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The processing of emotional body expressions within architectural experience: electroencephalography and eye-tracking studies in virtual reality

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Abstract

The perception of emotional body expressions is crucial to human social behavior. Historically, researchers have investigated how we perceive emotional body expressions isolated from their context, characterizing the underlying brain mechanisms without considering the effect of the natural background in which we typically interact. Therefore, the present dissertation aims to study how the processing of emotional body expression is influenced by the surrounding architectural space in which human beings spend most of their lifetime.

To this aim, I conducted two initial studies to characterize both avatars' body postures and virtual architectures in terms of their affective components. The obtained results laid the basis for a third study where avatars and architectural spaces were combined to recreate a controlled environment resembling a social scenario. Specifically, using Virtual Reality (VR) technology, participants dynamically experienced the surrounding architectural space and then faced a virtual avatar with different emotional body postures.

The analysis of electroencephalographic (EEG) signals and eye-gaze behavior revealed that the processing of emotional body expressions was influenced by the architectural experience, which modulated early evoked potentials and oscillatory activity related to attentional mechanisms as well as the visual exploration of the avatar's body. Moreover, the source localization analysis revealed that the processing of both the architecture and body expressions activated motor-related brain areas, proving that the space/cognition interplay is rooted in common neural substrates.

Overall, these studies demonstrate that the architectural experience modulates brain mechanisms underpinning the processing of others' affective states, showing that the mere manipulation of the surrounding architecture is sufficient to influence human behavior in social interactions.

Summary

Despite most of our everyday social interactions occurs within built environments, too often the effect of the surrounding space has been neglected or considered as marginal in influencing our social behavior. In the last decades, the way we perceive others' emotional body postures, conveying important affective information, has been considered fundamental in social interactions, yet to date only few studies have tried to understand how the perception of such emotional cues is influenced by contextual factors. For this reason, the aim of the present dissertation was to shed light on brain mechanisms underpinning the processing of emotional body expressions modulated by the surrounding architecture, being the natural context in which individuals spend most of their lifetime and engage social interactions. In Chapter 1, I will introduce the theoretical framework of my dissertation. Firstly, the reader will find a brief review about the role of the body in conveying affective states, exploring the neurophysiological and behavioral mechanisms underlying the processing of emotional body expression. Then, I will show how little is known about the influence of the context on such mechanisms, especially considering the surrounding architectural space as the natural context of our everyday social interaction. Therefore, I will examine the neural mechanism underpinning the space processing in general, showing then how the architectural space is processed in particular, impacting on inhabitants' affective state and behavior. At the end of Chapter 1, I will briefly present the studies conducted during my doctoral program, pointing to the need of investigating the interplay between the processing of others' affective state and the architectural experience.

For the purpose of this dissertation, three separate experiments were conducted. In the first study, presented in Chapter 2, specific bodily cues were exploited to transfer affective information from dynamic emotional walking recorded on real actors to static avatars' body postures. The validity of the proposed methodology was evaluated by means of two online surveys, where participants were asked to judge the level of arousal and valence conveyed by the avatar' body posture. Results showed that participants

coherently judged the affective state portrayed in the automatically constructed body postures of the avatar.

In the second study, presented in Chapter 3, I evaluated how a dynamic experience of the surrounding architectural space impacted on participants' affective states. Specifically, I exploited a VR headset to make participants virtually walking within a set of 54 different architectures. Architectures varied according to three form factors (sidewalls distance, ceiling height and windows sill heigh) and color (cold and warm). After virtually crossing the space, participants were asked to rate the architectural experience in terms of perceived arousal and valence. Results revealed that spaces characterized by a progressive reduction of the surrounding space were perceived as more anguishing, because rated as high arousing and unpleasant.

Finally, in the third study, presented in Chapter 4, I have recreated a realistic social scenario in VR exploiting the results of the previous studies. The EEG activity and eye-gaze behavior of participants were recorded while they observed avatars' body posture after the dynamic experience of architectural spaces realized as a virtual promenade. At a late stage of processing, the different arousal level of the body postures was indexed by the modulation of the late positive potential (LPP) over centro frontal electrodes as well as by the alpha desynchronization over parietal and frontal sites. Strikingly, the effect of the architecture preceded such evaluation of about 250 ms. In fact, when the avatar was presented within low arousing architectures, the EEG analysis revealed a higher P200 peak amplitude locked to the avatar presentation and a higher theta synchronization over central electrodes at an early stage of processing. In the same experimental condition, we found higher fixation times on the head of the avatar and higher arousal ratings. Finally, source localization highlighted a contribution of the dorsal premotor cortex to both P200 and LPP.

Overall, the studies conducted across all the three years of my doctoral program allowed me to reveal brain and behavioral mechanisms underlying the processing of emotional body expressions influenced by the dynamic architectural experience. Main results revealed that the dynamic architectural experience modulates attentional mechanisms at an early stage of emotional body processing by facilitating the redirection of attentional resources on the body of the avatar. Instead, at a later stage of processing, the evaluative process of arousal discrimination of the avatar’s body posture takes place, regardless of the surrounding environment. In addition, the motor system plays a role in processing both architecture and body expressions proving how the space/cognition interplay is rooted in common neural substrates. In conclusion, these findings highlight that when social interactions occur within an enclosed space, the way we approach each other may also depend on the architectural experience, proving that the manipulation of mere architectural space is sufficient to influence human social behavior. A general discussion and the conclusion of this dissertation is presented in Chapter 5.

CHAPTER I – Introduction

1. The role of the body in the expression of affective states

A crucial aspect of human's social behavior is the capability to comprehend the emotional state expressed by another person. Starting from "*The Expression of Emotion in Man and Animals*" by Darwin in 1872, it has been claimed that emotion eliciting situations are reflected in typical postures of the body, for both humans and animals (Darwin & Prodger, 1998). Nevertheless, in the field of Affective Neuroscience researchers were firstly focused on face expressions, and only in the last decades a growing interest has been shown also for body expressions, leading to the consciousness that our body is not simply a tool for actions but also an important medium for emotion expressions. The lack of interest towards body rather than face expressions was probably due to daunting results of first studies including the body in emotion perception (de Gelder, 2009; Ekman, 1965). Nevertheless, in recent studies, it has been proved that participant's accuracy in recognizing emotions from body movements and postures was comparable to that of faces (Atkinson et al., 2007; Zieber et al., 2014). Moreover, under certain circumstances, body expressions provide useful information that facial expressions would be unable to afford. For instance, this is the case of looking a person from a great distance, which make the larger size of the body a powerful cue facilitating the recognition of the emotion (de Gelder, 2009). Also, while faces are important to recognize the identity of a person, the body conveys useful information to understand actions and intentions of the other (de Gelder et al., 2010; di Pellegrino et al., 1992; Iacoboni et al., 2005), giving to the perception of the other's body expression a pivotal role during social interactions. This is the reason why, during social interactions, people spend almost half of the time looking at the body of the other person, trying to decode other's affective states and intentions (Bindemann et al., 2010).

In this regard, several studies have already demonstrated that our perception of others' affective states is based on specific bodily cues (Kleinsmith & Bianchi-Berthouze, 2013; McColl & Nejat, 2014; Stephens-Fripp et al., 2017). This is because different affective states are communicated to the external world through the adjustment of specific body part's positions, or through the dynamicity of the gestures. The leaning of the head/trunk as well as the overall extension of the body can discriminate between pleasant and unpleasant emotions. For instance, walking with a downward leaning of the head/trunk highlights unpleasant affective states such as anger and sadness. On the other hand, an upward orientation identifies joyful and pride walking (Hicheur et al., 2013; Karg et al., 2010; Venture et al., 2014). The dynamicity of the movement is usually linked with the intensity of the emotion reflecting its arousal component. High arousing emotional states are typically communicated to the external world with rapid and dynamic gestures, while low arousing states are characterized by more slow movements. In this direction, previous studies reported that the speed of an emotional walking was positively correlated with the arousal dimension (Deligianni et al., 2019; Halovic & Kroos, 2018a; Roether et al., 2009). Specifically, sad walking were characterized by slow movements, while joy and anger walking, typically considered high arousing emotions, were characterized by fast and rapid movements (Barliya et al., 2013; Bernhardt & Robinson, 2007; Gross et al., 2012; Randhavane, Bera, Kapsaskis, Sheth, et al., 2019).

1.1. The processing of emotional body expressions

The evidence of the importance of the body in being able to effectively communicate humans' affective states is reflected also in the increasing number of studies investigating the mechanisms underpinning the processing of emotional body expressions. In the following paragraphs I will firstly describe the brain areas and the correspondent neural mechanisms involved in the processing of emotional body expressions. Then, I will characterize more in detail the temporal dynamics of such processing, by reporting several ERPs studies revealing how different cognitive processes occur in correspondence of specific latencies from the presentation of the emotional body expression. Finally, I will describe how emotional body expressions are processed in terms of visual exploration, reporting evidence from a series of eye-tracking studies.

1.1.1. Neurophysiological basis of emotional body expression processing

The first neuroimaging studies were focused on localizing brain areas involved in the perception of neutral human bodies. In a fMRI study, Downing and coworkers in 2001 (Downing et al., 2001) found that, compared to control stimuli, the presentation of human bodies selectively activated a brain area located in the lateral occipitotemporal cortex, i.e., the extrastriate body area (EBA) (Peelen & Downing, 2007). Later fMRI studies also found common areas activated both during the processing of faces and bodies in the mid-fusiform gyrus (mid-FG). Specifically, one of such region in the FG, partially overlapping with the fusiform face area (FFA), was found to be selectively activated during the perception of human bodies, i.e., the fusiform body area (FBA) (Downing et al., 2001; Hadjikhani & de Gelder, 2003; Peelen & Downing, 2007; Schwarzlose et al., 2005; Spiridon et al., 2006). On the other hand, the processing of emotional human bodies activates more complex networks involving different brain areas. Specifically, Beatrice de Gelder elaborated two interrelated systems acting in parallel for the processing of emotional body postures (de Gelder, 2006). The primary network is involved in an automatic perception of emotional body postures thus fostering a rapid preparation of adaptative reflexes. Subcortical structures, such as the superior colliculus, pulvinar, striatum (putamen and caudate) and basolateral amygdala are part of this network, which also have direct and strong connections with motor structures. For instance, such a network is recruited whenever angry or threating expressions are presented and a fear adaptative behavior is recalled. The second system is more involved in processing the emotional body in detail, computing the potential behavioral consequence of the emotional stimulus and subsequently prepare an adaptative response action. Hence, it includes the frontoparietal motor system, involving the lateral occipital complex (LOC), superior temporal sulcus (STS), intraparietal sulcus (IPS), fusiform gyrus (FG), amygdala (AMG) and the premotor cortex (PMC).

