dilation reflects prediction error during simple and repetitive tasks. On the contrary, we planned to measure prediction error during navigation in the VR scenario described in study 2: unlike the afore-mentioned studies, expectations are violated in a complex, dynamic, and multi-sensory setting. Therefore, it was necessary to confirm that the prediction error is associated with pupil dilation in such conditions as well. This is the aim of the study described here. Note that, differently from study 1, we needed to make sure that all participants in the experimental condition experienced a violation of their expectations. So, in this case, the violation had to be blatant.

More generally, the present study aims to test whether the relationship between prediction error and pupil dilation holds in a naturalistic context. As mentioned earlier, VR is ideal for this purpose because it enables researchers to reconcile ecological validity with experimental control (Blascovich et al., 2002). To our knowledge, this is the first study to pursue such an approach. While Harris et al. (2022) show that pupil dilation occurs in response to unexpected events within a VR environment, their paradigm involves a simple, repetitive task (hitting bouncing balls) and does not exploit the opportunity offered by VR for creating both naturalistic and controlled experimental settings.

## Methods

### *Experimental Design*

For this study, we adopted a within-between subject design with two groups of participants and repeated measures of pupil size across time. A mixed model was used to account for the individual variability in pupil size.

### *Participants*

The study complied with the principles of the Declaration of Helsinki (World Medical Association, 2013) and was approved by the ethics committee of the University of Milano Bicocca as an amendment to Study 1.

A Monte Carlo power analysis (1,000 simulations) was conducted in R (v4.0) using lme4 and lmerTest. We simulated a 2 (group) × 540 (time-point), random intercepts (*SD* =1.0), residual *SD*=1.0, and a true group × time slope difference of 0.20. Considering a significance level $\alpha$ = 0.05, the simulation revealed that 50 participants in total were enough to achieve the desired power to detect an interaction between time and condition. Thus, 53 university students ($M_{Age}$ = 22.23; Female = 30, Male = 23) with normal or correct-to-normal vision were recruited on campus by word of mouth.

### *VR scenarios*

Two VR scenarios were created with Unity graphic engine (version 2020.3.27f1) and rendered through a Pico Neo 3 Eye Pro headset. This device is equipped with native Tobii eye-tracking.

A “normal” scenario consisted of two square rooms connected through a corridor (Figure 7A). The first room was furnished with a carpet, while the second room was furnished with a statue, three armchairs, two lamps, a tray table, and a chandelier. The colors of all these elements had comparably low levels of saturation and brightness. Also, the scenario was evenly illuminated by a single directional light source. Another scenario, called the “flipping” scenario, was almost identical to the normal scenario, with an important difference: the environment suddenly turned upside down when participants heading to the second room passed through a trigger location halfway in the corridor (Figure 7C). Note that the level of irradiance in the second room, which is calculated in Unity based on the rendering of the lights, was the same in the two scenario -i.e., it was not affected by the rotation of the room.

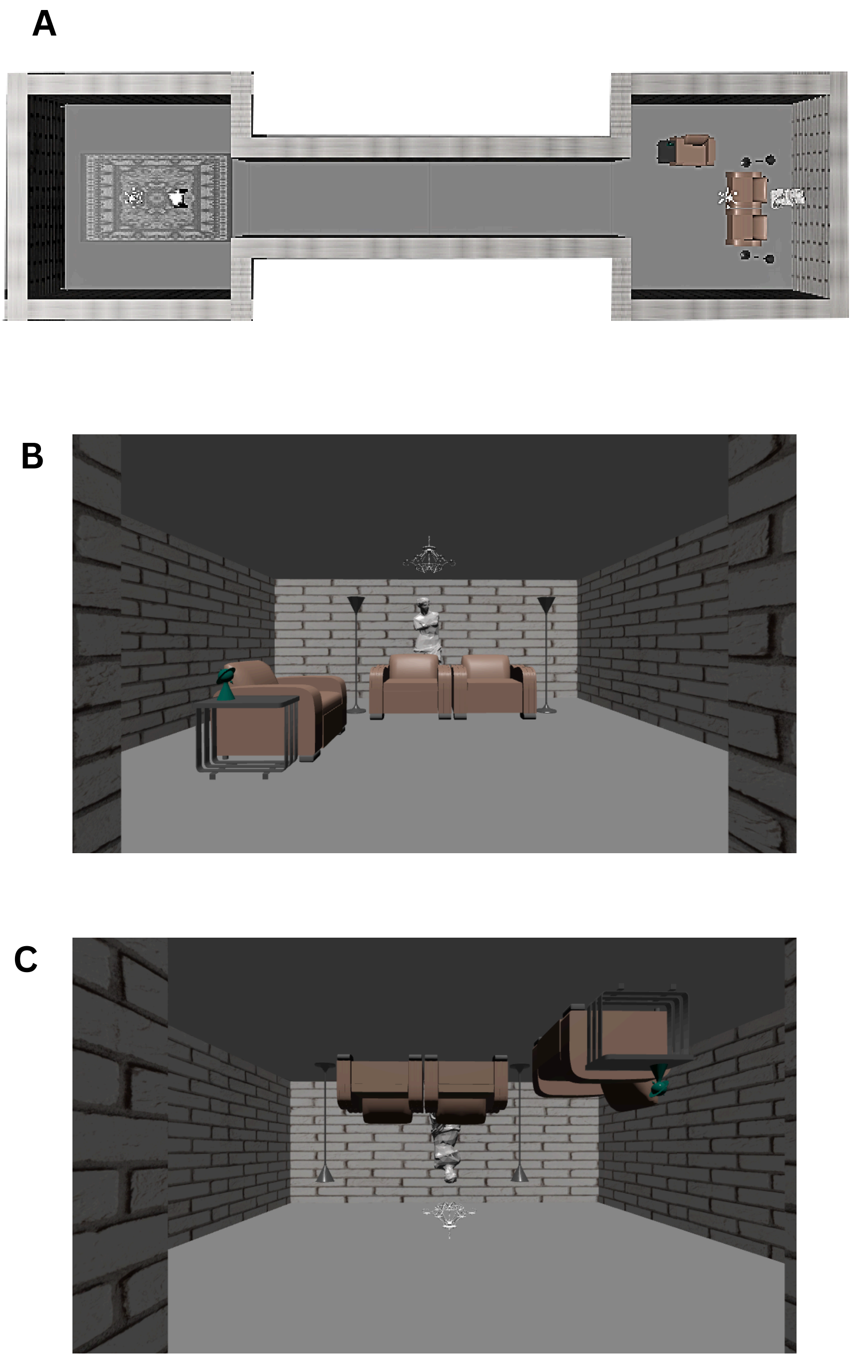


**Figure 7.** Map of the VR scenario with two rooms connected through a corridor (A); view of the second room (B); view of the second room after the scenario turned upside down (C)

### *Procedure*

Participants were divided in two groups. Both groups experienced the normal scenario first. Eight numbered coins were present in the scenario, and participants were tasked to collect them all in the correct order. At the start of the experience, participants found themselves in the first room (i.e., the room with the carpet) and collected the first 4 coins at its corners. Then, they passed through the corridor and entered the second room (i.e., the room with the armchairs, statue, etc.) and collected the last 4 coins at the corners of that room.

We told all participants they were going to perform the task a second time in the same scenario: this created expectations about the environment in which they were going to repeat the task. While participants in the Control condition repeated the task in the normal scenario, and thus experienced no violation of their expectancy, those in the Upside-down (i.e., experimental) condition repeated the task in the flipping scenario, which unexpectedly flipped upside-down (Figure 8).

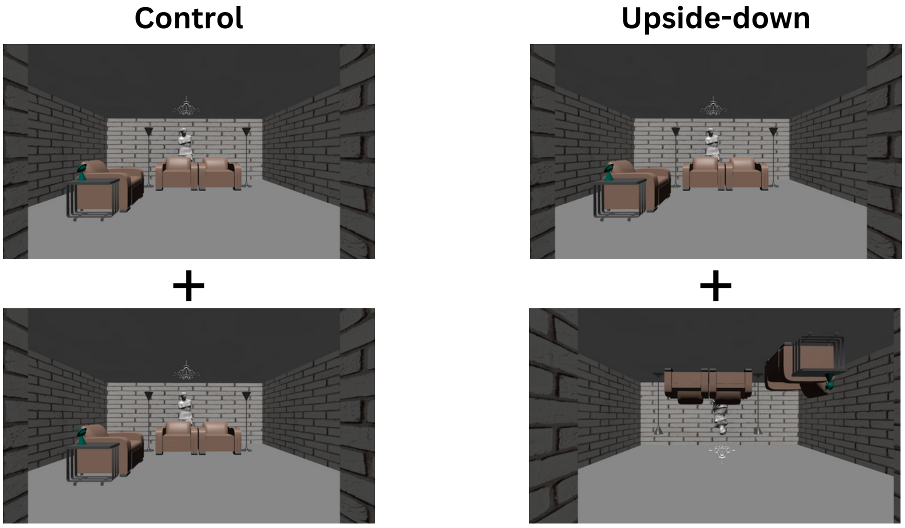


**Figure 8.** In the Control condition, participants experience the normal scenario twice; in the Upside-down condition, they first experience the normal scenario and then the flipping scenario

During the VR experience, pupil size data were sampled through the Tobii eye tracker built into the HMD at 90 Hz. In both conditions, we only collected pupil data during the second repetition of the task, since the first repetition was merely for familiarization. Therefore, we recorded pupil size while participants were navigating the normal scenario in the Control condition, and while they were navigating the flipping scenario in the Upside-down condition (Figure 8).

### *Data Pre-Processing and Analysis*

The data were processed through the Pupil Preprocessing Pipeline (Relaño-Iborra & Bækgaard, 2011) on Matlab. Eye blinks were removed, and the resulting gaps were interpolated. Data points that were more than 3.29 *SD* away from the mean (i.e., 0.001% of the distribution) were considered outliers, so they were removed, and the missing values were forward-filled (Harris et al., 2022). The data were also denoised with a Butterworth low-pass filter at 25 Hz, baseline corrected, and divided by their standard deviation (Mathôt & Vilotijević, 2023).

We considered two epochs of 6 seconds. The first epoch started 200 ms after the participants appeared in the first room; during this epoch, participants were navigating the first room, so we call the first epoch “Room 1.” Note that we used the first 200 ms time window to compute the baseline: such a time window can still be considered baseline due to the latency of the pupil response (Calignano et al., 2024).

The second epoch started as soon as the participants passed through the target location in the corridor (where the scenario flipped in the Upside-down condition). During this epoch, participants were entering the second room, so we call the epoch “Room 2.”

Note that we chose 6 seconds to maximize the length of the epochs, and a longer “Room 2” would have contained empty data in the case of some participants: given that the VR experience ended immediately after participants collected the last coin in the second room, the fastest participants reached the end about 6 seconds after they passed through the target location.