In this regard, the activation of motor-related area during the observation of emotional bodies is of particular interest, suggesting the involvement of motor resonance mechanisms which are thought to facilitate intersubjective empathy (Arioli et al., 2021; Calbi et al., 2017; Rizzolatti & Craighero, 2004). The emotional content of the posture elicits a different motor activation as if watching an action that is performed with an emotion induces an affective modulation of the motor program (de Gelder, 2006; Grosbras & Paus, 2006; Pichon et al., 2009). This is made possible via the fronto-parietal Mirror Mechanisms, comprising the inferior parietal lobule (IPL), inferior frontal gyrus (IFG), PMC, and STS (Jastorff et al., 2016; Rizzolatti et al., 2001; Rizzolatti & Craighero, 2004), which provides the neurobiological basis for many emotional and social cognition skills (de Gelder, 2006; Gallese et al., 2004) by linking the observation of an action with the triggering of action representation and emotion understanding (Carr et al., 2003; Preston & Waal, 2002). In this direction, body expressions of fear were compared to neutral ones using an event-related fMRI paradigm (de Gelder et al., 2004; Grèzes et al., 2007), showing that activations in the STS and PMC were stronger for fear expressions rather than for neutral actions. Interestingly, such result did not simply reflect a quantitative difference in low-level motion information between the two conditions as the movement component was similar for fear and neutral expressions, and thus encoded the emotional component. Similarly, viewing anger body expressions compared to neutral ones generated a greater activation in the STS, FG, and PMC irrespective the presence of movement in the stimulus (Pichon et al., 2008). In a study combining fMRI and EEG techniques, Conty and colleagues found a greater activation of motor-related cortical areas (PMC and supplementary motor area (SMA)) just after 200 ms from the presentation of angry body postures. They argued that such activity may reflect an embodied response that serves for the comprehension of the others' inner states, thus facilitating the preparation of an adaptative response. Specifically, the PMC activity was linked to the degree of potential social interactions and consequently observing angry body postures was the experimental condition that elicited the highest activity (Conty et al., 2012). Overall, these studies confirm the straight link between actions, emotions and social behavior highlighting that the processing of emotional body expressions activates canonical action representation circuits along with the mirror neuron system, i.e., neural circuits directly involved in social cognition (de Gelder et al., 2004; Gallese et al., 2004).

1.1.2. Temporal dynamics of emotional body expression processing

Thanks to its high temporal resolution, the electroencephalography (EEG) enables the evaluation of the temporal dynamics underpinning the processing of emotional body postures. Over the last few years, paralleling the growing interest about the understanding of how we process emotional body expressions, several studies have been conducted evaluating event-related potentials (ERPs) time locked to the presentation of emotional human bodies. Typically, the processing of emotional stimuli is reflected in the modulation of several brain components across different latencies, and the timing of this modulation tell us important information about the undergoing cognitive and affective processing (Mueller et al., 2017). At a very early stage of processing, the P100 component arises at occipital electrodes and is characterized by a positive deflection around 65 – 135 ms after the presentation of the stimulus (Meeren et al., 2005). At this very early stage, different emotions are not discriminated by the P100 peak amplitude, yet higher-order information from the body are already processed. For instance, the emotional incongruency between facial and bodily expressions generates higher P100 peak amplitude compared to emotional congruent face and bodies (Meeren et al., 2005; van Heijnsbergen et al., 2007). Around 160 – 220 ms from the presentation of body stimuli, a negative deflection named N190 occurs in the right-dominated middle temporal gyrus, approximately in the EBA (de Gelder et al., 2015). This component reflects the visual encoding of the body and was found to be sensitive both to the emotional content and motor information displayed in the body expression (Borhani et al., 2015; Thierry et al., 2006). For instance, in a recent work conducted by Ding and colleagues, they found that fear body expressions generated a higher N190 peak amplitude with respect to neutral ones over parietal electrodes (Ding et al., 2022). Ranging from 150 to 300 ms after the stimulus onset, the P200 occurs, which is a positive deflection localized over more central and frontal electrodes (Ibanez et al., 2012; Pauligk et al., 2019; Rossignol et al., 2013). The P200 modulation generally reflects early attentional processes directed towards the presented stimulus, with higher peak amplitude coding a higher allocation of attentional resources on emotional salient stimuli (Ashley et al., 2004; Calvo et al., 2013; Paulmann et al., 2013; C. Wang et al., 2022). Hence, emotional body expressions were typically found to generate a greater P200 peak amplitude. For instance, Jessen and coworkers found that both angry and fearful body expressions evoked a greater P200 amplitude compared to neutral ones (Jessen et al., 2012; Jessen & Kotz, 2011). Another interesting research evaluating the P200 modulation was conducted by Conty and colleagues, who recreated stimuli using photographs of actors where different social parameters were manipulated: gestures (pointing or not pointing), emotion (neutral or angry) and gaze direction (directed ore averted gaze direction). Their results revealed that the higher P200 amplitude was reached when the actor expressed anger and look and pointed toward the participant, i.e., the stimulus with the highest degree of potential social interactions, showing that, at this stage of processing, the P200 indexes an early binding of social relevant cues (Conty et al., 2012). Finally, the discrimination between different emotional expressions is made at a late stage of processing, producing a modulation of a slow and sustained positive component known as late positive potential (LPP) (Calvo et al., 2013; Hajcak & Olvet, 2008). LPP modulations occur between 300 – 900 ms after the stimulus onset at centroparietal sites and indicates an evaluative process of emotional stimuli, with higher amplitudes for emotional vs neutral stimuli (Cuthbert et al., 2000; Hajcak & Foti, 2020). Higher LPP was also associated with high arousing stimuli, possibly reflecting a greater sustained attention to motivationally relevant stimuli (Lang & Bradley, 2010; Leite et al., 2012; MacNamara et al., 2022; H. Schupp et al., 2004; H. T. Schupp & Kirmse, 2021). In this direction, the observation of high arousing body postures generates higher LPP amplitude compared to low arousing one (Flaisch et al., 2011; Li & Wang, 2021).

1.1.3. Brain oscillatory activity during processing emotional body expression

Besides the evaluation of the temporal dynamics underlying the processing of emotional body expressions realized through ERPs studies, the EEG also permits the analysis of the cortical oscillatory activity evoked by the processing of external stimuli. Analysis of the oscillatory response, which reflects fluctuations in the synchronization of neural populations, provides key information on the physiology of the brain dynamics. Specifically, the EEG signal can be treated as a sum of sinusoids which are separated into characteristic frequency bands describing different cognitive and computational processes. Typically, the considered bands of interest to investigate the processing of social stimuli such as emotional facial and body expressions are theta (4 – 7 Hz), alpha (8 – 13 Hz), beta (15 – 30 Hz), and gamma (30 – 40 Hz). A relative increase/decrease in power of each frequency is usually referred to as event-related synchronization/desynchronization when it is time-locked to the presentation of an external stimulus. Facial expressions and emotional pictures such as IAPS pictures (International Affective Picture Systems) are by far the most studied stimuli in this field, whereas the number of studies investigating the oscillatory activity related to body expressions is more limited. In a study by Jessen and colleagues (Jessen & Kotz, 2011), they focused on multimodal perception of emotional stimuli by combining facial, body and vocal expressions. Stimuli were presented either simultaneously or alone and were characterized by two emotional contents expressing either fear or anger, plus a neutral condition where non-emotional stimuli were used. Interestingly, they found that oscillatory activity was mainly influenced by the visual condition and not by the auditory signal when processing emotional vs neutral stimuli. Specifically, they found stronger desynchronization for both alpha and beta frequency range for the emotional stimuli compared to neutral ones. Alpha suppression was associated with a greater attentional load on emotional expressions, and thus on highly salient stimuli (Ward, 2003). Instead, beta suppression was associated to action planning in response to both visual and audiovisual emotional stimuli (Tzagarakis et al., 2010). In another work by Siqi Liu and colleagues (Siqi-Liu et al., 2018), authors compared the brain oscillatory activity when participants observed emotional (happiness, sadness and anger) and neutral body movements resembled by point-light displays (PLDs) in coherent biologically plausible and scrambled configuration. They found the processing of coherent vs scrambled as well as emotional vs neutral PLDs elicited a stronger alpha desynchronization over sensorimotor areas up to 2 s after the presentation of the stimulus. Known as the μ – rhythm, this oscillatory activity is typically observed in the alpha frequency range and localized over central electrodes (Niedermeyer & Silva, 2005). Suppression of the μ – rhythm has been associated with action understanding, empathy and social processes, reflecting motor resonance mechanisms activated by the observation of others' actions and emotions (Perry et al., 2010, 2017; Rizzolatti et al., 2001; Ulloa & Pineda, 2007).

In addition, Bossi and colleagues (Bossi et al., 2020) investigated the theta and gamma activity associated with the processing of emotional face and body expressions presented either upright or inverted. As for the body expressions, they found only a modulation in theta, showing an increased synchronization while observing upright rather than inverted postures related to a faster configural processing. In fact, theta modulations are typically associated with several cognitive and attentional mechanisms, showing an enhanced synchronization when orienting attention towards emotional salient stimuli at an early stage of processing (Aftanas et al., 2003; Balconi & Pozzoli, 2009; Bossi et al., 2020; Ding et al., 2022; Knyazev et al., 2009; Spadone et al., 2021; Symons et al., 2016). Conversely, face expressions elicited also a stronger gamma activity, reflecting an holistic processing of the stimulus (Anaki et al., 2007).

Overall, the perception of emotional body expressions has been associated with several modulations of brain oscillatory activity, each one associated with different cognitive processes that can occur either at the very early stage of processing, as for the theta activity, or at later stage, as for the alpha activity.

1.1.4. Body expression processing through visual exploration

The visual exploration of body expressions reflects the cognitive processes underling the perception of their affective content. For such reason, during the last few years, eye-tracking techniques have been adopted to evaluate participants' gaze behavior during the observation of emotional body expressions. In this direction, Kret and colleagues firstly compared the amount of time spent looking at the body with respect to the time spent looking at the face when they conveyed emotional information. Hence, in this study they used combined stimuli of emotional faces and body postures conveying either congruent or incongruent emotions. Interestingly, they found that in the incongruent conditions, especially whit happy faces, participants spent more time looking at the body posture, as it may provide useful information for the identification of the emotion in an ambiguous situation (M. Kret, Stekelenburg, et al., 2013). Overall, they found that greater attention was directed towards motivational salient cues, regardless of their provenience from both face and posture (M. Kret, Roelofs, et al., 2013). As regards the visual exploration of different body parts, a typical approach is to identify specific region of interests (ROIs) thus dividing the body in separate districts which are particularly expressive for different emotions, and then compute the time or the frequency of fixations per each ROI. In this framework, researchers agree on the so-called upper body bias, according to which the regions of the upper body, i.e., the torso, the head, and the arms, generally receive more attention compared to the legs, which instead are not often identified as diagnostic for emotional body expressions (Dael et al., 2012a, 2012b; Pollux et al., 2019). A possible explanation is that viewers do not rely on the presence of just one diagnostic gesture or body part but attended all the upper body regions to optimize information seeking (Pollux et al., 2019). In this view, emotional body postures are processed in an integrative way, i.e., observes tend to adopt a holistic viewing strategy. On the other hand, in the last few years, several research have investigated the salience of specific body parts for different emotions. One of the first study that exploited eye-tracking system to unveil the existence of emotion-specific gaze pattern on emotional body expressions was conducted by Fridin and colleagues in 2009 (Fridin et al., 2009). In this study, when perceiving body postures expressing joy, participants tended to fixate on the head, whereas for angry and fear body postures, most attention was directed to the hands and arms. Legs almost never drew the viewer's attention. Interestingly, they also found that the higher attention on the arms and hands was emotion rather than location dependent. In fact, the position of the hands at the center of the body was a common feature for both sadness and fear, but the amount of time spent looking at that body region was significantly higher for fear rather than for sadness body expressions. Pollux and colleagues compared fixation times when participants observed emotional static and dynamic body expressions. They found that the arms were attended longer for happy and fearful static expressions and for angry expressions dynamic displays, respectively (Pollux et al., 2019). In a recent study from Andrea Kleinsmith and colleague (Kleinsmith & Semsar, 2019), they animated a simplistic 3D humanoid avatar with affective body expressions selected from the UCLIC Database of Affective Postures and Body Movements (Kleinsmith et al., 2011) and then evaluated the observers' gaze behavior over 4 different ROIs (head/shoulders, trunk, arms, and legs) in terms of fixation counts and durations. They found that the number of fixations over the arms and the head/shoulder region discriminated between active (high arousing) and passive (low arousing) states. Specifically, the frequency of fixations was higher on the arms with triumphant and frustrated expressions and over the head/shoulder regions with defeated expressions.

Overall, the above-mentioned studies show that the use of eye-tracking techniques could provide important information about how we process emotional body postures, revealing how attentional processes are modulated by the emotional content of the body posture.

2. The influence of the context in perceiving body expressions

In naturalistic viewing condition, we usually do not perceive body expressions separated from their context, yet almost all the research conducted so far have neglected this aspect, studying how we perceive the human body as an isolated object without considering the surrounding scene. Nevertheless, this is crucial considering that the perceived emotion is often influenced by numerous contextual factors.

Research on context effect has focused initially on object recognition, showing that it can facilitate object detection and recognition (Biederman et al., 1982; Boyce et al., 1989; Boyce & Pollatsek, 1992), even when the context can be ignored (Davenport & Potter, 2004), or conversely a context incongruency led to worst performances in terms of recognition accuracy and reaction times (Joubert et al., 2008). Such an interaction occurs because object and context are processed in parallel in common brain areas, and this possibly produces a reciprocal interference.

As regards human emotion perception research, whether on the one hand the perception of facial expressions has been widely studied, even considering the effect of the context, on the other hand the same is not yet true for body expressions. For instance, emotion perception in facial expressions was found to be influenced by the social situation (Carroll & Russell, 1996), the background scene (Righart & de Gelder, 2006, 2008), voices (Van den Stock et al., 2007) and so far so on. Also, researchers have started to investigate how facial expression is perceived not as an isolated body part but as an integrated part of the whole body, i.e., as it is encountered in our natural world (Meeren et al., 2005; Reschke & Walle, 2021; Van den Stock et al., 2007). In this regard, Meeren and colleagues (Meeren et al., 2005) used face-body compound stimuli with either matched or mismatched emotional expressions and recorded the EEG signal of 12 participants that were asked to judge the emotion conveyed by the face. They found that congruent emotional bodies improved the recognition of facial expression whereas incongruent conditions biased the perception of facial expression toward the emotion conveyed by the body. The concurrent EEG analysis revealed a modulation of the P100 over occipital sites, showing an increased amplitude for incongruent face-body condition. Their results suggested that, when judging the emotion conveyed by the facial expression presented also with the body, does exist a rapid automatic perceptual integration between information derived from the target and from outside the focus of attention, i.e., from the facial and bodily expression, respectively. Hence, the evaluation of the relation between facial and body expressions occurred in this case right before the structural encoding of the facial target stimulus. In a following studies, Van de Stock and colleagues (Van den Stock et al., 2007) proved that the influence of the body on the perception of facial expression depended on the ambiguity of the emotion portrayed by the face, i.e., the more ambiguous is the face, the stronger is the influence of the body. Overall, these studies proved that the perception of emotional social relevant stimuli as face expressions is influenced by external factors.

As already mentioned above, the number of studies that investigated the effect of the context on body expression perception is much lower. In one of this studies, Kret and colleagues (M. E. Kret & de Gelder, 2010) used ad-hoc stimuli with the target emotional body posture presented over a picture resembling social scenes composed by a group of people engaged in an intense action either neutrally or affectively laden. Stimuli were presented for 100 ms and then participants were asked to categorize the emotion conveyed by the target body expression. They found that happy body expressions were better recognized when presented in happy contexts such as people dancing at a party, as well as fearful body postures were better recognized in a context of people run away from a danger. Hence, they argued that a facilitation effect was generated by the context probably affecting early stage of processing. In a following study (M. Kret, Roelofs, et al., 2013), the same authors measured physiological responses to emotional face-body-scene combinations. Specifically, fixation times, electromyography (EMG), and pupil size were measured while participants freely viewed a combination of congruent or incongruent face-body and body-scene stimuli. Results revealed that, in line with the motivated attention theory (Bradley et al., 2003; Lang & Bradley, 2010), no matter of either the source or congruency between stimuli, participants attended more to angry and fearful rather than happy or neutral ones. Hence, a threating surrounding scene made participants scan the body expression differently, because their attention was drawn elsewhere within the scene. To date, the only study that investigated the brain areas involved in the perception of emotional body expressions modulated by the surrounding scene was conducted by Van de Stock and colleagues in 2014 (den Stock et al., 2014). In this study, participants underwent to a fMRI scan while observing fearful and neutral body postures presented against affective matching or mismatching background scenes. They found a greater activity in the bilateral EBA for fearful body expressions compared to neutral ones, regardless of the background scenes. More interestingly, the same brain area was stronger activated for threatening scenes vs neutral ones but only with neutral body expressions. In the same direction, in a following behavioral experiment, the same neutral body postures were judged as more fearful when presented in a threatening background compared to a neutral one. Such an effect could be explained as a perceptual bias effect. In fact, the neutral body posture is also the most ambiguous and consequently the most susceptible to be influenced by the affective content of the background scene.

Although these evidence about the role of the context in shaping the perception of social relevant cues such as bodily expression, the temporal dynamics of the correspondent cognitive processes underpinning this dual interaction are still unknown.

2.1. The architectural space as the context of our everyday social interactions

Considering that we spend almost the 90% of our time within built environments (Klepeis et al., 2001), the architectural spaces that we inhabit can be considered the surrounding stage of most of our social interaction with other people, i.e., the context in which we constantly try to decode and comprehend the other’s affective state. In fact, in real-life situations we typically share the same enclosed space with other people and two neural processes may run in parallel: one involved in processing the other’s affective state and the other in processing the surrounding space. Hence, the next paragraphs are organized as follows. In paragraph 2.1.1 I will briefly describe mechanisms underlying space processing, showing that do exist in the brain numerous space maps involving different fronto-parietal networks. Then, in paragraph 2.1.2 I will provide more details about the neural mechanisms which characterize the architectural experience, showing how different architectural elements impact on inhabitants’ affective states and behavior. Special regard will be given to the involvement of motor-related brain areas in processing the architectural experience.

2.1.1. Neural mechanisms underpinning the process of the surrounding space

There is now large consensus that do not exist a unitary representation of the space in the brain but contrarily that there are numerous spatial maps that involve different neural circuits (Berti & Rizzolatti, 2002; Rizzolatti et al., 1997, 2002). One of the most studied dual representation of the space is that dividing the surrounding space in near (peripersonal space) and far (extrapersonal space). Specifically, the peripersonal space defines the immediate space near to the body, in which objects can be grasped and manipulated and where we interact with other people (Costantini et al., 2010; Fini et al., 2014). Space is coded in terms of egocentric coordinates, hance considering the relative position from body parts such as the hand, the head, and the trunk. Recent fMRI studies in humans found that the representation of peripersonal space involves a fronto-parietal network showing that regions within the intraparietal and premotor cortices respond to multisensory stimuli presented in the peripersonal space (di Pellegrino & Làdavas, 2015; Gentile et al., 2011, 2013; Makin et al., 2007). On the contrary, the extrapersonal space refers to the space beyond the grasping distance, that can be reached for instance by walking. Space is coded in retinal coordinates and its processing involves a different fronto-parietal network devoted to oculomotor visual exploration (Berti & Rizzolatti, 2002; di Pellegrino & Làdavas, 2015). Whitin built environments, boundaries of the extrapersonal space are defined by the configuration of the surrounding architectural forms.

2.1.2. Brain processes involved in the architectural experience

In this framework, during the last few years, a growing interest has been shown in studying the “architectural experience”, i.e., the study of how different architectural features impact on the inhabitants' states and consequent behavior. According to Coburn and coworkers (Coburn et al., 2020), the architectural experience is mediated by three neural systems, i.e., knowledge-meaning, emotion-valuation, and sensorimotor system (Chatterjee & Vartanian, 2014; Coburn et al., 2017) which reflect separate psychological processes, i.e., cognition, emotion and behavior, respectively (Izard et al., 1984; Lench et al., 2013). In this perspective, the cognitive judgement of the architecture is modulated by a top-down control serving the evaluative process of the surrounding space in terms of external qualities such as the visual complexity, the naturalness, the beauty, and modernity. On the other hand, a bottom-up process is also engaged by the architectural experience, characterizing how the surrounding space "stirs our feeling, our passion" (Alexander, 2004), thus modulating affect, emotions, and other inner states of being. Finally, the architectural space influences psychological aspect of behavior, movement, and motivation linked to sensorimotor processing in the brain and behaviorally measured in terms of interest, approachability and explorability.

An interesting line of research is that linking the inhabitants' affective state and consequent behavior with the architectures' visual and motor permeability. For instance, the perception of spaciousness of an environment, modelled by several factors such as the height of the ceiling, the distance between lateral walls, and the presence of openings, has been found to play a key role in influencing the inhabitants' emotion and behavior. In fact, enclosed spaces which are characterized by a reduced possibility to move-through and see-through, were typically associated to uncomfortable states (Stamps, 2010). In such spaces, inhabitants are more likely to feel stressed (Fich et al., 2014), as the reduced surrounding space generates fear and confinement sensations (Im, 1987a; Stamps, 2005). In a fMRI study by Vartanian and colleagues in 2015 (Vartanian et al., 2015), they examined the effects of ceiling height and perceived enclosure on aesthetic judgements of beauty and approach-avoidance decision. They found that open rooms with high ceilings were more likely to be judged as beautiful. At the neural level, they found that spaces characterized by a greater visual and motor permeability elicited a stronger activity in brain areas linked to visuospatial processing and attention, such as the precuneus and the middle temporal gyrus (Cavanna & Trimble, 2006; Kravitz et al., 2011). Activity in the same area was also associated to the perception of spaces rated as pleasant and beautiful (Vartanian et al., 2013). Also, they found that enclosed spaces, with a reduced visual and motor permeability, elicited a negative emotional reaction, leading to an increased decision to exit the space. The enclosed vs opened contrast, revealed a stronger activity in the anterior middle cingulate cortex (aMCC), i.e., a brain area connected with the amygdala and involved in fear processing (Vogt & Pandya, 1987; Whalen et al., 1998). Activity in the anterior cingulate cortex (ACC) was also associated to the architectural experience in a recent study conducted by Banaei and colleagues (Banaei et al., 2017). They integrated the use of a VR headset with a portable EEG, measuring the affective response to the perception of architectural spaces characterized by different forms and geometries. Participants were permitted to move and visually explore the virtual rooms, thus perceiving the space in realistic and dynamic way and then rated the architectural experience using a virtual self-assessment manikin describing scales of arousal, pleasure, and dominance. Results revealed that spaces rated as pleasant elicited a rapid higher synchronization in the ACC, which activity was also linked to the processing of specific architectural features in the built environment (presence of 2D rectangular geometries). Hence, they argued that activity in the ACC may index the architectural experience because it reflected both the affective response to the architecture as well as the perception of different architectural elements.