We expected no difference between the two conditions in Room 1, as the two groups would have had the same VR experience in that epoch. Instead, we expected a difference between the two conditions in Room 2, as the participants in the Upside-down conditions would have had their expectations violated by seeing the scenario upside-down.

### *Pretesting of Scenarios*

For this study, it was crucial that the pupil size measure was time-locked with the position of the participant in the VR scenario, so that we could assess the pupil response to the prediction error elicited by entering the flipped room.

Thus, we had to ascertain the correct synchronization between eye-tracking data and position. We developed a third scenario and tested whether we could detect a pupil dilation as a response to a change in environmental lighting occurring at a specific location. Such a scenario was the same as the normal scenario except for a red switch placed on the floor halfway through the corridor. When the participants stepped on the switch, the light intensity reduced dramatically.

To calibrate the procedure, we collected data from 4 participants and found a 2 *SD* increase in pupil size that was time-locked to the moment participants stepped on the switch (Figure 9).

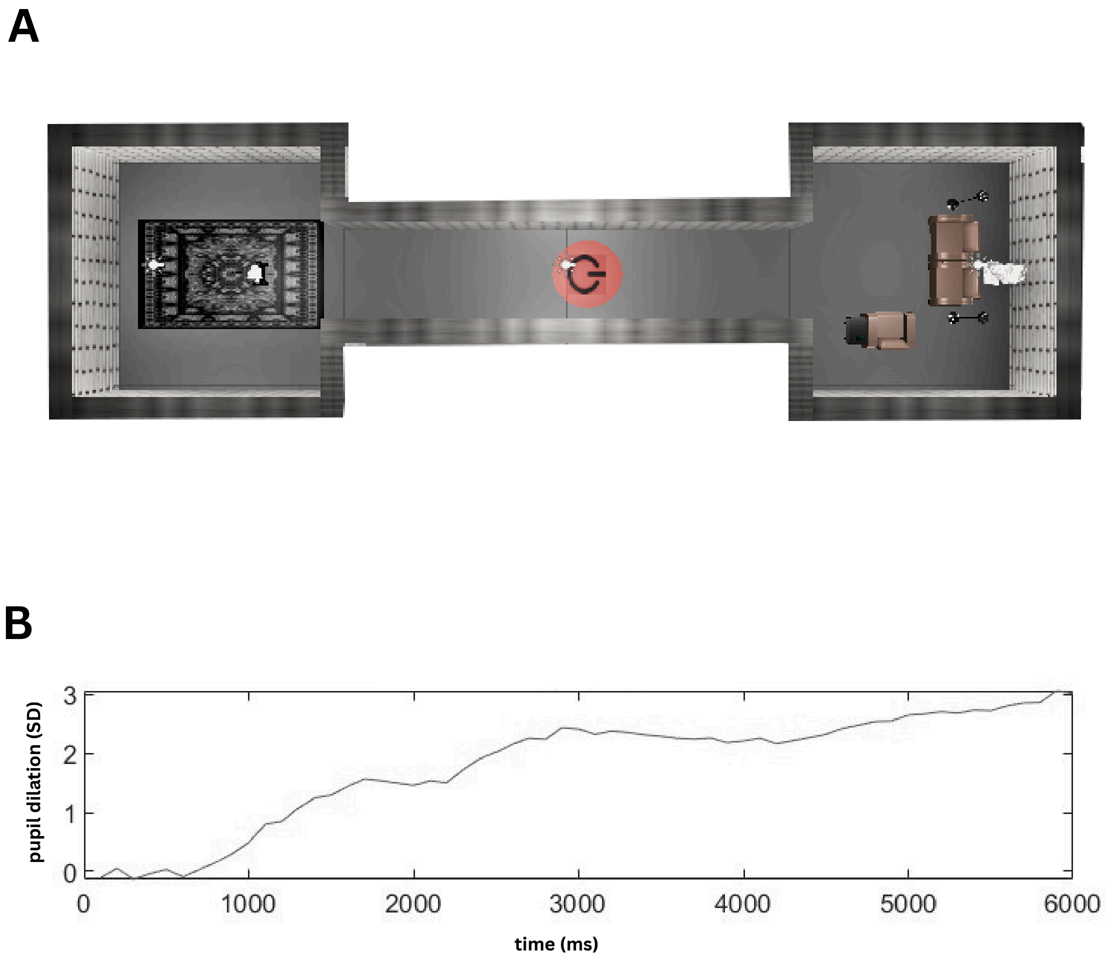


**Figure 9.** Map of the scenario for confirming the synchronization between the position in VR and the eye-tracker, featuring the light switch on the corridor's floor (A); plot of the time course of pupil size after the light went off, showing a conspicuous increase in pupil size (B)

## Results

Out of 53 participants, four were excluded due to a large amount of missing data ( >50%). This was likely due to excessive blinking or a mis-calibration of the eye-tracker. Therefore, the final sample was composed of 49 participants.

In Room 1, the grand mean of pupil sizes across participants was 5.2991 mm in the Upside-down condition and 5.2707 mm in the Control condition. In Room 2, the grand mean was 5.1975 mm in the Upside-down condition and 5.1694 mm in the Control condition. The change over time of pupil size in the two conditions, averaged across participants, is shown in Figure 10 for both epochs.

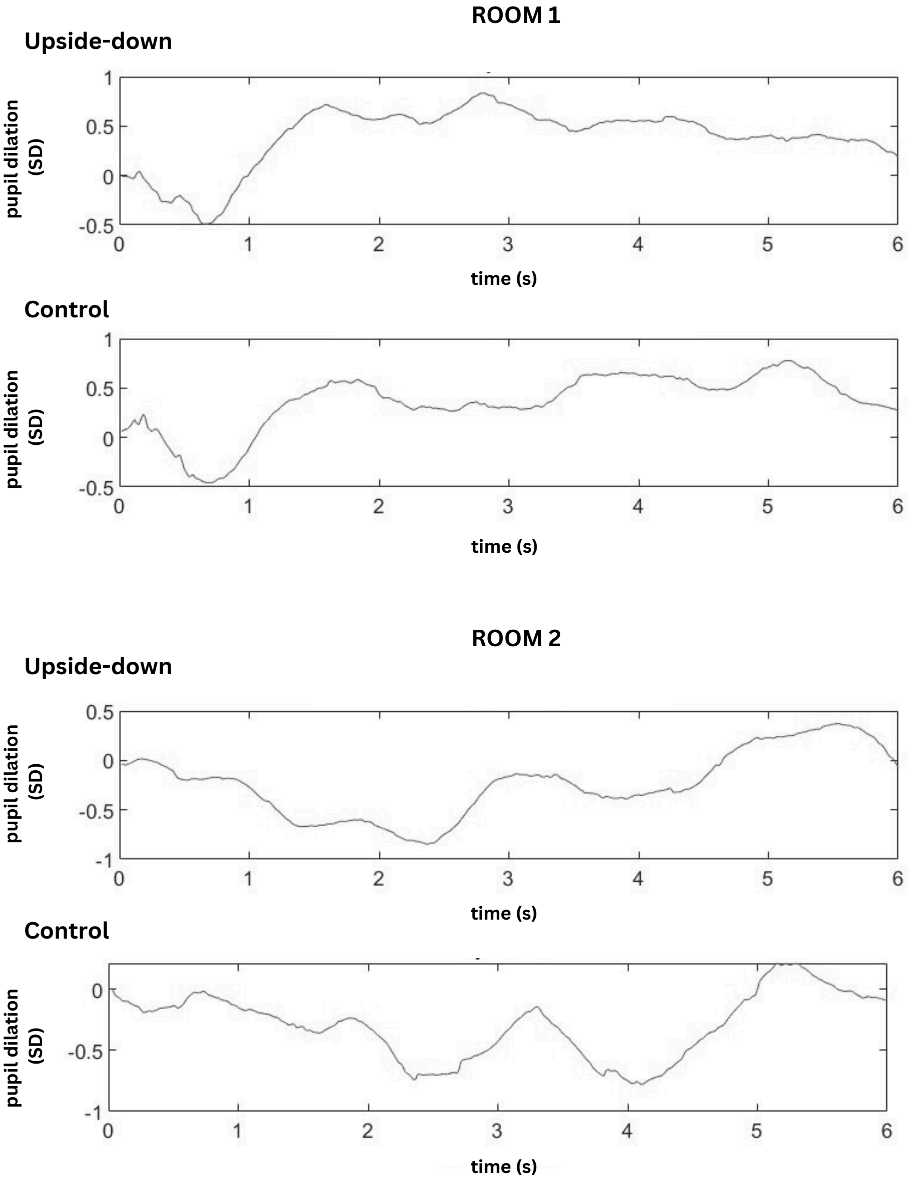


**Figure 10.** Time course of pupil size averaged across participants in the two conditions after they entered the VR scenario (Room 1) and after they passed through the target location in the corridor, where the scenario flipped in the Upside-down condition (Room 2).

We analyzed pupil size using linear mixed-effects models and tested whether the two conditions differed. Time was entered as a continuous predictor, modeled with linear, quadratic, and cubic terms. Participants were treated as the clustering variable, with random intercepts specified. We also set random slopes of linear, quadratic, and cubic time. Time was standardized (z-scored) before the analysis. We had initially modeled residuals with a first-order autoregressive (AR1) structure to account for temporal autocorrelation. However, the model did not converge, so we removed it. All this was done for both Room 1 ($ICC$ = 0.876, $var(time)$ = 0.705, $var(time^2)$ = 0.214, $var(time^3)$ = 0.186) and Room 2 ($ICC$ = 0.760, $var(time)$ = 1.098, $var(time^2)$ = 0.147, $var(time^3)$ = 0.263), both displayed in Figure 11.