A parallel line of research is also investigating the architectural experience in terms of embodiment, sensorimotor integration, and spatial navigation. In this direction, Vecchiato and colleagues (Vecchiato, Jelic, et al., 2015; Vecchiato, Tieri, et al., 2015) have recorded the EEG signals during the perception of virtual rooms with different interior designs, which were reproduced exploiting a CAVE system. They found that rooms rated as more pleasant elicited a higher theta activity in occipital, frontal, and orbito-frontal regions, possibly reflecting the planning of potential actions within the virtual rooms. The same virtual spaces also elicited a higher alpha activation in left-central parietal and frontal areas, which may index an increase in visuo-spatial processing. Finally, the EEG analysis also revealed a mu-desynchronization for virtual rooms with high scores of pleasantness and comfort. Such result may account for an embodied perception of the surrounding architectural space, thus retrieving similar mechanism to those involved in the aesthetic experience of artworks. Indeed, according to the theoretical framework proposed by Freedberg and Gallese in 2007 (Freedberg & Gallese, 2007) the motor system is directly involved in the aesthetic experience of artworks, sculptures and even architectural forms due to an empathetic relationship established between the observer and the object. For instance, the observation of images of classical sculptures evoking a sense of motion activated brain areas such as the premotor cortex and the inferior parietal lobule (Di Dio et al., 2007). Similarly, the observation of Lucio Fontana's cut canvas was found to generate a mu suppression in motor-related areas, possibly due to the internal representation of the artist's hand movement that produced the painting (Umilta' et al., 2012). In this direction, Jelic and colleagues proposed the enactive approach as a guide to study architectural experience, emphasizing the role of embodiment and motivational factors as constituents of the body-architecture interactions (Jelić et al., 2016).

Activation of sensorimotor brain areas during the experience of the architectural space was also related to the affordances provided by the spatial environment (Djebbara et al., 2019, 2021). Architectural affordances are defined as the possibilities for, or even constraints on, an action offered by the surrounding environments. For instance, Djebbara and coworkers (Djebbara et al., 2019) used a brain/body imaging approach recording brain activity of participants while they were asked to pass through architectural virtual transitions of different dimensions ranging from wide to impossible to pass. They found that impassable transitions produced significantly different early evoked potentials (P1 and N1) compared to passable transitions over frontocentral and occipital electrodes. Specifically, they argued that the modulated activity over frontocentral electrode reflects the involvement of the SMA, i.e., a brain area devoted to action preparation thus essential for processing continuous affordances.

Overall, the afore mentioned studies highlight the central role of motor-related brain areas in processing the architectural experience. Indeed, the architectural forms delimitate the surrounding extrapersonal space in which the inhabitant can potentially see-through and move-through, as well as trigger an embodied simulation mechanism on the perceiving inhabitant.

3. The interplay between the architectural experience and the perception of emotional body expression: the conducted studies

From the studies mentioned before, we understand that the body is a powerful tool to convey affective states and that the perception of emotional body expression is influenced by the context. However, little is known about the interplay between the perception of emotional body expression and the architectural space, which is the context where individuals are constantly exposed during everyday social interactions. The research I have conducted across the three years of my PhD program aims to bridge this gap by studying the cognitive processes underpinning the perception of emotional body postures modulated by the architectural experience.

To achieve this goal three separate studies were conducted, presented in detail in the next chapters of this dissertation. The first two studies aimed to characterize a set of body postures and virtual architectures in terms of arousal and valence. Arousal and valence dimensions have the most replicable evidence for explaining emotional states, posing, as stated in the circumplex model (Russell, 2003), as two independent and bipolar axes anchoring a circular structure, ranging from unpleasantness to pleasantness for valence[1] and from inactivated to activated for arousal[2]. I considered the arousal and valence dimension to create a common affective ground for the experimental stimuli, especially considering that architectures can hardly be described by a specific discrete emotion.

Specifically, with the first study (presented in Chapter 2), I created a set of body postures with different affective states in terms of arousal and valence. Indeed, the possibility of modeling static body postures preserving affective information is still fundamental in a

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[1] *Valence refers to the intrinsic pleasantness or goal conduciveness of the emotion-eliciting object or event* (Dael et al., 2013)

[2] *Arousal represents the degree of physiological excitation of the sympathetic nervous system* (Dael et al., 2013)

broad spectrum of experimental settings exploring time-locked cognitive processes. For this purpose, I implemented a novel automatic method for creating virtual affective body postures starting from kinematics data. Exploiting body features related to postural cues and movement velocity, I transferred the affective components from dynamic walking to static body postures of male and female virtual avatars. Such methodology allowed me to animate a virtual avatar with different arousing body postures, which I will then exploit to recreate social scenarios within different architectural spaces.

In the second study (presented in Chapter 3) a set of virtual architectures were designed by manipulating specific architectural features. The VR headset allowed participants to live an immersive and realistic experience by means of a virtual promenade within the architectural space. The aim of this study was to characterize the architectures in terms of perceived arousal and valence, asking participants to rate their affective state at the end of the virtual promenade. In such a way I was able to select two different virtual architectures, with opposite (low vs high) level of induced arousal.

In the third study (presented in Chapter 4), I will finally investigate the impact of the architectural experience on the perception of emotional body expressions. The EEG activity and eye-gaze behavior of participants were recorded while they firstly made a virtual promenade within the architecture and then faced the avatars' body posture to be judged in terms of conveyed arousal. The aim was to characterize the cognitive processes and the correspondent temporal dynamics relative to the perception of emotional body expression modulated by the architectural experience. I hypothesized that the architectural experience would have influenced the perception of the body posture, due to the activation of common cortical regions engaged in space coding as well as devoted to action and intention understanding, possibly indicating a functional binding between spatial and social processing.

Chapter II – Study 1: The Affective Characterization of Avatars' Body Postures

Dynamic virtual representations of the human being can communicate a broad range of affective states through body movements, thus effectively studying emotion perception. However, the possibility of modeling static body postures preserving affective information is still fundamental in a broad spectrum of experimental settings exploring time-locked cognitive processes. We propose a novel automatic method for creating virtual affective body postures starting from kinematics data. Exploiting body features related to postural cues and movement velocity, we transferred the affective components from dynamic walking to static body postures of male and female virtual avatars. Results of two online experiments showed that participants coherently judged different valence and arousal levels in the avatar's body posture, highlighting the reliability of the proposed methodology. In addition, esthetic and postural cues made women more emotionally expressive than men. Overall, we provided a valid methodology to create affective body postures of virtual avatars, which can be used within different virtual scenarios to understand better the way we perceive the affective state of others.

1. The avatar's gist: how to transfer affective components from dynamic walking to static body postures

The rapid development of virtual technologies makes it possible to investigate human behavior in fictive environmental and social scenarios, which are otherwise difficult to reproduce and study within standard laboratory settings (Presti, Ruzzon, Avanzini, et al., 2022, p. 20; Sanchez-Vives & Slater, 2005; Slater & Sanchez-Vives, 2016). In this context, the dynamic information of body kinematics allows virtual representations of human behavior with specific emotional contents. Researchers showed body kinematics provide significant recognition accuracy of emotions (Atkinson et al., 2004), and postural information allows the discrimination of emotion intensity (Aviezer et al., 2012), demonstrating that body cues are fundamental for a comprehensive understanding of the other's emotion (de Gelder, 2006, 2009; de Gelder et al., 2010). The possibility to model virtual static bodily configurations preserving a sense of dynamicity and affective information is still of particular interest, given the predominant use of static bodily expressions in a broad spectrum of experimental settings which explore time-locked cognitive processes such as event-related potential with electroencephalography, evoked-potential with transcranial magnetic stimulation and reaction times in behavioral studies. Moreover, virtual environments without a realistic depiction of human behavior can be uninteresting, resulting in a lack of attention, often required to study cognitive processes in social scenarios. Creating an expressive virtual character is difficult because of the complex nature of human nonverbal behavior, such as body posture, and there is surprisingly little research on models that generate affective behavior (Coulson, 2004; de Gelder, 2006; Vinayagamoorthy et al., 2008). Therefore, the issue to solve is identifying bodily variables that can be used to build a model of affective behavioral cues.

A strategy to model the posture of a virtual avatar with emotional content involves using motion capture technologies to record an actor's movement and then select the most expressive posture based on subjective judgment (De Silva & Bianchi-Berthouze, 2004; Kleinsmith et al., 2006). Another way is to exploit 3D modeling software to artificially shape the avatar posture by changing the angles between contiguous body parts (Buisine et al., 2014; Clavel et al., 2009). Other systems characterizing emotional expressions depend on the degree of subjective inference and granularity of the measure, whose combination deeply impacts the reliability and efficiency of the categorization in terms of time coding. For instance, the Body Action and Posture Coding System (BAP) consists of 141 behavioural variables, whose combination describes anatomical articulation, form and functional level of the movement. A reliability study reports that it took 2,280 minutes to encode the dataset of 6.28 minutes, thus yielding a coding ratio of 1:363 (Dael et al., 2012b). The Facial Action Coding System (FACS) consists of 44 Action Units that can be coded at different levels of intensity with a coding ratio of 1:100 (Cohn et al., 2007). The Laban Movement Analysis (LMA) describes how the observed motor action uses components of movement and how each component of movement is related to one another with a coding ratio of 1:30 (Bernardet et al., 2019). Since these procedures are highly subjective and time-consuming, there is the need to identify an automatic procedure to transfer the affective information from a body kinematic to a static emotional posture. Hence, the present work aims to overcome reliability and time coding issues by automatically extracting body features from kinematic data of walking to transfer the corresponding dynamic affective components to static body postures.

Walking is a natural day-to-day motion that can convey different affective states by combining upper and lower limbs movement (Karg et al., 2010; Montepare et al., 1987; Roether et al., 2009; Zhao et al., 2019). Previous works have shown that virtual representations of human beings can communicate different affective states through emotional walking (Hicheur et al., 2013; McHugh et al., 2010; Randhavane, Bera, Kapsaskis, Gray, et al., 2019; Randhavane et al., 2021). A recent study of Bhattacharya and colleagues (Bhattacharya et al., 2020) found that participants correctly recognized the emotion expressed by virtual avatars according to different gait patterns. Similar results were found in a study where emotional walking was used to animate virtual avatars in different virtual scenarios (e.g., a park, street, and garden) (Randhavane, Bera, Kapsaskis, Sheth, et al., 2019). Previous studies in kinematic-based movement analysis and affective computing returned that both postural and kinematic features are essential for an accurate description of the individual's affective states (Kleinsmith & Bianchi-Berthouze, 2013; McColl & Nejat, 2014; Stephens-Fripp et al., 2017). In this regard, valence and arousal are typically associated with different body features and are considered crucial characteristics to describe the human affective experience on continuous and dimensional scales (Kragel & LaBar, 2016; Kuppens et al., 2013; Lindquist et al., 2012). Valence dimension is described by postural cues defining the body's shape during the movement. Hence, joint angles between contiguous body segments and the position assumed by specific body parts are crucial cues for identifying the valence level conveyed by the movement. Head and trunk orientation discriminate between positive and negative valence levels. Walking with a downward leaning of the head/trunk highlights unpleasant affective states as such posture is associated with sadness and anger. On the other hand, an upward orientation identifies joyful walking

(Crenn et al., 2016; Hicheur et al., 2013; Karg et al., 2010; Randhavane, Bera, Kapsaskis, Sheth, et al., 2019; Venture et al., 2014). The volume calculated from the expansion of the body in the three-dimensional space is another postural feature widely exploited for the affective characterization of walking. Instead, a compact posture is associated with sad walking, while an expanded one stands for positive expressions (Crenn et al., 2016; Randhavane, Bera, Kapsaskis, Sheth, et al., 2019). The dimension of arousal is well described by kinematic cues considering the quantity of motion of the gesture, which is highly correlated with velocity, acceleration and jerk of the movement (Karg et al., 2010; Randhavane, Bera, Kapsaskis, Sheth, et al., 2019; Sanghvi et al., 2011) (Nakagawa et al., 2009). Previous studies reported that walking speed is correlated with the arousal level (Deligianni et al., 2019; Halovic & Kroos, 2018a; Roether et al., 2009). Sad walking was characterized by slow movements, while joy and anger walking, typically considered high arousal emotions, were characterized by fast and rapid movements (Barliya et al., 2013; Bernhardt & Robinson, 2007; Gross et al., 2012; Randhavane, Bera, Kapsaskis, Sheth, et al., 2019).

The present work provides a procedure enabling the automatic creation of emotional body postures by identifying the corresponding most salient time frame from a whole kinematic. For this purpose, emotional walking kinematics were described frame per frame by two distinct body features, namely, the Body Pleasantness (BP) and the Body Dynamicity (BD), which were based on the combination of postural cues and movement velocity of male and female actors.

We hypothesize that the time frames automatically selected with different levels of BP and BD should correspond to coherent valence and arousal levels, separately, reflecting those perceived in the corresponding walking actions.

Results of a first experiment showed that participants coherently assigned valence and arousal scores to avatars' body postures with different levels of BP and BD, and that such scores were strongly correlated with those provided on the correspondent walking actions. Findings also showed that female avatar were judged as more emotionally expressive than male ones. With the hypothesis that the physical appearance of the avatar could contribute to the judgment of valence and arousal, we performed a second online experiment by disrupting the coherence between the gender of the actor and that of the avatar. Hence, the male avatar assumed those body postures derived from female actresses and vice versa. Findings of this second experiment revealed that the combination of both aesthetic and postural characteristics makes females appear more emotionally expressive than males.

Overall, we demonstrated that the proposed methodology successfully transferred affective components from emotional walking to static body postures. The use of body pleasantness and body dynamicity allowed to select representative emotional frames in a reliable and time-efficient way, leading to the automatic creation of affective body postures. The proposed procedure could be exploited to design stimuli for a broad range of experimental studies investigating time-locked cognitive processes related to the perception of emotional body postures.

2. Material and methods

Emotional Kinematics. We considered the EMILYA database to select emotional kinematics for this study (Fourati & Pelachaud, 2014, 2018). Such a database includes daily actions performed by actors and recorded through inertial motion capture technology. We considered the 912 simple walking actions comprising the whole body's movement of 5 female and 5 male actors. A .mat file (Matlab, The Mathworks, Inc., Natick, MA, USA) contains the time-varying root-related positions of 28 body joints for each action. They refer to a 3D space where the xy, yz, and xz planes describe the coronal, sagittal, and transverse planes, respectively, and the origin of the axes corresponds to the middle point between the right and left hip.

Body Pleasantness. The valence dimension is generally linked to postural features more than kinematic ones (Nakagawa et al., 2009). Previous findings show that the bowing and the expansiveness of the body discriminate the pleasantness of the performed action (Fourati & Pelachaud, 2015, 2018; Karg et al., 2010). Here we defined Body Pleasantness

(BP) as the feature adopted to transfer the valence information of the walking to a static body posture. Such score was computed as a combination of three distinct body features, namely the leaning of the head (LH), the position of the head (PH), and the openness of the body (OB), according to the following procedure. For each kinematic, the LH was computed as the time average distance between the body joints representing the head and the neck in the sagittal direction:

$$\overline{LH} = \frac{\sum_{t=1}^{F}(p_{t,z\,head} - p_{t,z\,neck})}{F} \tag{1}$$

where $p_{t,z\,head}$ indicates the z coordinate at time t of the body joint related to the head, and $p_{t,z\,neck}$ indicates the z coordinate at time t of the body joint related to the neck, and F stands for the total number of recorded frames for that kinematic.

The PH was computed as the time average distance of the body joint representing the head and the origin on the z axis:

$$\overline{PH} = \frac{\sum_{t=1}^{F}(p_{t,z\,head})}{F} \tag{2}$$

Finally, the openness of the body was defined as the time average body spatial extension in the transverse, sagittal, and coronal plane and computed as follows:

$$\overline{OB} = \frac{\sum_{t=1}^{F}((\max p_{t,x} - \min p_{t,x}) * \left(\max p_{t,y} - \min p_{t,y}\right) * (\max p_{t,z} - \min p_{t,z}))}{F} \tag{3}$$

where $\max p_{t,x} - \min p_{t,x}$ stands for the maximum extension of the body in the lateral direction, $\max p_{t,y} - \min p_{t,y}$ for the maximum extension in the vertical direction, and

$\max p_{t,z} - \min p_{t,z}$ stands for the maximum extension of the body in the sagittal direction, each one considered at time t.

To describe the valence dimension of the kinematic with a unique value combing the information conveyed by the above mentioned body features, we performed a Principal Component Analysis (PCA) (Abdi & Williams, 2010) using the LH, PH, and OB variables as inputs. We extracted the first principal component explaining the 83% of data variance and defined the Bodily Pleasantness (BP) as the weighted sum of the three input variables. Hence, for each kinematic, we were able to compute the BP frame by frame according to the following formula:

$$BP_t = 0{,}77 * LH_t + 0{,}63 * PH_t + 0.10 * OB_t \tag{4}$$

and then select the frame which BP score was the closest to the mean BP of the whole kinematic, as representative of the kinematic:

$$BP = \min_{t \to F}\left(\left|BP_t - \frac{\sum_{t=1}^{F} BP_t}{F}\right|\right) \tag{5}$$

Figure 1 shows the body-joint configurations representing the body features adopted to compute the BP, i.e., the LH, PH, and OB, and illustrates the distribution of the 912 walking actions in the plane defined by the first two components of the PCA, according to their value of LH, PH, and OB.

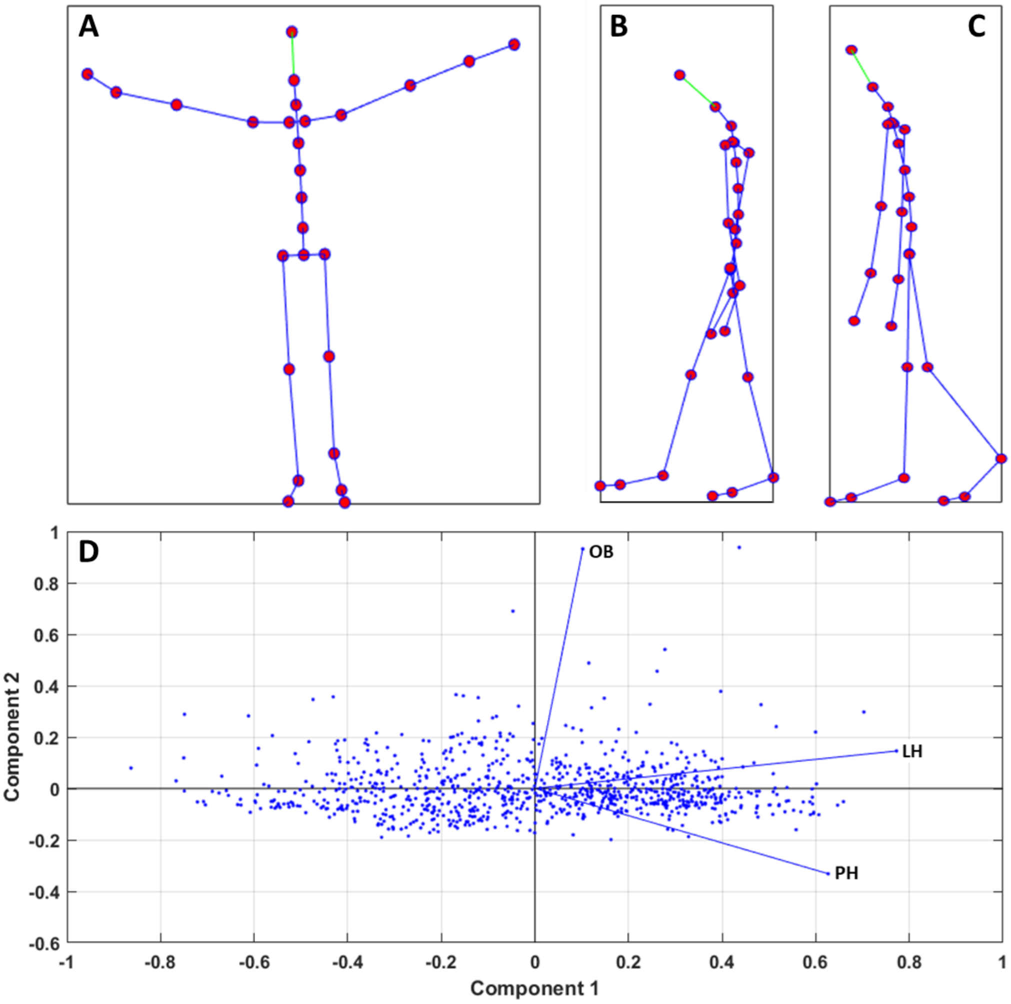


Fig. 1. Panels A, B and C show an example of body joints configurations (red dots) depicting a characteristic body posture for the body features OB, LH, and PH, respectively. Panel D displays the distribution of the 912 simple walking actions (blue dots) described by a particular score of OB, LH, and PH, over the plane composed by the Component 1 and Component 2 derived from the PCA.

Body Dynamicity. The dynamicity of the performed action typically contains affective information concerning the arousal dimension (Dael et al., 2013; Nakagawa et al., 2009; Paterson et al., 2001; Pollick et al., 2001). In order to transfer the dynamicity of the whole kinematic to a static body posture, we defined a body dynamicity (BD) score and computed this metric for each time frame of the kinematic. We identified the frame associated with the maximum BD value and then selected the corresponding body posture as representative of the arousal level of that action. In detail, for each body joint, we first computed the distance between the position at the time t and t+1 divided by the duration of the time frame:

$$BD_{j,t} = \frac{P_{t+1} - P_t}{T_f} \tag{6}$$

where j and t identify the specific body joint and the time frame. To obtain the frame-by-frame BD of the full-body kinematics, we averaged the BD related to the body joints:

$$\overline{BD}_t = \frac{\sum_{j=1}^{N} BD_{j,t}}{N} \tag{7}$$

where N is the number of body joints. Finally, we considered the highest BD value across the time frames as representative of the kinematic:

$$BD = \max_{t \to F} \overline{BD}_t \tag{8}$$

where F stands for the total number of recorded frames for that specific kinematic. Figure 2 shows body joint configurations representing two body postures with low and high levels of BD. Also, the BD time course of the original walking actions is presented.