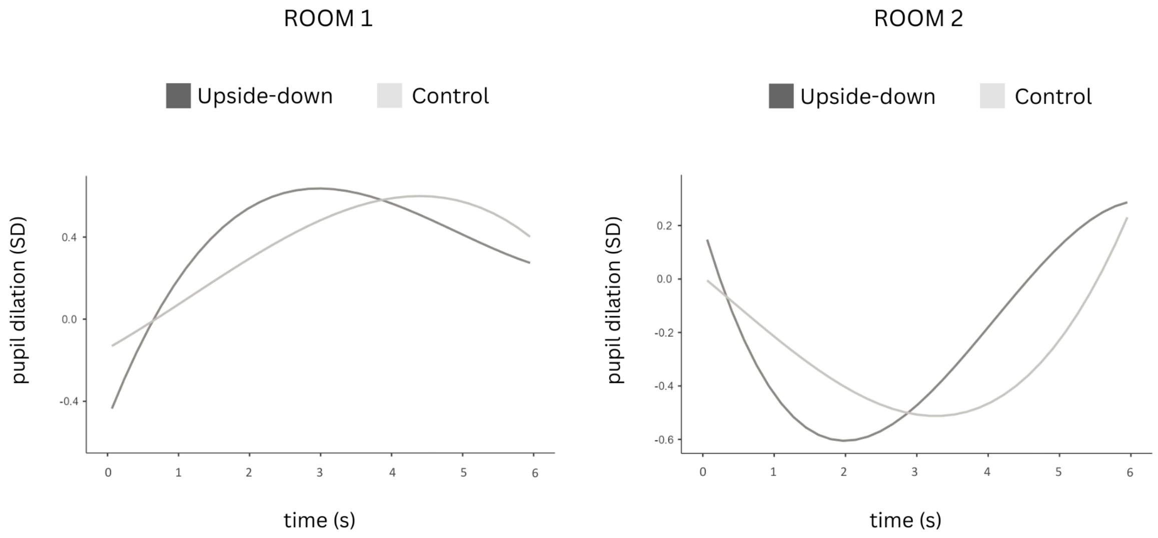


**Figure 11.** Pupil size changes (standardized values) over time in the Upside-down and Control conditions, shown separately for the two epochs. Lines represent model-derived estimates from a linear mixed-effects model.

In Room 1, the analysis revealed a significant quadratic effect of time ($F(1, 47) = 7.74$, $p = .008$). No significant main effects were found for condition ($F(1, 47) = 0.08$, $p = .773$), linear time ($F(1, 47) = 1.14$, $p = .291$), or cubic time ($F(1, 47) = 0.09$, $p = .764$). The interactions between condition and time were also non-significant, including condition × time ($F(1, 47) = 1.31$, $p = .259$), condition $\times time^2$ ($F(1, 47) = 0.93$, $p = .339$), and condition $\times time^3$ ($F(1, 47) = 0.84$, $p = .364$).

In Room2, the mixed-model analysis showed a significant quadratic effect of time ($F(1, 47) = 16.99$, $p < .001$), indicating a non-linear trajectory across time. No significant main effects emerged for condition ($F(1, 47) = 0.01$, $p = .921$), linear time ($F(1, 47) = 1.32$, $p = .257$), or cubic time ($F(1, 47) = 0.30$, $p = .584$). Likewise, none of the interactions between time and condition reached significance, including condition × time ($F(1, 47) = 2.55$, $p = .117$), condition $\times time^2$ ($F(1, 47) = 0.05, p = .830$), and condition $\times time^3$ ($F(1, 47) = 1.43, p = .237$).

We noticed that the average time course of pupil size in Room 2 (Figure 10) exhibits complex, non-linear dynamics that were not adequately modeled by a polynomial trend. We therefore analyzed the data also using a generalized additive mixed model (GAM) with a first-order autoregressive error structure. Time was modeled using regression splines with a basis dimension of $k = 20$. The model included smooths of time for each condition, as well as participant-specific random smooths. We did so for both epochs.

In the case of Room 1, the overall model fit explained 96.6% of the deviance ($adj.R^2$ = .966, Figure 12). Accordingly, pupil size varied significantly over time, with a non-linear trajectory ($F$(16,16.56) = 33.39, p < .001), and subject-specific variability in the time course of pupil size ($F$( 426.25,440) = 1481.12, $p$ < .001).

To directly test whether the temporal trajectories differed between conditions, we refitted the model with a smooth representing the deviation of the Upside-down condition from the Control condition, which was compared to the smooth of the Control condition. This “difference smooth” was not significant ($F$(13.04,14.83) = 1.03, $p$ = .332), indicating that the time courses of pupil size did not differ between the two conditions in Room 1. Taken together, the analyses show significant time-related changes in pupil responses but no evidence for systematic differences across conditions.

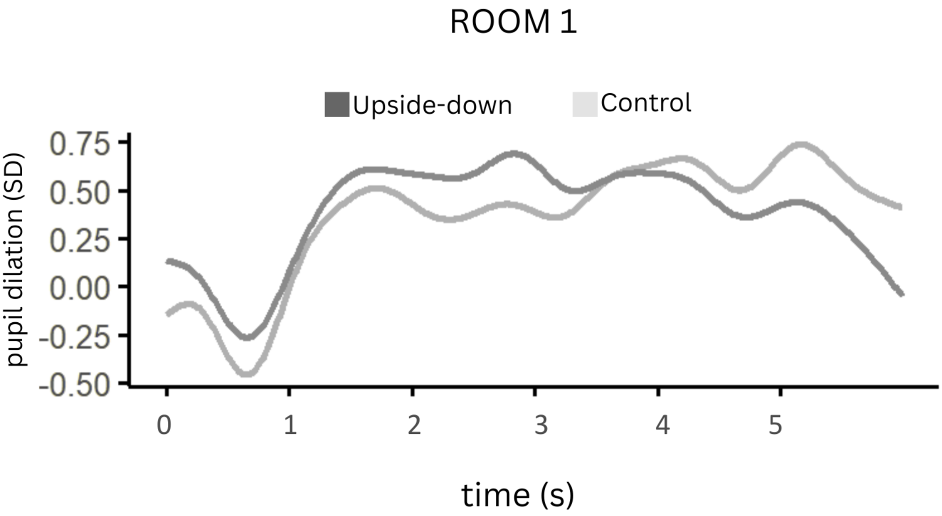


**Figure 12.** Pupil dilation (standardized values) over time in the Upside-down and Control conditions for Room 1. The lines represent smooth functions estimated through a generalized additive model (GAM).

In the case of Room 2, the overall model fit explained 95.5% of the deviance ($adj.R^2$ = .96, Figure 13). Although the global smooth for time was not significant ($F$(3.75,3.84) = 0.03, $p$ = .998), most of the temporal variation was captured by the condition-specific smooths. Indeed, both condition-specific trajectories showed significant non-linear changes over time (Control: $F$(15.46,15.88) = 3.64, $p < .001$; Upside-down: $F$(15.41,15.80) = 4.14, $p < .001$). This confirms the complex dynamic in both groups. Again, there was substantial individual variability ($F$(424.39,440) = 1174.55, $p < .001$).

The refitted model with the difference-smooth showed that the time course of pupil size in the Upside-down condition diverged significantly with respect to the Control condition ($F$(18.08,18.60) = 14.57, $p < .001$).

**Figure 13.** Pupil dilation (standardized values) over time in the Upside-down and Control conditions for Room 2. The lines represent smooth functions estimated through a generalized additive model (GAM).

## Discussion

As expected, no difference between the Control and Upside-down conditions was found in Room 1. During this epoch, the two groups were navigating the same VR environment while collecting coins at the same locations. In other words, the results show no systematic differences in pupil size across groups in spite of the inherent individual variability of pupil data. The fact that participants were gazing freely at the environment does not seem to have affected pupil dilation at the group level.

We found no difference in mean pupil size across conditions in Room 2. This could be due to the relatively high level of baseline dilation, which is believed to affect an evoked dilation negatively (Gilzenrat et al., 2010; Grujic et al., 2024). Such tonic dilation could, in turn, result from the inherent novelty of using VR, which currently has a narrow user base (Pan & Hamilton, 2018) and might have put participants in an exploratory state since the beginning. Also, other factors might have contributed to the tonic dilation in both conditions - entering the second room, spotting the coins, etc.

Still, we detected a difference in the dynamics of pupil diameter between the two conditions. Unlike the aforementioned studies, however, we did not detect a clear phasic dilation (Harris et al., 2022; Liao et al., 2018; Preuschoff et al., 2011; Raisig et al., 2010; Reisenzein et al., 2006), which normally appears around one second after a novel stimulus (Geva et al., 2013; Hoeks & Levelt, 1993; Strauch et al., 2022). Participants in those studies were merely attending to a computer screen. In a dynamic situation like our VR experience, instead, pupil diameter can be influenced by multiple factors, which complicate the detection of a phasic response. Also, in our case, the unexpected occurrence did not impact the performance of the task, and task-irrelevant changes were found not to trigger a phasic response (Umemuro & Yamashita, 2003). In the future, it would be interesting to test whether a phasic response is detected after a task-relevant change - such as by the absence of the coins.

The response we detected is more complex and may reflect the inherent complexity of a real-life situation such as entering a furnished room. Specifically, while a transient increase in pupil size is observed in the Control condition after participants entered the second room, the dilation is more sustained in the Upside-down condition (Figure 13).

We interpret our results as evidence that the dynamics in pupil size can characterize an exploratory state of mind triggered by expectancy violations in a naturalistic environment (Dragone et al., 2018; Gilzenrat et al., 2010; Kamp & Donchin, 2015). These results provide preliminary evidence that specific pupil size dynamics associate with prediction errors in a complex, multi-sensory setting. More generally, this method improves on past research that often relied on repetitive tasks or poorly ecological stimuli. In other words, a combination of VR a pupillometry may allow the study of prediction errors in lifelike settings while retaining experimental control.

In conclusion, pupil dilation could be considered a good candidate for characterizing expectancy violation in a VR scenario. Therefore, we decided to seek to replicate Study 1 and implement pupil size as an implicit measure of acknowledgement of the spatial anomaly.

### Limitations

This study has some limitations. First, we lack robust control for environmental luminance. Although the lighting level was even in the scenario and the irradiance was the same across conditions, different shadows can result from whether the furniture was flipped or not;

this could, in theory, produce some tiny differences in the perceived luminance between the two groups. However, given that the irradiance was the same, these shadows are unlikely to cause systematic differences in luminance level. Still, this issue can be resolved in a future study by recording the gazing behavior of the participants and controlling for the perceived luminance throughout the VR experience, frame by frame.

Second, in the Upside-down condition, the furniture in the second room appeared closer to participant's head because it was hanging from the ceiling. This might have affected pupil size through the accommodative reflex, which occurs in response to objects in the vicinity of the face (Reeves & Swenson, 2004). However, it should be noted that the accommodative reflex consists of a contraction of the pupil, whereas we observed a dilation in the Upside-down condition.

Third, this study offers only preliminary results and awaits being confirmed with a larger and more varied sample, which should account for the high inter-individual variability of pupil data. Indeed, we only collected data from University students.

# Chapter 6

## Quantitative and Qualitative Assessment of Individual Differences in Processing non-Euclidean Geometry in VR (Study 3)

In Study 1, we tested whether individual differences predict reporting a violation of a core cognitive model. Participants explored a VR environment designed to break Euclidean geometry, then drew a map to elicit reports of the anomaly. Lower PNS was associated with a reduced likelihood of reporting the spatial violation.

However, we could not rule out that other participants had noticed the anomaly even if they did not report it. Therefore, in study 2, we tested whether we could differentiate between participants facing a blatant violation of their expectations (i.e., the environment turning upside down) from those who did not on the basis of physiological data. Our results suggest that it is indeed possible to tell the two groups apart on the basis of pupil dilation, which is considered an indicator of prediction error and surprise.

The first objective of this study was to further elucidate the factors that affect the response to violations of fundamental expectations. We thus sought to replicate the effect of individual differences found in study 1. Specifically, we used the hyperbolic non-Euclidean scenario of study 1, and tested whether individual differences can predict the acknowledgment of its impossible geometry.

We capitalized on the results of study 2 and paired the explicit evidence of participants' awareness of the spatial anomaly (i.e., their verbal reports) with physiological data. So, the second aim of this study was to confirm that participants who report the incongruence also showed a different physiological response compared to those who do not.

### Methods

#### *Experimental design*

Unlike study 1, we did not have a control group. Firstly, we were only interested in studying which participant would have acknowledged the VR scenario as impossible. Secondly, and more importantly, the control scenario (i.e., the Euclidean counterpart of the hyperbolic scenario used in study 1) features a shorter transverse corridor compared to the corridor in the hyperbolic scenario. So, participants in the control scenario would take less time to cross the corridor and go back to the main room. Because we wanted to record pupil data precisely in the transverse corridor, this would have resulted in the data being sampled at different locations depending on the condition. For this reason, we chose to test the non-Euclidean scenario. Still, we adopted a between-subject design with two groups, and we assigned participants to either group based on whether they reported the spatial incongruence.

### *Participants*

The study complied with the Declaration of Helsinki and was approved by the ethics committee at the University of Barcelona.

We performed a Power analysis for a logistic regression with G*Power software (version 3.1). In the pilot study, we found a significant effect of PNS, which predicted the lack of awareness of the incongruence with an odds ratio of 0.089. Yet, because these results were based on a small sample ($N$ = 17 participants, among whom only 4 noticed the incongruence), we decided to adopt a safeguard approach (Perugini et al., 2014). We used the upper bound of a 75% confidence interval, namely 0.503. Note that such an odds ratio is more than 5 times bigger than the actual odds ratio resulting from the study. Considering this parameter, 79 were needed for the non-Euclidean group to achieve a power of 0.8 at a significance level $\alpha$= 0.05. Eighty participants were enrolled ($M_{Age}$ = 22.41, Female = 42, Male = 38). They were students of Psychology at the University of Barcelona, who were recruited through fliers and word of mouth.

### *VR Scenarios*

The VR scenarios corresponded to the hyperbolic scenario described in the pilot study (Figure 2 and 3). However, we made a change to address an issue raised by participants in the pilot study. Namely, some participants reported being unsure about which panel was where because they were too focused on collecting the tokens. Therefore, we decided to change the color of the panels to make them more conspicuous. We added white horizontal stripes to the red panel and black stripes to the green panel (Figure 14). Note that, although we were not interested in the estimation of the panels' width anymore, the panels could still be used by the participants to map the otherwise empty environment and, above all, to form their expectations about the length of the transverse corridor (as discussed in study 1).

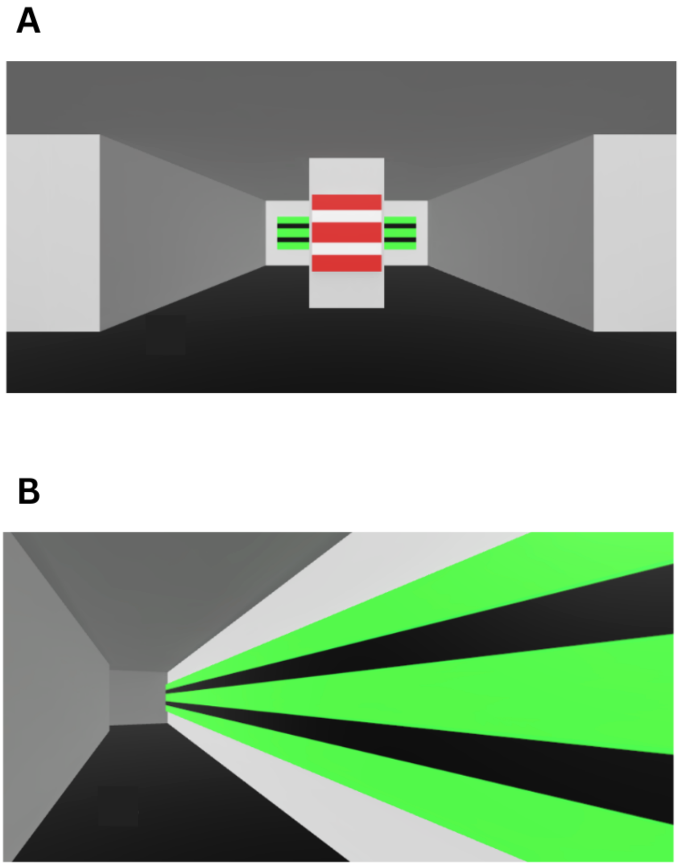


**Figure 14.** View of the modified panels from the main room (A) and from inside the transverse corridor (B)

### *Procedure*

Participants entered the VR environment through a Pico Neo 3 Eye Pro headset featuring a built-in Tobii eye tracker (https://www.picoxr.com/it/products/neo3-pro-eye). Pupil size data were sampled at 90 Hz and pre-processed as in study 2.

The procedure was the same as in the pilot study, although we performed the calibration of the eye tracker before the training scenario.

At the end of the VR experience, participants were administered the SSQ and the PNS on a computer as in the pilot study. Yet, the questionnaires were administered in Spanish (Campo-Prieto et al., 2021; Gil et al., 2024)).

Unlike the pilot study, we did not assess SS. Indeed, this trait did not correlate with the awareness of the incongruence. We replaced it with the Openness to Experience subscale of the Big Five Personality test (OE, Cronbach's $\alpha$ = 0.80; John et al., 1991), which has been widely used to quantify the tendency to seek novel experiences (Ivancovsky et al., 2024). Also, people with higher OE are generally less reliant on previous knowledge and more prone to update it (Ivancovsky et al., 2024). In this questionnaire, participants are requested to state the extent to which each of the 10 items (e.g., "I see myself as someone who has an active imagination") applies to their personality on a 5-point Likert scale (1 = *Completely Disagree*, 5 = *Completely Agree*). The maximum score is 50. We assessed OE in Spanish (Benet-Martínez & John, 1998).

Finally, we tested whether the effect of gender was genuine or mediated by differences in video game experience. To do so, we asked participants to report the latter on a 7-point Likert scale ("How much experience do you have with video games?"; 1 = *no experience*, 7 = *A lot of experience*).

### *Data Analysis*

Pupil size data were pre-processed as in study 2. We considered a 6-second epoch (reflecting the procedure of study 2) since the moment each participant turned the corner and entered the transverse corridor for the first time. Indeed, the first passage through the transverse corridor corresponds to the moment in which participants' expectations about the length of this corridor are violated.

## Results

Among the 80 participants ($M_{SSQ}$ = 31.93, $SD_{SSQ}$ = 24.97), 3 of them reported not remembering the layout of the VR area when they were asked to sketch the map. Therefore, we excluded these participants. Beside them, 20 participants reported that the geometry of the environment was impossible, and attempted to draw it in different ways (see Figure 15 for some examples). The remaining 57 participants sketched maps that were comparable to those drawn by the control group in study 1 (Figure 4F), and represented the Euclidean version of the area - with parallel corridors not diverging. It can be said they drew the Euclidean control scenario of study 1 (Figure 1A).

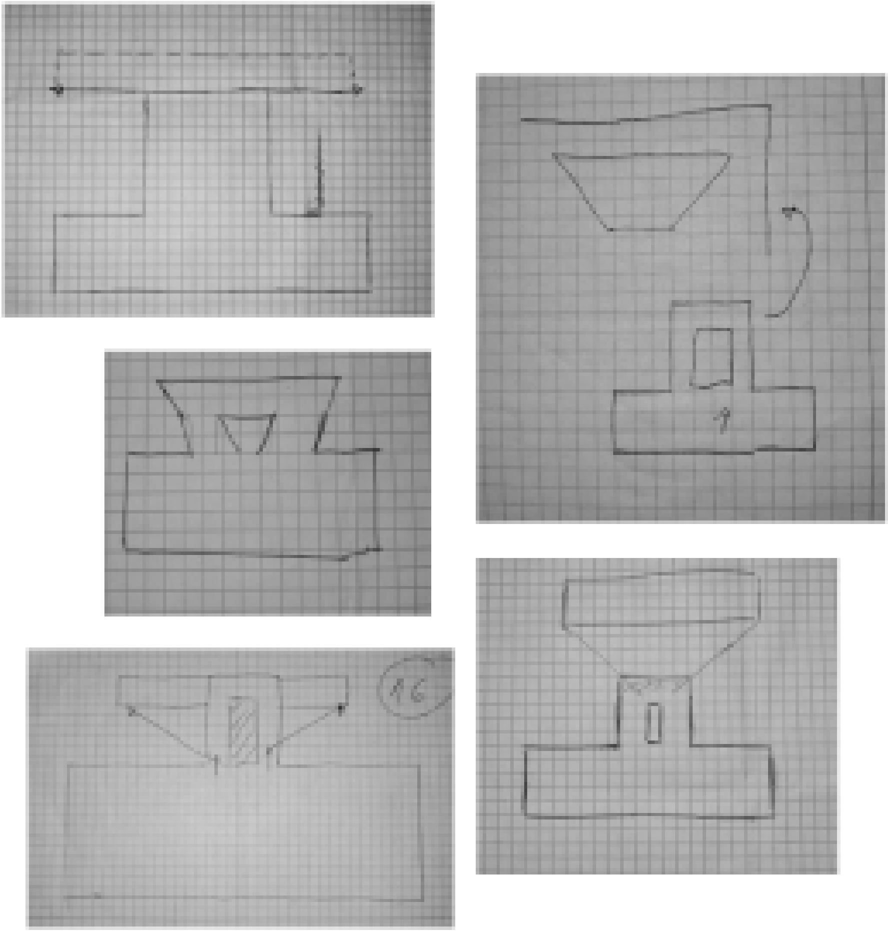


**Figure 15.** Example of the sketches drawn by the participants who reported the geometric anomaly of the VR scenario.

We then assessed whether PNS, OE, and gender could predict the realization that the VR environment was impossible (1 = Reported, 0 = Not reported). We analyzed the data by computing a generalized linear model ($\chi^2$(5) = 17.6, $\mathrm{R}^2 = 0.200$).