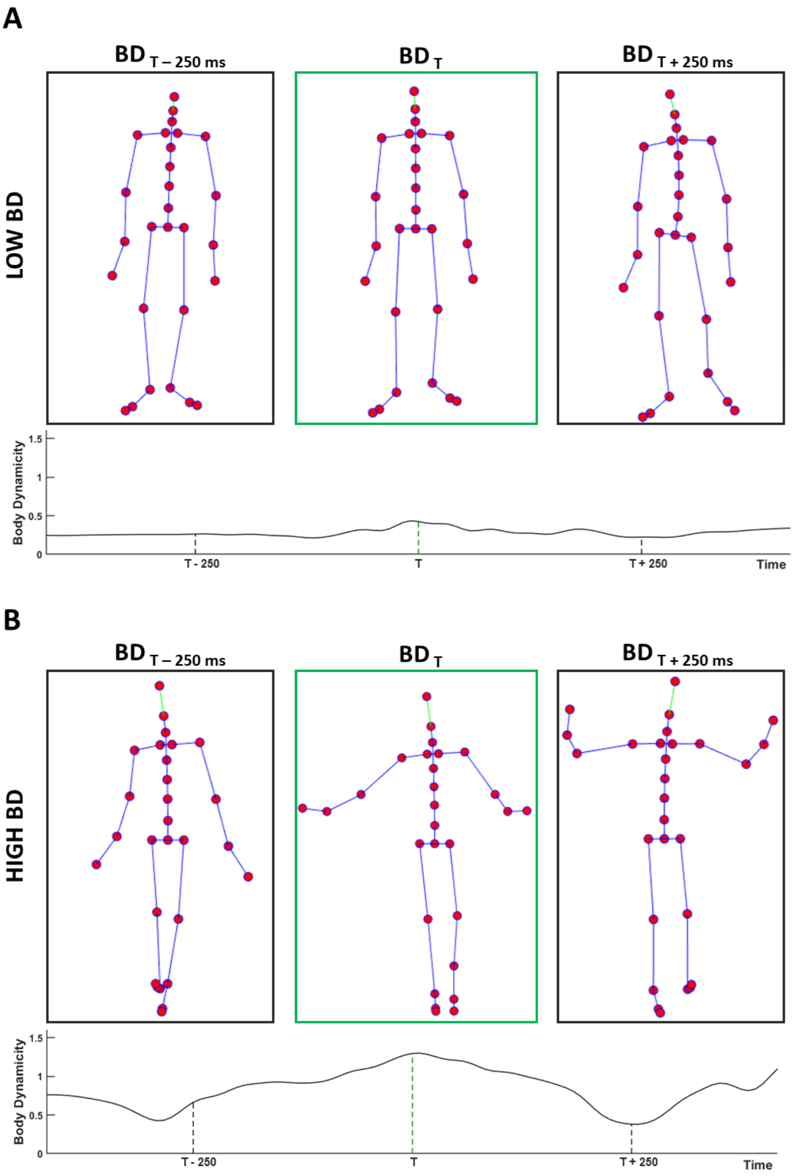


Fig. 2. Panels in A (B) show three body joints configurations depicting body postures with low (high) level of BD extracted from two different walking. The BD time course of the walking is reported below each panel, which shows the precise time-point from which postures are extracted. Middle panels in green illustrate the representative frames of the whole kinematic, extracted according to the procedure described in the section Material and Methods. Instead, the first and third panels of the two rows represent two frames extracted 250 ms before and 250 ms after the time of the representative BD, respectively.

Emotional Body Postures. Motion capture data were firstly converted from .bvh to .fbx file extension using 3ds Max 2020 and following the recommendation described by the Xsens Company (https://www.xsens.com/integrations/3dstudiomax). As explained in the previous sections, for each kinematic, we extracted the two configurations of body joints – representative of body postures – associated with the values of expressed arousal and valence. We then selected 90 body postures in three groups corresponding to the low, middle, and high level of BP, each one counting 15 male and 15 female body postures. Analogously, we selected 90 body postures with low, middle, and high values of BD. We performed two one-way ANOVAs with factors BD ($F(2,87) = 1197.5$, $p < .001$) and BP ($F(2,87) = 1187.4$, $p < .001$) to assess differences among the levels Low, Middle and High of the corresponding emotional dimension. Bonferroni corrected pairwise comparisons highlighted significant differences among all the three levels of BD and BP. The selection procedure of body postures with different levels of BP and BD is presented in Appendix A. The corresponding statistical analysis shows that BP and BD levels are balanced between male and female actors. Then, we used these data to animate two humanoid avatars (one male and one female) (available on https://renderpeople.com/free-3d-people/) exploiting Unity (2019.1.0f2). Here, we covered the avatar's faces with a skin-colored mask, allowing participants' responses to depend only on the avatar's body posture and not on facial expressions.

3. Experiment 1: actor – avatar gender congruency

The Experiment 1 consisted in two separate online surveys. In Experiment 1.A, participants rated the valence and arousal levels expressed by static body postures. In Experiment 1.B, participants rated the valence and arousal level conveyed by the corresponding walking actions from which the postures were originally extracted. The study was approved by the local ethical committee (Comitato Etico dell'Area Vasta Emilia Nord, https://www.aou.mo.it/ComitatoEticoAVEN) and conducted according to the principles expressed in the Declaration of Helsinki. Each participant provided written informed consent before participating in the experiment.

3.1. Experiment 1.A: rating of static body postures

3.1.1. Stimuli

The 180 body postures (90 BP, 90 BD) extracted from actions recorded on male (female) actors were assigned to a male (female) avatar to guarantee coherence between the gender of the actor and that of the virtual avatar. Figure 3 illustrates the representative avatar's body postures with different levels of BP and BD.

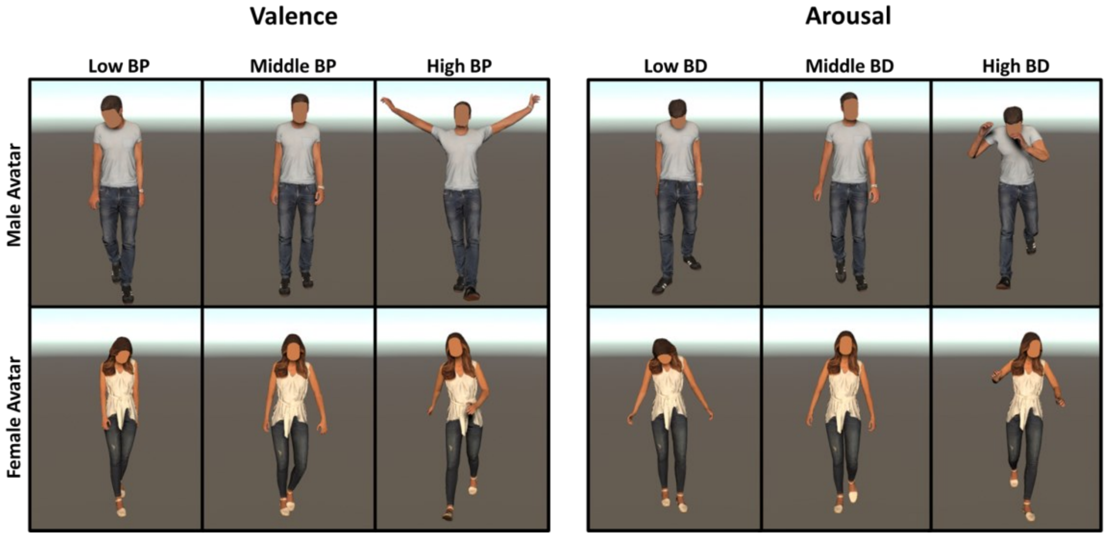


Fig. 3. Example of avatar's body postures with different levels of BP (left panels) and BD (right panels).

3.1.2. Participants, experimental procedure, and data analysis

We used the online platform Prolific (https://www.prolific.co/) to recruit participants for the experiment (Palan & Schitter, 2018). To ensure a reliable sample of participants, we recruited only those who reached almost 95% of the approval rate in previous online experiments and declared to speak English fluently. In line with Prolific policy, participants received a payoff (3.20 £) after completing the experiment. Fifty-four age-matched participants (27 women 26.3 ± 5.9 years, 27 male aged 23.4 ± 4.3 years; two-sample t-test, t(52) = -1.366, p = 0.177) were recruited for the online survey. The sample size was determined using a power analysis computed through the G*Power software (Faul et al., 2007) considering the "as in SPSS" option and setting the significance level

(α) at 0.05, the desired power (1- β) to 0.95, the number of groups to 2, the number of repetition to 6 and the non-sphericity correction ε to 1. Since we did not find any previous work related to emotional body perception performed online reporting the values of ηp2, we set the ηp2 to 0.16, based on this research performed in a laboratory setting (M. E. Kret & de Gelder, 2010), and then doubled the estimate sample size, to compensate the limited control on subject attention and accuracy in doing the online experiment.

Our experiment ran on the online platform Pavlovia (https://pavlovia.org/). At the beginning of the experiment, participants read written instructions explaining the concepts of valence and arousal and information on how to express their judgments. Valence was described as the pleasantness state expressed by the body posture of the avatar, referring to the positive or negative character of the event that the body is experiencing. Unpleasant states were associated with bad feelings or a negative state of mind, while pleasant states were associated with good feelings or a positive state of mind (Colombetti, 2005). The arousal dimension was described as the state of activation expressed by the body posture of the avatar, representing a change of the individual physical and psychological asset. A deactivated state was associated with a low heartbeat, sweating decrease, slow breathing, absence of energy, and decreased attentional and decisional capability. Instead, an activated state was associated with a high heartbeat, sweating increase, fast breathing, feelings of vigor, energy, tension, and increasing attentional and decisional capability (Kreibig, 2010). In each experimental trial, participants judged the arousal and valence level conveyed by the avatar's body posture. Specifically, on the left side of the screen, a picture representing an avatar with a specific body posture was presented, while two questions appeared on the right side with which participants could rate the arousal and valence level expressed by the avatar's body posture. Specifically, as concerns the arousal, they answered the question: "This person looks in a … state" by mean of a visual analog scale (VAS) where the lowest value was "Deactivated", numerically associated to 0, and the highest one was "Activated", numerically associated to 1. As concerns valence, they answered the question: "This person looks in a … state" by means of a VAS where the lowest value was "Unpleasant", numerically associated to 0, and the highest one was "Pleasant", numerically associated to 1. Participants gave their judgment by clicking the mouse left button on each rating scale and then pressed the space bar to move to the next trial, thus they had no time limits to answer. The whole experiment comprised 180 trials randomly presented in 5 separate blocks of 36 trials each. Blocks were separated by a self-paced pause during which participants could rest.

Valence and arousal ratings were normalized between 0 and 1 with the normalize.m Matlab function (method, 'range'). This function computes a z-score transformation rescaling changes the distance between the minimum and maximum values in a data set by stretching or squeezing the points along the number line, preserving the shape of the z-score distribution according to the following formula:

$$X_{rescaled} = \frac{X - minX}{maxX - minX} \tag{9}$$

Normalized valence and arousal data complied with a normal distribution as confirmed by Shapiro – Wilk tests (W = 0.97 for valence data; W = 0.97 for arousal data).

Normalized data are then analyzed via two mixed-design ANOVA with Avatar Gender (Male, Female) and Body Pleasantness/Dynamicity (Low, Middle, High) as within-subject factors and Subject Gender (Male, Female) as between-subject factor.

3.1.3. Results

Valence. Results of the rm ANOVA on valence ratings are illustrated in Figure 4 (upper panels). A significant effect for the main factor Body Pleasantness was found (F(2,104) = 476.631, p < .001, ηp2 = .902). Instead, neither the factor Avatar (F(1,52) = .413, p = .523, ηp2 = .008) nor Subject Gender (F(1,52) = .014, p = .906, ηp2 < .001) showed a significant effect on valence ratings. Bonferroni corrected pairwise comparisons revealed that participants differentially judged avatars whose body postures belonged to different levels of BP (Low < Middle, p < .001; Middle < High, p < .001; Low < High, p < .001). Also, the interaction Body Pleasantness x Avatar was significant (F(2,104) = 35.615, p = < .001, ηp2 = 0.406). Specifically, Bonferroni corrected pairwise comparison showed that female avatar with low level of BP were judged as less pleasant than male avatar with low level of BP (p < .001). Also, female avatar with high level of BP were perceived as more pleasant than male ones with high level of BP (p = < .001).