We found a significant main effect of gender ($\chi^2$(1) = 4.7623, $p$ = 0.029, $\eta^2$=0.0540), replicating the results of study 1. While neither PNS ($\chi^2$(1)=0.1018, $p$ = 0.750, $\eta^2$=0.0012) nor OE ($\chi^2$(1) = 0.0494, $p$ = 0.824, $\eta^2$ = 0.0006) predicted the awareness of the incongruence, we did find a significant interaction between gender and PNS ($\chi^2$(1) = 7.8290, $p$ = .005, $\eta^2$ =

0.0888). On the contrary, we found no interaction between OE and gender ($\chi^2(1) = 0.9221$, p = 0.337, $\eta^2 = 0.0105$). To further elucidate the effect of PNS, we then tested for a simple effect of PNS in each gender. We found that PNS significantly predicts awareness in males ($\chi^2(1) = 6.53$, $p = .011$, $OR = 0.362$) but not in females ($\chi^2(1) = 1.94$, $p = .163$, $OR = 2.209$, Figure 16).

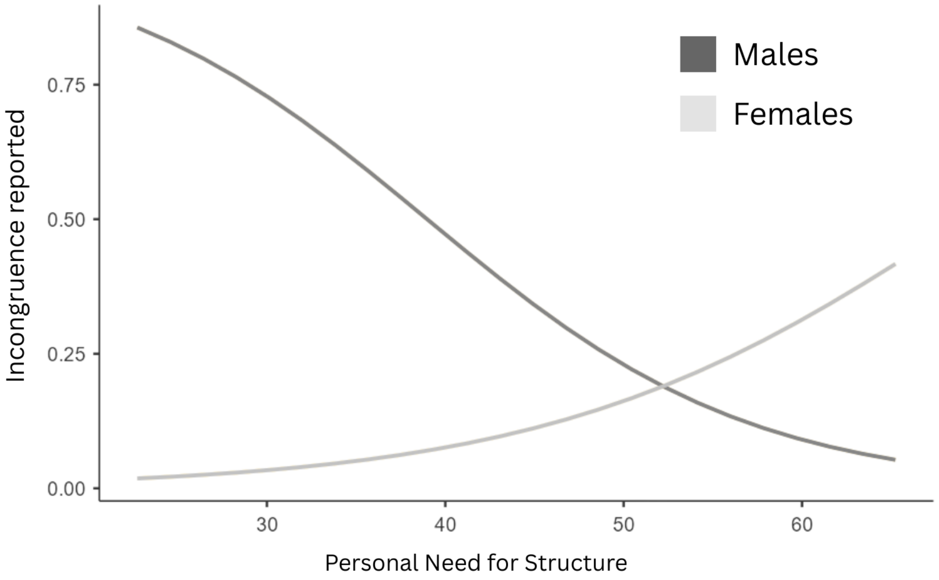
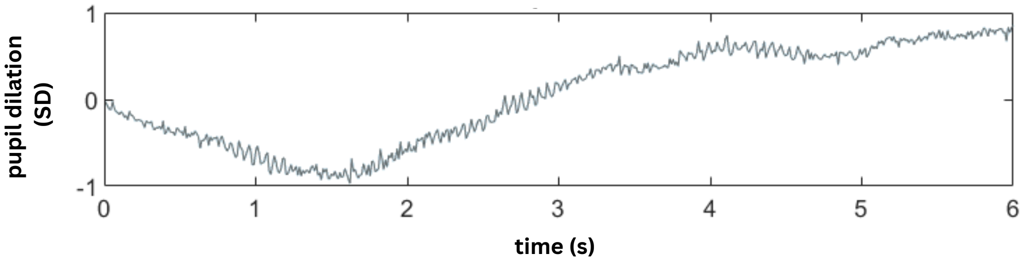


**Figure 16.** Probability of reporting the incongruence as a function of Personal Need for Structure in males and females.

Because we found that males and females differed in their experience with video games ($t(75) = 5.63$, $p < .001$, *Cohen's d* = 1.29), we investigated whether this could explain the effect of gender. We did so by introducing the experience with video games as a further covariate in our mixed model. After doing so, the significant effect of gender disappeared ($p = .181$), suggesting that the effect of gender was indeed mediated by the experience with video games. Notably, the interaction between gender and PNS stayed significant ($p = 0.004$).

Finally, we assessed whether participants who reported the anomaly showed a different pupillary response compared to those who did not report it when they were passing through the transverse corridor for the first time (Figure 17).

**Not Reported**



**Reported**

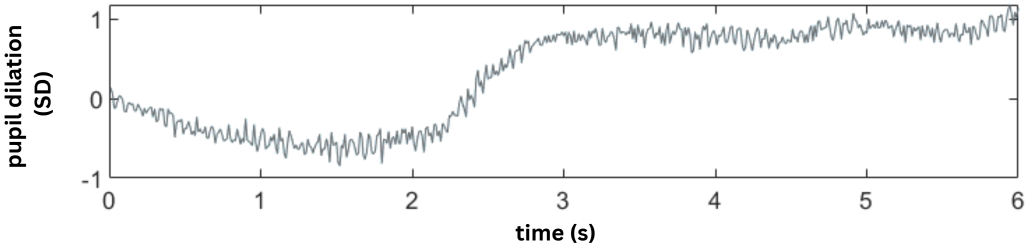


**Figure 17.** Change in pupil size after participants first entered the transverse corridor, averaged across participants who Reported or Not reported the incongruence.

We computed a general mixed model with two groups (Reported vs Not reported) and time as a continuous independent variable: we tested its linear, quadratic, and cubic effects. We considered participants as the clustering variable. We set a random within-cluster intercept, a random within-cluster slope for linear, quadratic, and cubic time. We also set autoregressive residuals. The results of the model (*ICC* = 0.712, $\Phi$=0.671, *var(time)* = 0.655) are displayed in Figure 18.

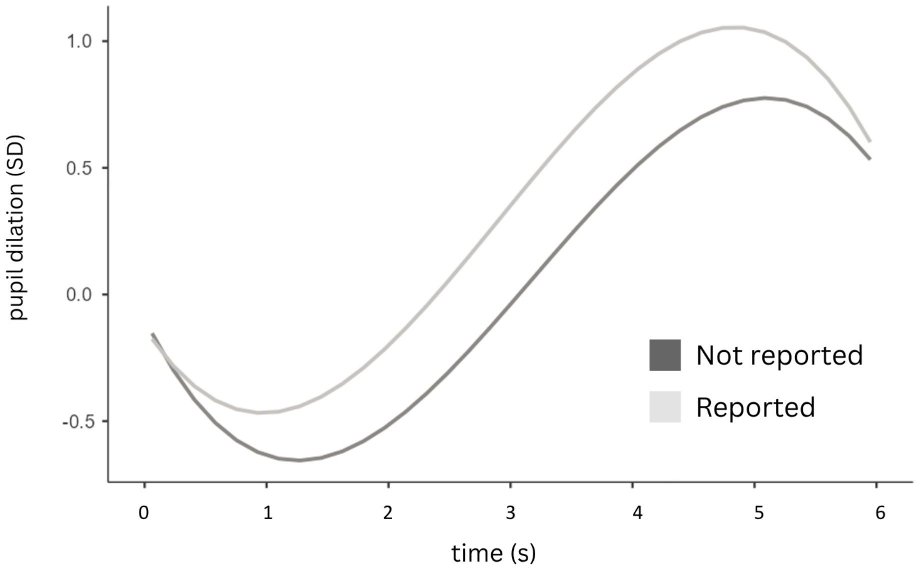


**Figure 18.** Pupil dilation (standardized values) over time after participants entered the transverse corridor for the first time, showing participants who Reported versus Not reported the incongruence. The lines represent fitted values from a linear mixed-effects model.

The analysis revealed a significant main effect of linear time ($F(1, 41{,}497) = 84.69$, $p < .001$) and a significant effect of cubic time ($F(1, 41{,}497) = 34.65$, $p < .001$), indicating a non-linear time course of pupil size. The quadratic effect of time was not significant ($F(1, 41{,}497) = 0.22$, $p = .636$). The main effect of condition was also non-significant ($F(1, 75) = 2.05$, $p = .157$). No significant interactions emerge: neither condition × time ($F(1, 41{,}497) = 0.08$, $p = .779$), nor condition $\times time^2$ ($F(1, 41{,}497) = 2.03$, $p = .154$), nor condition $\times time^2$ ($F(1, 41{,}497) = 0.02$, $p = .899$).

As in study 2, we also analyzed the data through a generalized additive model (GAM) with a first-order autoregressive error structure. Time was modeled using regression splines with a basis dimension of $k = 20$. The model included smooths of time for each condition, as well as participant-specific random smooths. The model accounted for 88.1% of the variance in pupil size ($adj.R^2 = .88$; Figure 19).

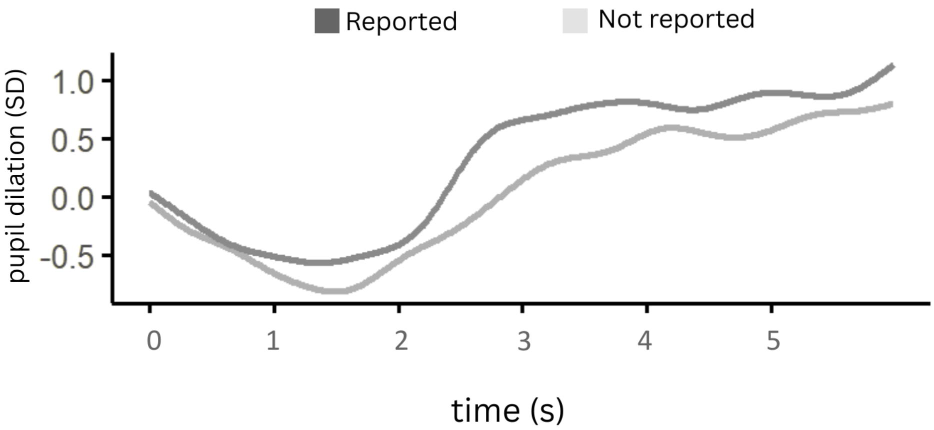


**Figure 19.** Pupil dilation (standardized values) over time in the two groups (Reported vs Not reported) after they entered the transverse corridor for the first time. The lines represent smooth functions estimated through a generalized additive model (GAM).

The global smooth of time was not significant ($F(0.01,0.01) = 0.06$, $p = .986$), but both condition-specific trajectories showed significant non-linear temporal changes (Not reported: $F(14.79,16.64) = 8.28$, $p < .001$; Reported: $F(13.51,15.57) = 5.73$, $p < .001$). There was also significant individual variability across time ($F(663.41, 691.00) = 180.86$, $p < .001$).

To test whether these time courses differed, we refitted the model with a difference smooth as in study 2. This term was significant ($F(15.11,16.99) = 5.10$, $p < .001$): although both conditions showed non-linear changes in pupil size over time, the shapes of their trajectories diverged significantly.

## Discussion

In this study, we employed a similar paradigm as in study 1, without a control condition. We let participants experience the hyperbolic environment from study 1 and divided them into two groups based on whether they reported the spatial incongruence. The results partially replicate those of study 1.

To begin with, we found a main effect of gender such that male participants were more likely to report the spatial anomaly than female participants. This effect was explained by male participants having more experience with video games and, supposedly, more familiarity with mapping a digital environment.

However, other factors may play a role. For example, a meta-analysis by Nazareth et al. (2019) confirmed that males out-perform females in encoding spatial relations, building maps, and spatial cognition in general. Also, males consistently show better performance in the mental rotation task, indicating better visuo-spatial abilities (Hugdahl et al., 2006; Lauer et al., 2019). In a future study, it might be interesting to control for this aspect, for example, through a VR version of Morris' water labyrinth (Commins et al., 2020).

It should be noted that males' better performance is not necessarily a biologically determined trait. In fact, the gap between males and females appears during childhood (Lauer et al., 2019). This suggests that cultural factors may play a role, such as males being more involved in activities requiring spatial cognition. These also include playing action video games. Indeed, Feng et al. (2007) found that playing action video games enhances spatial abilities in both males and females, and shrinks the gap between the genders. In sum, males' better performance at spatial tasks and their experience with video games might be two sides of the same coin.

For the purpose of our research, however, this topic is relevant as long as it allows us to account for factors influencing the acknowledgement of the spatial incongruence other than personality traits. Indeed, if participants are not able to map the environment accurately enough, they are not be able to notice its incongruous layout.

The key finding of this study is that PNS significantly predicts the awareness of the spatial anomaly in male participants. We thus speculate that, in our case, PNS plays a role provided that participants have sufficient spatial abilities and are capable of mapping the environment well enough.

More specifically, male participants with higher PNS were less likely to report the anomaly. The effect of PNS confirms the results by Bressan et al. (2008), who found that more conservative participants were less likely to report expectancy violation. PNS captures a tendency to categorize information in a clear and rigid way, resulting in a preference for certainty and an aversion to unpredictability (Gocłowska et al., 2014, 2017). This attitude can prove advantageous to a certain extent.

According to the Predictive Coding framework, the brain evolved to extract predictive models from the environment and exclude background noise (Friston, 2005, 2009; Kaaronen, 2018). Thus, when new information contrasts with prior models, it can be adaptive to neglect it to prevent model over-fitting.

Indeed, if a model were updated to account for any tiny discrepancy, it would end up being poorly generalizable. It would no longer be useful for making predictions. So, the brain might have evolved to treat some of these discrepancies as noise. However, an excessive discard of inconsistent information leads to model under-fitting. This equally impairs the ability to make correct predictions. The brain would thus seek the optimal balance between that which should be attended and that which should be neglected (Kaaronen, 2018).

Participants with higher PNS might have a higher tendency to discard inconsistent information to avoid model over-fitting, leading to dismiss that a VR environment was geometrically different from any physical space. Conversely, participants with lower PNS acknowledged the inconsistent information and supposedly resolved the prediction error by reconciling it with higher-level information -i.e., the awareness of being in a human-made environment (Kaaronen, 2018).

Notably, these correspond to the two different strategies with which cortical layers are hypothesized to deal with prediction errors arising at lower levels (Friston, 2005). That is, higher levels can either explain away the unresolved prediction error or suppress the inconsistent bottom-up signal.

The data from study 1 and 3 may suggest that a tendency to seek novel experience has no effect on awareness of the spatial anomaly. While OE is sometimes regarded as the opposite of PNS, the former is a more complex construct compared to PNS Gocłowska et al. (2017). Besides a preference for novelty, it captures artistic sensitivity, intellectual curiosity, emotional depth, etc.

Pupil size data support the conclusion that participants who did not report the incongruence were indeed unaware of it. Pupil dilation is considered a measure of surprise and expectancy violation (Grujic et al., 2024). We found that participants who reported the incongruence showed a steeper increase in pupil size when they first entered the transverse corridor, whose length is incompatible with Euclidean geometry.

This interpretation is corroborated by the results of study 2. Accordingly, the pattern of pupil dilation differs between participants who experienced blatant expectancy violation and participants who did not. We speculate that, in the case of those who reported the incongruence, the more dramatic dilation is a correlate of the realization that the corridor is longer than expected. On the other hand, participants who did not report the incongruence showed a less steep increase in pupil size, possibly because they suppressed the prediction error otherwise generated by the excessively long corridor.

Noteworthy, this finding might seem at odds with those by Bressan et al. (2008). They report that conservative participants were more likely to neglect a violation of their expectations and yet showed a more pronounced physiological response to such a violation. In light of this, one would expect participants who do not acknowledge the spatial incongruence to respond more strongly.

The experimental paradigm of Bressan et al. (2008) is somewhat comparable to ours. Yet, a key difference is that, in their case, the violation was on a perceptual level: the deviant stimulus was a black word on a white background, whereas previous stimuli were white words on a black background.

In our case, instead, the violation was at a higher level. Participants never saw the non-Euclidean area as a whole. To notice the impossible geometry, they had to integrate the dimensions of the corridor with the dimensions of the main area, and specifically with the dimensions of the central block (i.e., the one bearing the red panel, Figure 3). These elements were not visible to the participants as a whole. In our case, a lack of awareness may reflect a lack of integration rather than perceptual neglect.

This interpretation is corroborated by the results of study 1, which suggest that participants who did not report the incongruence still remembered (and thus perceived) the width of the green panel, even if such an overly long panel would not fit in Euclidean space.

In general, as Perugini et al. (2010) point out, the relationship between implicit and explicit measures can be complex and highly context-dependent: sometimes they confirm each other, sometimes they are in contrast. Yet, this is beyond the scope of the present study.

### Limitations

This study has an important limitation: We did not include a control group because the Euclidean counterpart of the hyperbolic scenario (which we used in study 1 as a control scenario) was characterized by a shorter transverse corridor compared to the hyperbolic scenario. Since the pupil data were sampled precisely in the transverse corridor, the Euclidean counterpart of the hyperbolic scenario would not have been an appropriate control.

Yet, this prevents us from concluding that participants who did not report the incongruence showed a physiological response as if there was no incongruence. In fact, we can only say that there was a significant difference in the pupillary response between those who reported the anomaly and those who did not, and that, in study 2, we found similar differences between participants who experienced overt expectancy violation and participants who did not.

# Chapter 7

## Integrative Discussion and Concluding Remarks

### Implications for Creativity Research

DXs are experiences that widely challenge one's expectations and preconceptions (Chirico et al., 2020; Gocłowska et al., 2018; Ritter et al., 2012). They cause high-level prediction errors and manifest the need of updating preexisting cognitive models. They also improve cognitive flexibility and creative thinking (Beghetto, 2021; Leung & Chiu, 2008, 2010; Ritter et al., 2012)). VR is the ideal tool for studying the effect of DXs in the laboratory: it enables researchers to bring expectancy violations to the extreme, as VR scenarios are unrestricted by the limitations of the physical world (Blascovich et al., 2002; Wiseman & Watt, 2022).

Ritter et al. (2012) capitalized on this opportunity: they show that VR experiences defying the laws of physics can indeed result in higher cognitive flexibility. However, people with certain personality traits might benefit from DXs more than others in terms of creativity (Leung & Chiu, 2008, 2010). That is, individuals with a more rigid mindset tend to respond negatively to a violation of their expectations (Gocłowska et al., 2017), or refuse to update their priors to the extent of dismissing the violations (Bressan et al., 2008).

We addressed the relationship between prediction error suppression and personality traits by testing the awareness that a VR environment had an impossible geometrical layout. This required participants to challenge the preexisting model of spatial geometry. We found evidence that PNS -but not OE- predicts the likelihood of acknowledging the impossible geometry.

Our results might thus clarify the findings by Gocłowska et al. (2014). While the authors report that incongruous stimuli boosted creativity only in participants with low PNS, they also report that such stimuli diminished creativity in participants with high PNS. To explain the latter effect, the authors remark that people with high PNS tend to prefer a persistence-driven strategy over a flexibility-driven one when performing creativity tasks (Rietzschel et al., 2007). Although schema inconsistencies can foster flexibility, the authors note, high PNS scorers would not capitalize on this effect because of their inherent bias against flexibility. Yet, the authors did not specify how and why schema inconsistency favors the flexibility approach.

Furthermore, according to the proposed explanation, one would expect DXs to leave cognitive flexibility unaffected in the case of high-PNS participants, as they could not benefit from them. Also one would expect DXs to disrupt the preferred strategy of high-PNS participants, namely persistence. Yet, the opposite occurred: Gocłowska et al. (2014) directly assessed both flexibility and persistence, and found that schema violations decreased flexibility (but not persistence) when PNS was high.

In light of our findings, an alternative explanation can be conceived: While participants with low PNS might be more likely to challenge and update their models when facing a violation of such models, participants with high PNS might respond to the violation by strengthening their cognitive models to avoid cognitive dissonance (Kaaronen, 2018; Leung & Chiu, 2008). This would result in an even stronger tendency to adopt a persistence-driven approach at the expense of flexibility.

Regarding the mechanisms through which DXs -and schema violations in general - induce flexibility, there can be various explanations. For example, DXs may trigger cognitive restructuring to resolve the contradiction, which in turn might produce an increase in the complexity of semantic networks (Bieth et al., 2024). By promoting new associations between a given set of concepts, they might induce a generalized state of hyper-associativity (Girn et al., 2020). This hypothesis is supported by evidence that novel concept associations enhance creativity (Miron-Spektor et al., 2011; Wan & Chiu, 2002). However, the direct assessment of semantic networks' structure showed that new associations between certain distant concepts, which were the key for solving a riddle, do not produce new associations between concepts unrelated to the riddle (Bieth et al., 2024). Future research on the changes in semantic networks' structure after DXs may shed light on this point.

Another possibility is that DXs trigger an exploratory cognitive mode, which in turn enhances creativity by favoring cognitive flexibility, diminishing latent inhibition of seemingly irrelevant ideas, and broadening the scope of attention (Boot et al., 2017; Ivancovsky et al., 2024; Jauk, 2019; Nijstad et al., 2010).

That is, if the environment manifests the inadequacy of prior cognitive models, an exploratory mode is warranted. It can be said that adapting to unprecedented situations is comparable to solving an ill-defined problem with a creative approach. Because no validated behavioral strategy is available, individuals need to come up with novel strategies and consider various possibilities (Beghetto, 2021; Ivancovsky et al., 2024). To do so, it is crucial to acquire knowledge about the new situation, and to attend to a broad range of elements as it is unknown which elements will be relevant. Accordingly, while people entering a well-known environment quickly focus on salient elements, those entering a novel environment scan all elements before identifying the relevant ones (Küçüktütüncü et al., 2025; Stark, 1981). In such cases, a flexible state of mind is required to update cognitive schemata, accommodate the new information, and shift away from old preconceptions (Ivancovsky et al., 2024).