Arousal. Figure 4 (lower panels) presents the results of the rm ANOVA on arousal ratings. We found a significant effect for the main factors Body Dynamicity (F(2,104) = 383.447, p < .001, ηp2 = 0.881) and Avatar (F(1,52) = 15.073, p < .001, ηp2 = 0.241). Conversely, the between-subject factor Subject Gender did not return a significant effect (F(1,52) = .367, p = .547, ηp2 = .007). Bonferroni corrected pairwise comparisons showed that differences among the levels of the main factor Body Dynamicity were all significant (Low < Middle, p < .001; Middle < High, p = 5.3*10-7; Low < High, p < .001). The significant main factor Avatar showed that participants judged female avatar as more arousing than male ones. The interaction Body Dynamicity x Avatar (F(2,104) = 101.907, p < .001, ηp2 = 0.662) was also significant, revealing that female avatar with low level of BD were perceived as less arousing compared to male avatar with the same level of BD (p = < .001). Also, female avatar were judged as more arousing than male ones when they belonged to the middle BD level (p < .001). Finally, we found no significant difference between arousal ratings provided on female avatar with a middle level of BD and female avatar with a high level of BD.

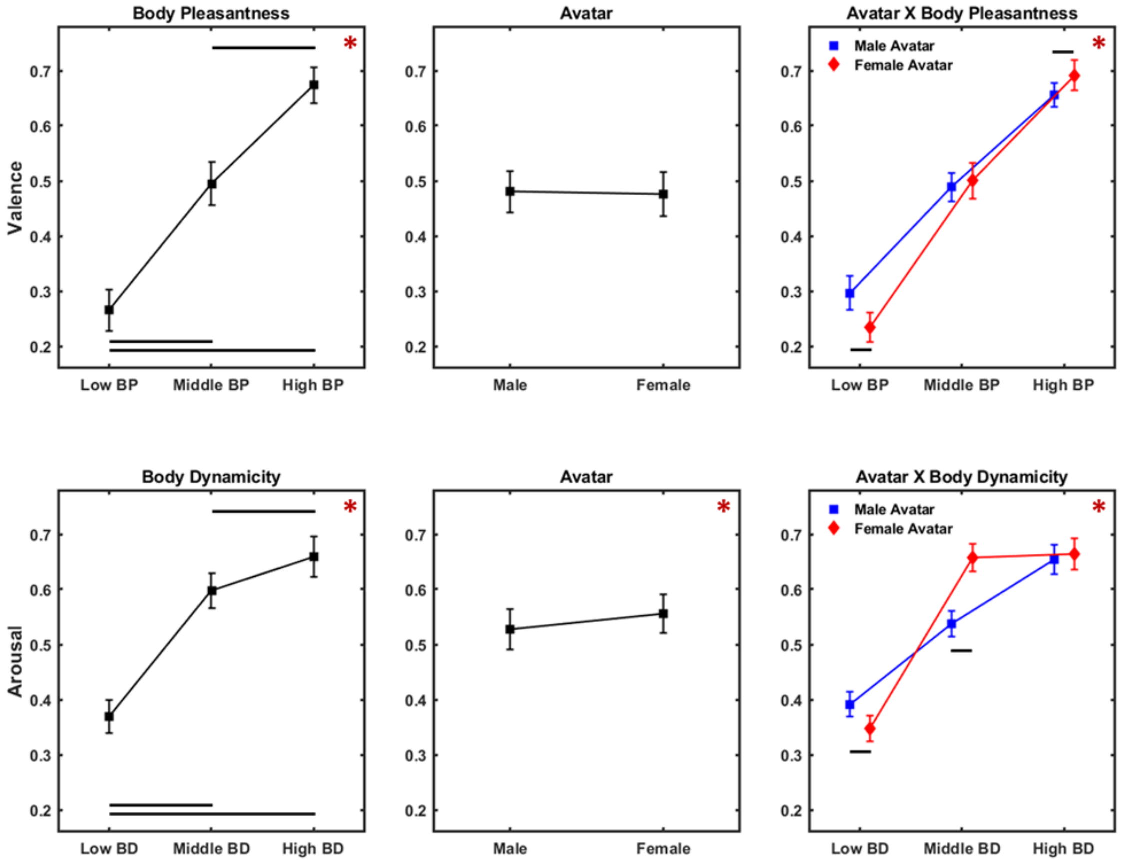


Fig. 4. Results of the ANOVA on Valence (upper panels) and Arousal (lower panels) ratings. Upper panels present mean and 95% confident interval of the distribution of the valence scores for the main factors Body Pleasantness (left), Avatar (middle), and the interaction Avatar X Body Pleasantness (right panel). Lower panels present mean and 95% confident interval of the distribution of the arousal scores for the main factors Body Dynamicity (left), Avatar (middle), and the interaction Avatar X Body dynamicity (right panel). Red asterisks indicate significant main effects, while black lines show significant pairwise comparisons.

3.2. Experiment 1.B: rating of emotional walking

3.2.1. Stimuli

One-hundred-eighty videos were created reproducing the walking actions from which the postures of Experiment 1.A were originally extracted. Walking actions recorded on male (female) actors were used to animate a male (female) avatar, thus ensuring coherence between the gender of the actor and that of the virtual avatar.

3.2.2. Participants, experimental procedure, and data analysis

Twenty-two gender and age-matched participants were recruited and performed the experiment on Pavlovia (11 women 29.4 ± 4.3 years, 11 men 27.9 ± 4.6 years; two-sample t-test, t(52) = -0.766, p = 0.453).

The adopted experimental procedure was the same as in Experiment 1.A, with the only difference that participants rated the valence and arousal perceived in the emotional walking instead of the corresponding representative static frame. Hence, on the left side of the screen, a video appeared for two seconds showing the walking action, while the two questions were presented on the right side with which participants could rate the arousal and valence level expressed by the avatar's walking through a VAS.

Valence and arousal ratings were normalized according to the same procedure used in the Experiment 1.A. Then, the Pearson's linear correlation coefficient was computed to assess the correlation between valence (arousal) ratings that participants gave on static body postures and those given on the corresponding walking actions.

3.2.3. Results

Results of the correlation analysis are illustrated in the Figure 5. Panel A shows the positive correlation between valence ratings between the two experiments (R = 0.85, p < .001; best linear fit: y = 0.82x – 0.01). Similarly, Panel B shows the correlation between arousal ratings (R = 0.79, p < .001; best linear fit: y = 0.95x – 0.05).

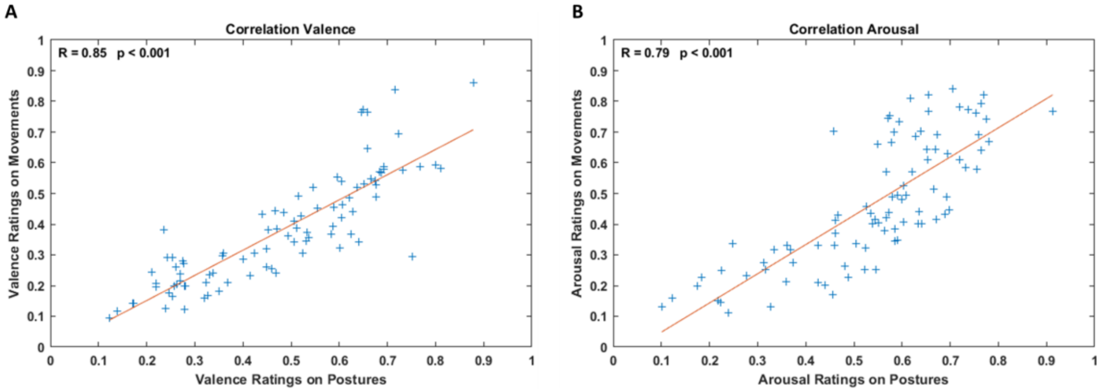


Fig. 5. Panel A (B) shows the correlation between valence (arousal) scores when subjects rated static postures and the corresponding walking actions. The Pearson's linear correlation coefficient and the p-value are reported on the top of both panels. Red lines indicate the best linear fit between ratings.

3.3. Discussion

We defined two body features related to pleasantness and dynamicity based on kinematic and postural information extracted from a set of emotional walking recorded with a motion capture system. We created a male and female avatar with body postures corresponding to three levels of body pleasantness and body dynamicity, coherently to the gender of the actor on which the kinematics were recorded. Experiment 1.A showed that participants coherently judged the avatar's bodily valence and arousal according to the defined body pleasantness and dynamicity levels. We also investigated whether the gender of the avatar influenced the perception of both valence and arousal, finding that participants perceived female avatar as more emotionally expressive than male ones. Experiment 1.B provided a ground truth comparison showing that valence and arousal levels perceived in the static body postures were consistent with those perceived in the corresponding walking actions.

Overall, we can argue that the defined bodily features allowed the affective information transfer from a full-body kinematic to a static body posture (see Appendix A for additional information). The adopted experimental procedure pointed to a difference in perception, possibly due to the avatar's gender. Despite the existing literature related to the gender difference in affective perception (Codispoti et al., 2008; Samadani et al., 2012), we did not observe any significant difference in the valence and arousal scores between males and females participants.

These results demonstrate that the defined body pleasantness, computed as the weighted sum of the openness of the body, leaning of the head, and leaning of the trunk, is a reliable descriptor of the valence dimension (Fourati & Pelachaud, 2018; Karg et al., 2013; Kleinsmith & Bianchi-Berthouze, 2007; Poyo Solanas et al., 2020), being able to transfer the affective information conveyed by an emotional walk to a static body posture. In fact, in this experiment, participants judged the valence level of the avatar coherently to the body pleasantness of the posture, distinguishing among low, middle, and high levels. In addition, the female avatar was rated in a more unpleasant state in the low body pleasantness condition and more pleasant in the high condition than the corresponding male avatar' judgments. Thus, participants judged the pleasantness state of the female avatar over a broader range, denoting that these postures were perceived as more expressive when characterized by unpleasant states and when expressing pleasant feelings. This result may reflect the female's higher emotional expressiveness. Because we normalized the displayed bodily features for the actor's gender, we may assume that the resulting differences depend on the observer's perception. Indeed, in line with biological and social models (Brody & Hall, 2008; Eagly & Wood, 1991), women are usually considered more emotionally expressive than men (Chaplin & Aldao, 2013; Deng et al., 2016; M. E. Kret & De Gelder, 2012; Kring & Gordon, 1998). When moving towards a virtual world, such biased perception is transferred from humans to virtual characters, thus making the female avatar seem to be more expressive when compared with their male counterpart (Bailey & Blackmore, 2017; DeWester et al., 2009; Yang & Ryu, 2021; Zibrek et al., 2015).

As to the arousal dimension, we defined the body dynamicity as a parameter correlating with the velocity of the performed movement. Our results demonstrated that such affective information was transferred to static body postures. Indeed, participants coherently judged the three levels of body dynamicity, thus discriminating different arousal levels in the avatar's body posture. Previous research has shown that features such as velocity, acceleration, and jerk of the movement were highly correlated to the arousal content of emotional gaits as well as of more specific movement such as drinking and knocking (Karg et al., 2010; McColl & Nejat, 2014; Paterson et al., 2001; Pollick et al., 2001). In automatic affect recognition, the quantity of motion is considered a discriminant factor to distinguish low arousing movement from high arousing ones (Castellano et al., 2007). Also, we found that arousal scores were significantly higher for female avatar than for males. Specifically, such biased perception depends on the higher arousal scores that participants gave female avatar with a middle level of body dynamicity. Indeed, these scores were comparable to those provided in the high condition. In addition, when compared with the male counterpart, female avatar were perceived as less arousing if characterized by low body dynamicity and more arousing if characterized by middle body dynamicity. We interpret such results as further evidence of the higher emotional expressivity of females (Brody & Hall, 2008; Grossman & Wood, 1993; Hess et al., 2000). However, this gender characteristic seems to be balanced in the high body dynamicity condition where the higher emotional expressivity of females is matched with the higher male tendency to show specific high arousing emotions such as anger (Chaplin & Aldao, 2013). In fact, we found no differences in scores between male and female avatar in the high body dynamicity condition.