It can be speculated that people living in a stable environment are biased towards exploitation and persistence, while those living in a volatile environment are biased towards exploration and flexibility. On the one hand, a fixed environment warrants persisting in behavioral strategies fine-tuned to those specific circumstances, and rewards dismissing conflicting information as noise rather than updating the strategies (Beghetto, 2021; Kaaronen, 2018). On the other hand, a volatile and ever-changing environment rewards constant updates of cognitive models and strategies (Beghetto, 2021; Kaaronen, 2018). This would explain the higher creativity of those with turbulent upbringings and diverse social backgrounds (Martindale, 1972; Simonton, 1999). Beghetto (2021) even argues that creativity primarily stems from uncertainty.

The theory of Predictive Coding offers some insight into the neuro-computational mechanism regulating the interplay between flexibility and persistence depending on environmental circumstances (Constant et al., 2024; Friston et al., 2017). Accordingly, the brain seeks to minimize prediction errors, which would theoretically imply a preference for predictable environments. This logic is pushed to an extreme by the “dark room problem”: If the brain aims for predictability, living in a completely dark room would maximize it (Sun & Firestone, 2020). However, many people do exactly the opposite and actively seek novelty (Friston et al., 2017).

Indeed, the dark room problem underlies a naive conception of Predictive Coding (Friston et al., 2017). That is, living in a dark room would be the optimal solution if all physiological needs were satisfied and the circumstances were absolutely stable (Friston et al., 2017). Clearly, this is not the case, as life is highly mutable and the brain had to adapt to face this instability. In fact, exploring the environment and actively engaging in novelties results in a more comprehensive and accurate model of the world; it increases the likelihood of insight learning, and ultimately reduces prediction errors (Friston et al., 2017).

Through a computational simulation, Constant et al. (2024) provide evidence that creative behaviors are advantageous in a volatile environment - where effective predictive models are difficult to build. Even though simulated agents with a fixed behavior in a fixed environment (i.e., the baseline) completed a task faster overall, many agents with a creative behavior in a dynamic environment completed the task faster than the baseline average - although this group displayed great score heterogeneity.

We did not directly assess whether DXs influence flexibility and creativity through expectancy violations. Yet, our finding that participants with high PNS are less likely to update their cognitive models, paired with evidence that DXs impair creativity in the case of these participants (Gocłowska et al., 2014), may provide indirect evidence of this relationship.

We found that neither OE nor SS influenced the likelihood of challenging preexisting schemata. Notably, OE was reported to modulate the positive effect of multicultural experiences (Leung & Chiu, 2008), yet this effect might have other explanations. In fact, the relationship between OE, DXs, and creativity might be complex (Wiseman & Watt, 2022).

Because high OE correlates with the enjoyment of expectancy violations (Gocłowska et al., 2017), individuals with high OE might be more likely to actively seek DXs and engage more deeply in a novel environment (Gocłowska et al., 2019; Maddux & Galinsky, 2009; Maddux et al., 2010). Indeed, Maddux et al. (2010) found that the positive effect of multicultural experiences on creativity is mediated by the extent to which expats merge in the foreign culture.

A greater engagement with a new environment, in turn, may foster creativity for various reasons. First, it promotes the encounter with ideas that are distant or even opposite to those of the mother culture: these new ideas can be incorporated and integrated, producing associations between seemingly contradictory elements (Chirico et al., 2022; Leung & Chiu, 2010; Maddux & Galinsky, 2009; Maddux et al., 2010). Second, it broadens the knowledge base, providing more elements to recombine during the creative process (Ivancovsky et al., 2024; Jauk, 2019). Third, it creates more opportunities to face unpredictable situations, which in turn may shift cognition towards exploration and flexibility even further (Beghetto, 2021; Ivancovsky et al., 2024; Jauk, 2019).

Still, since exploratory disposition and flexible mindset are associated with a higher tendency to revise cognitive models, individuals with high OE should also be more prone to challenge their mental schemata (Ivancovsky et al., 2024). This contrasts with our findings. It may be possible to shed light on this discrepancy by directly assess participants' exploratory state of mind. This can be done, for instance, through pupil dilation, a biomarker of exploratory state (Ebitz & Moore, 2019; Grujic et al., 2024).

Taking into account our results and those of previous studies (Gocłowska et al., 2014; Leung & Chiu, 2008, 2010; Ritter et al., 2012), we speculate that 1) DXs contradict prior models and manifest the need for a cognitive update, which in turn may bias cognition towards flexibility, and/or induce knowledge reorganization; 2) high PNS negatively influence this effect, as it entails resistance to challenging mental schemata; 3) OE implies higher flexibility by default and a higher tendency to seek DXs. These points are summarized in Figure 20), which may integrate the diagram proposed by Beghetto (2021) to schematize the effect of destabilizing events on creativity. Again, more experimental evidence is necessary to confirm this conceptualization.

In conclusion, our results may inform future research on this topic, which should seek to confirm that the creativity-boosting effect of DXs stems from challenging prior cognitive models, and that personality plays a modulatory role.

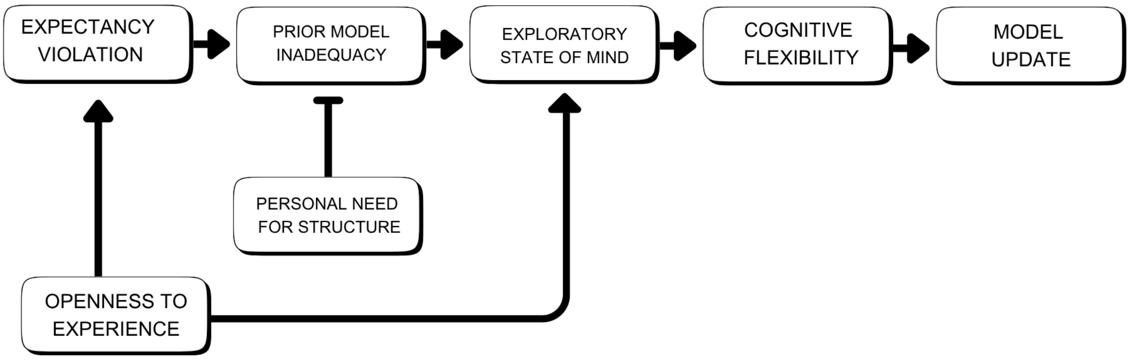


**Figure 20.** Diagram showing the hypothesized mechanism through which individuals respond to diversifying experiences, and through which personality traits like Personal Need for Structure and Openness to Experience influence the response.

## Future Directions of Research on Diversifying Experiences

More evidence will be required to elucidate whether DXs enhance creativity through expectancy violation and the need for cognitive update, and whether personality traits modulate this mechanism. In particular, it would be ideal to test a correlation between the extent of the model update and the creativity enhancement. This would help clarify whether the effect depends on the knowledge restructuring itself or on the need to reorganize the knowledge when facing the inadequacy of the old framework. In the former case, the creativity enhancement would correlate with the magnitude of the restructuring.

This can be done by assessing the performance of participants on a task that requires restructuring their knowledge. Studies on insight problem solving employed paradigms -e.g., solving riddles- that require this kind of approach to find a solution (Bieth et al., 2024; Ritter & Dijksterhuis, 2014; Tulver et al., 2023). However, in such cases, it is difficult to quantify the extent of the underlying restructuring (even if Bowers et al. (1990) attempted to do so by assessing the closeness to the correct answer). Once again, VR can be instrumental for this purpose. We thus developed a four-dimensional VR scenario in order to assess the extent of participants' update of their model of spatial geometry.

In a four-dimensional space, an additional spatial coordinate is required to describe the position of a point apart from the three canonical dimensions (height, width, depth). The scenario we designed is precisely a hypercube, namely the counterpart of a cube in four dimensions. Although we cannot directly visualize the shape of a hypercube, it can be represented in 3D as an object resembling eight cubes arranged as a cross (Figure 21). In reality, all such cubes are paradoxically interconnected. For example, two cubes apparently located at opposite ends are in fact attached as if the space were bent.

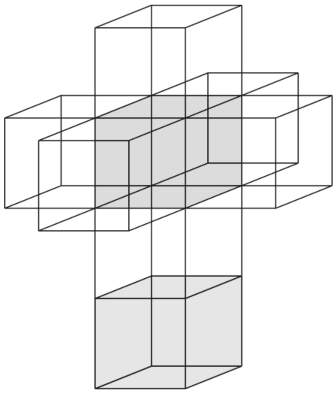


**Figure 21.** 3D representation of a hypercube, namely the four-dimensional counterpart of a cube. Note that the true structure of a hypercube can not be represented in 3D, this is only an approximation. As it is only possible to represent a cube in 2D by "unfolding" and "flattening" it in the two dimensions, a hypercube can be represented in 3D by "unfolding" and "flattening" it in the three dimensions.

More specifically, the scenario is a hypercubic villa inspired by the tale *And he built a crooked house* by Robert A. Heinlein, and is composed of eight rooms arranged as in figure 21. In such a villa, the rooms are all connected directly, even if they seem distant. For example, it is possible to travel between the top and bottom rooms without passing through any other room.

Participants will be asked to explore and map the virtual environment. To prompt the exploration of the whole villa and assess the extent to which they will have mapped the impossible space, they will be explicitly instructed to memorize the layout of the rooms, as this will be essential for the following task.

Indeed, after the exploration phase, they will be asked to collect a series of gems located in the various rooms of the villa as quickly as possible. To accomplish it, participants will have to understand the four-dimensional structure of the villa, orient themselves in a space that conflicts with any previous spatial experience, and capitalize on the impossible links between the rooms. In other words, participants will need to update their cognitive representation of space to account for a completely new type of spatial geometry.

Note that this can be considered the physical analogue of the very definition of the creative process - connecting remote concepts to solve a problem (James, 1890; Mednick, 1962). In this case, participants will need to connect rooms far apart to complete the task.

Noteworthy, when participants will be collecting the gems located in the rooms, it will be always possible to reach a subsequent room directly from the previous one. So, we will consider the length of the participant's path as a proxy of the accuracy of their cognitive map of the villa. In other words, we will consider it as a measure of their ability to update their model of spatial geometry.

In light of the findings described above, we will test whether PNS will impair the ability to map the villa and modulate the effect on creativity. We will also test whether shorter paths correlate with a more exploratory state of mind, which in turn may promote the creativity boost (Herz et al., 2020; Ivancovsky et al., 2024). We will do so by assessing pupil dilation during the exploration phase (Ebitz & Moore, 2019; Grujic et al., 2024).

If participants performing better (i.e., collecting the gems more quickly and taking shorter routes across the villa) will show a more pronounced increase in creativity, it will support the direct role of cognitive update in mediating the effects of DXs. On the contrary, if the creativity enhancement and the performance will be uncoupled, it will suggest that facing the inadequacy of the prior model may be enough to produce the effect through cognitive flexibility.

In light of the results of the present research, we hypothesize that both the performance and the creativity boost will be influenced by PNS. Because gender and video game experience were found to play a role in the previous studies, we will also control for these variables.

Regarding pupil dilation, it is difficult to make accurate predictions: not only does pupil size depend on the balance between exploration and exploitation, but it may also underlie other cognitive processes, such as the cognitive demands of the task (Kahneman & Beatty, 1966; Porter et al., 2007). Also, experiencing VR can itself trigger an exploratory state in VR naive participants - as we think it was the case in study 2. In light of this, the assessment of pupil size will only be exploratory.

## Theoretical Remarks and Conclusion

The present research focused on individual responses to violations of fundamental cognitive models. Our results are consistent with the long-standing idea that the experience of reality is a mental construct. In this regard, Slater and Sanchez-Vives (2022) discuss how virtual reality can be instrumental for testing this hypothesis. Indeed, VR simulates just the instance of conscious experience which does not underlie a "true," objective substrate. More generally, VR can be considered the ultimate tool for testing the way in which we experience reality: it allows experimenters to manipulate the experience of (virtual) reality as a whole.

We found that the experience of the geometry of a virtual space changes across individuals. Therefore, that which is normally believed to be a fundamental property of reality, namely space, might in fact "just" result from our brain applying a priori models to sensory inputs. This echoes the revolutionary intuition of 18th-century philosopher Immanual Kant, according to whom time and space are not properties of things “out there,” but rather *a priori forms* through which the mind gives a structure to the sensory experience of the world (Kant, 1999).

It can be said that Predictive Coding provides a neuro-scientific and neuro-computational scaffold to this idea (Friston, 2005, 2009). That is, rather than passively registering the properties of the external world, the brain would sculpt our conscious experience of the world through predictive priors. Just like cookie cutters, such models would impress a shape upon the amorphous flow of inputs reaching the brain every second, so that percepts can arise.

A remarkable difference is that Kant believed a priori forms of time and space to predate sensory experience, while predictive priors would instead arise with experience. A study by Wills et al. (2010) supports the latter view and explicitly challenges Kant’s philosophy, as the authors found that spatial cognition in new-born rodents is not innate but acquired.

A further, and perhaps complementary, conceptual framework that casts doubt on the existence of objects beyond our conscious experience is the Interface Theory of Consciousness (Hoffman, 2019). Accordingly, consciousness would "only" serve the purpose of allowing the most efficient interactions with the outside world, providing an interface between us and the environment. In other words, consciousness would be similar to a computer screen, and objects would be like icons that enable to perform the desired actions even though they do not "truly" exist beyond the screen. It follows that our conscious experience would not be tuned to reflect the outside world as faithfully as possible: it would only reflect its affordances.

Our results fit nicely with the Interface Theory of Consciousness (Hoffman, 2019). We show that how people represent space doesn't necessarily match how space actually is. Since the goal was simply to navigate the virtual environment and collect tokens, a straightforward Euclidean representation would have done the job.

In sum, our findings are consistent with the view that experienced reality is actively constructed by the brain, and provide additional support for theoretical frameworks that may help advance the century-old philosophical debate on the nature of human consciousness.

Besides this theoretical contribution, the present research can also inform the potential applications of DXs. Arguably, fostering human creativity becomes even more crucial as our world is rapidly reshaped by technological advancements. As automation transforms industries and redefines what it means to work, learn, and connect, creativity will enable individuals and societies to adapt, innovate, and find meaning amid constant changes. Indeed, creativity allows humans to cope with novel challenges in unpredictable and ever-changing environments (Beghetto, 2021),

Emerging technologies themselves, however, might pose an unprecedented threat to human creativity. In a pre-print that was boisterously - and often inaccurately - covered by the media, Kosmyna et al. (2025) report reduced EEG connectivity during the use of ChatGPT for writing an essay compared to a brain-only condition. If creativity is a muscle that can be trained (Ritter et al., 2020), it can also shrink.

We believe that emerging technologies are not necessarily a threat to human creativity. In fact, they can benefit human creativity and help ensure that human creative capacities remain competitive in the age of artificial intelligence.

VR might allow everyone to afford DXs such as multicultural experiences, even those individuals who otherwise lack physical or financial capabilities. In other words, VR has the potential to democratize experiences that are currently a privilege or a risk, potentially providing creativity booster for everybody. In this context, it is crucial to understand how individual differences can impact the effects of DXs. This knowledge would enable calibrated interventions in education and organizations (Beghetto, 2021; Ritter et al., 2020).

Also, while we discussed the applications DXs in VR to creativity, DXs can also have other applications. Gaggioli and colleagues (Chirico et al., 2022; Gaggioli et al., 2016) broadly discuss the potential of so-called *transformative experiences*, and how to achieve them in VR. Accordingly, these are out-of-the-ordinary experiences that induce a radical cognitive restructuring, leading to profound, long-lasting, and irreversible changes in an individual's identity, values, and worldview. They can foster personal growth, help overcome emotional blocks, and achieve a stronger sense of fulfillment.

They could also have clinical applications. For example, it was proposed that experiences manifesting the need for a cognitive update would ameliorate depressive symptoms (Chirico & Gaggioli, 2021). Indeed, cognitive restructuring potentially plays a crucial role in psychotherapy, especially in overcoming persistent maladaptive thoughts or behaviors (Clark, 2013).

More importantly, transformative experiences can produce changes so deep that they help discover new meanings and purposes. While Artificial Intelligence increasingly overtakes human tasks, the risk is that this will deprive our lives of meaning. Thus, it is crucial that technology not only automatizes human labour but also helps us find a new place for ourselves in a brand new world where many human activities are not essential anymore.

## Acknowledgements

I want to thank professor Alessandro Gabbiadini for allowing me to become a better scientist. His remarks and comments were blunt, sometimes harsh, yet always helpful and constructive. I will never forget his many lessons.

I want to thank professor Marcello Gallucci, who made me enjoy statistics (it sounds impossible but he could indeed). I want to thank professor Alberto Gallace, for welcoming me in MiBTech laboratory, where the future becomes present. I want to thank Professor Andrea Gaggioli who, despite not being my tutor anymore, never ceased to be my mentor and model.

I want to thank Sharon, Luca, and Emanuele, who tolerate my chaotic manners and my extravagant personality for so long. I am especially grateful to Sharon, whose kindness and sweetness often changed my days for the better.

I want to thank ChatGPT for helping me edit this manuscript by doing tedious tasks like paraphrasing and summarizing in my place.

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## Supplementary Figures

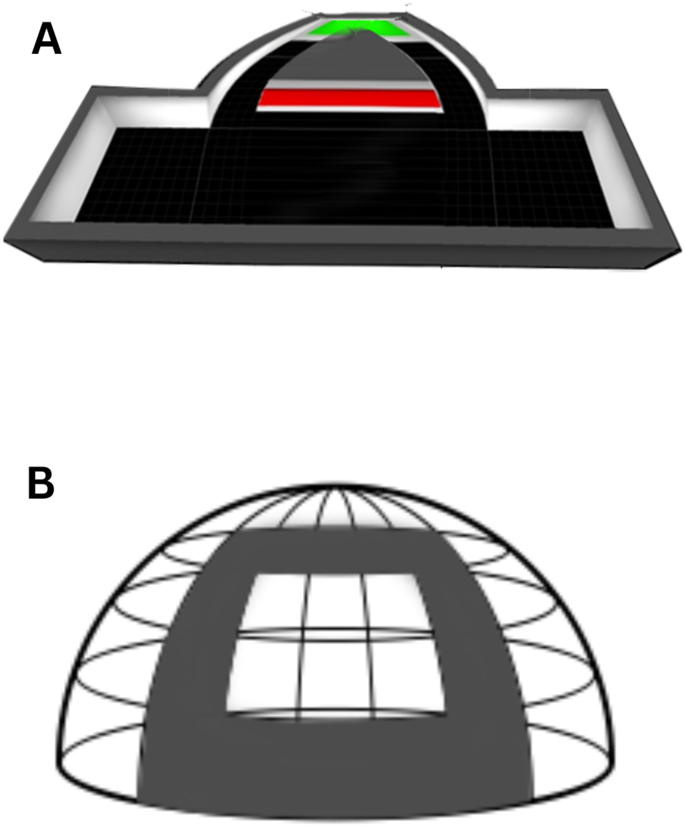

**Figure S1.** Attempt to describe the participant's experience of the elliptic environment (A): the longitudinal corridors are both parallel and convergent. They violate Euclid's 5th postulate, forming a non-Euclidean shape called the obtuse Saccheri quadrilateral (B). Please note that this is not the true map of the 3D scenario, since a non-Euclidean environment cannot be depicted in 3D.

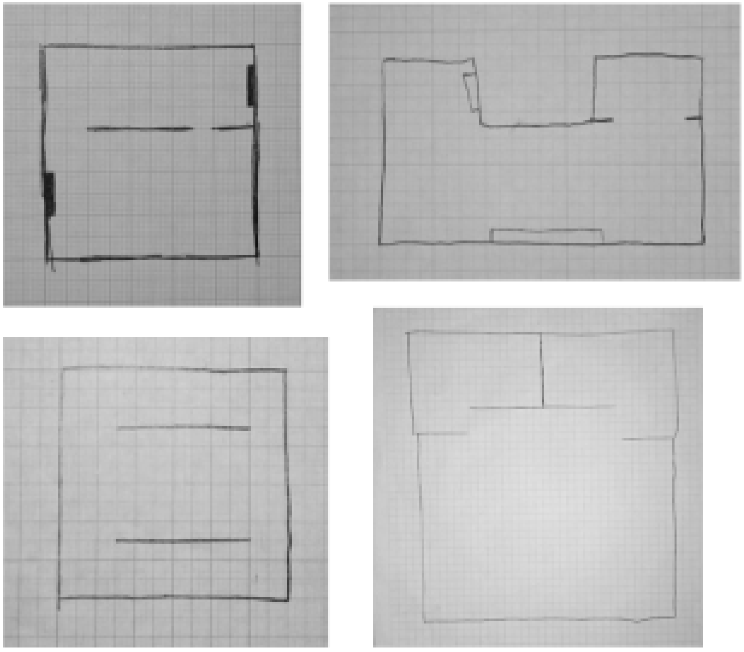

**Figure S2.** Puzzling maps of the VR environment drawn by participants who experienced the elliptic condition and its Euclidean counterpart.