These findings reveal that the female's higher emotional expressiveness may involve both the valence and arousal dimension, suggesting that participants perceive females as modulating the intensity of their affective states on a broader range than males.

To understand whether the female's higher emotional expressiveness could depend on the aesthetics characteristics of the avatar used for the experiment or on the methodology we used to create the actual postures they assumed, we conducted a second experiment in which female avatar assumed body postures derived by male actors' kinematics and vice versa, thus creating an incoherent condition. Should participants still perceive female avatar as more emotionally expressive, we could argue that the avatar's aesthetic characteristics (and not postures) mainly modulate the perceived emotional expressiveness. Conversely, should we find that female body postures are perceived more expressive even when assumed by a male avatar, we could conclude that female body postures (and not the avatar's aesthetic) mainly contribute to modulate expressiveness levels.

4. Experiment 2: actor – avatar gender incongruency

4.1. Stimuli

We used the same body postures of Experiment 1 to animate gender-opposite avatars to produce incoherence between the gender of the avatar and that of the actor from which we extracted the body posture. Hence, body postures extracted from actions recorded on a male actor were assigned to a female avatar and vice versa. This procedure led to the creation of 180 stimuli, 90 characterized by different levels of BD and the other 90 by different levels of BP. In Figure 6, we illustrate incoherent stimuli with different levels of BP and BD, showing the same body postures of Figure 3 represented by the gender-opposite avatar.

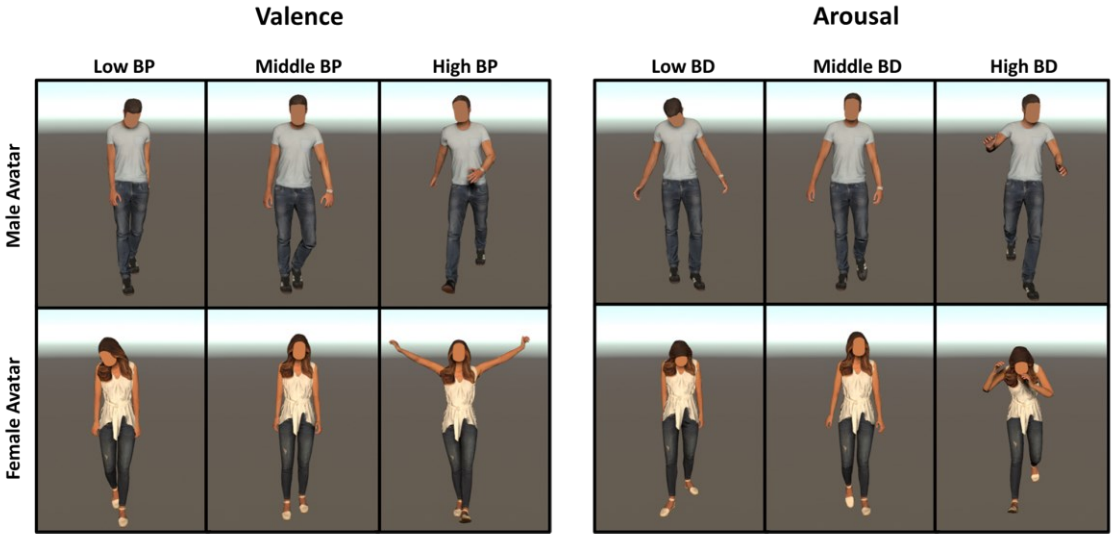


Fig. 6. Example of avatar's body postures with different levels of BP (right panels) and BD (left panels) used in Experiment 2. We assigned the body postures represented in Figure 3 to the gender-opposite avatar.

4.2. Participants, experimental procedure, and data analysis.

The adopted experimental procedure was the same as in Experiment 1. Fifty-four age-matched participants (27 women 25.2 ± 5.6 years, 27 male aged 23.4 ± 3.6 years; two-sample t-test, t(52) = -1.202, p = 0.234) were recruited through the online platform Prolific and then performed the experiment on Pavlovia. Also, participants were aged matched between Experiment 1 and 2 (2-way factorial ANOVA: no significant effect of the main factors Subject Gender (F(1,104) = 3.312, p = .072) and Experiment (F(1,104) = .793, p = .375)).

As in Experiment 1, valence and arousal ratings were normalized between 0 and 1 and then analyzed via two mixed-design ANOVA with Avatar (Male, Female) and Body Pleasantness/Dynamicity (Low, Middle, High) as within-subject factors and Subject Gender (Male, Female) as between-subject factor. The study was approved by the local ethical committee (Comitato Etico dell'Area Vasta Emilia Nord, https://www.aou.mo.it/ComitatoEticoAVEN) and conducted according to the principles expressed in the Declaration of Helsinki. Each participant provided written informed consent before participating in the experiment.

4.3. Results

Valence. Figure 7 (upper panels) shows results of rm ANOVA on valence scores. A significant effect for the main factors Body Pleasantness (F(2,104) = 570.417, p < .001, ηp2 = 0.916) and Avatar (F(1,52) = 61.615, p = 2.2*10-10, ηp2 = 0.542) emerged. Conversely, no significant effect was observed for the main factor Subject Gender (F(1,52) = 1.857, p = .178, ηp2 = .024). Bonferroni corrected pairwise comparisons revealed that each level of Body Pleasantness received significantly different scores (Low < Middle, p = < .001; Middle < High, p = < .001; Low < High, p = < .001).

Arousal. Figure 7 (lower panels) shows the results of rm ANOVA on arousal scores. A significant effect for the main factor Body Dynamicity (F(2,104) = 213.137, p < .001, ηp2 = 0.804) was observed, while both factors Avatar (F(1,52) = .891, p = .349, ηp2 = .017) and Subject Gender (F(1,52) = .031, p = .860, ηp2 < .001) did not reveal a significant effect. Bonferroni corrected pairwise comparisons showed that participants ratings were significantly different for each level of the factor Body Dynamicity (Low < Middle, p< .001; Middle < High, p < .001; Low < High, p < .001). Also, the interaction Avatar x Body Dynamicity (F(2,104) = 13.304, p < .001, ηp2 = 0.203) was significant revealing that female avatar with low BD were perceived as more arousing compared to male avatar with low BD (p = 0.026), and that male avatar with middle BD were perceived as more arousing compared to female avatar with middle BD (p = 0.002).

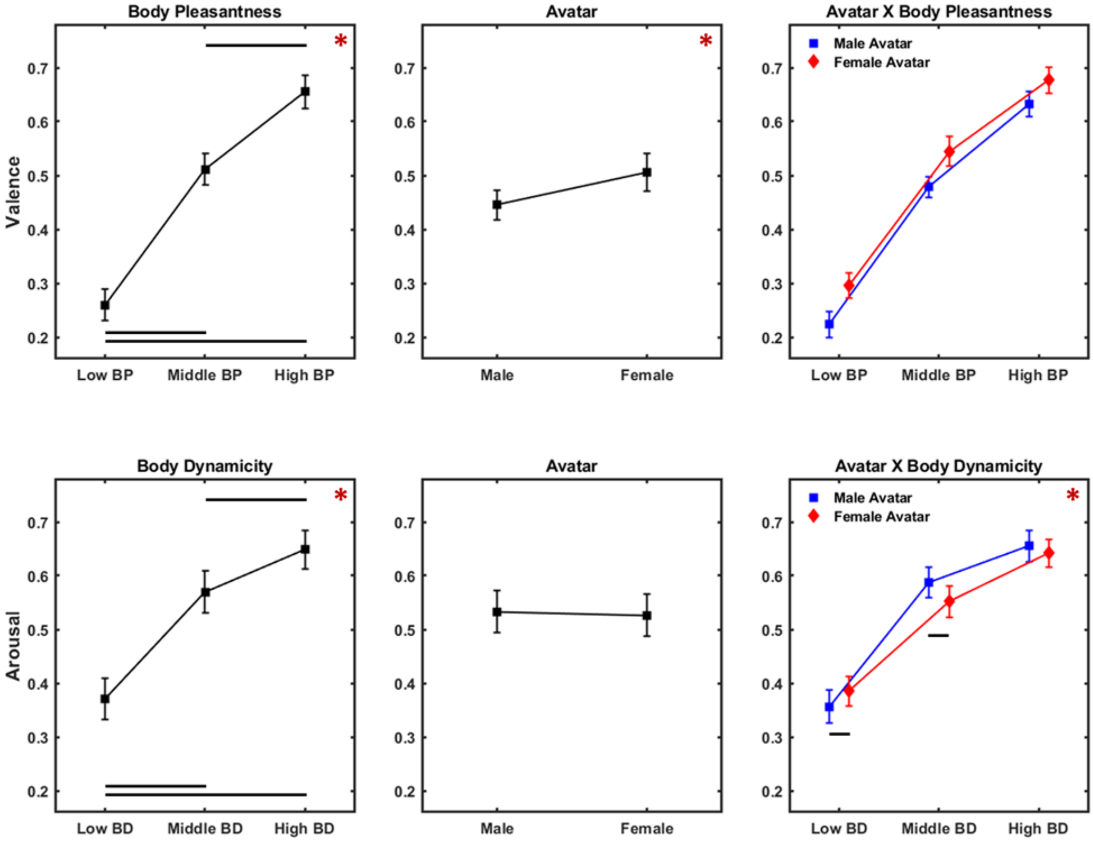


Fig. 7. Results of the ANOVA on Valence (upper panels) and Arousal (lower panels) ratings for Experiment 2. Upper panels present mean and 95% confident interval of the distribution of the valence scores for the main factors Body Pleasantness (left), Avatar (middle), and the interaction Avatar X Body Pleasantness (right panel). Lower panels present mean and 95% confident interval of the distribution of the arousal scores for the main factors Body Dynamicity (left), Avatar (middle), and the interaction Avatar X Body dynamicity (right panel). Same color code as Figure 4.

4.4. Discussion

In the second experiment, we disrupted the coherence between the actor's and avatar's gender to disentangle the relative contribution of body postures and avatars' aesthetic characteristics in judgments on valence and arousal. Findings returned that participants distinguished three levels of valence and arousal expressed by the avatars' bodies according to the defined body pleasantness and dynamicity levels. Such results highlight that even if the avatar assumed postures recorded on actors of the opposite gender, the body features we defined could still transfer the affective information contained in the walking kinematic to a static body posture in terms of valence and arousal. Furthermore, we found that the combination of aesthetic characteristics and body postures, i.e., the coherence between the actor's and avatar's gender (and not singularly posture or aesthetic factor), confers the higher emotional expressiveness to females.

As to the valence ratings, female avatars (with male postures) were perceived in a more pleasant state, regardless of the body pleasantness levels to which they belonged. However, considering the interaction between avatar gender and body pleasantness, the three levels of the body feature were similarly perceived between female and male avatar. Hence, disrupting the coherence between the gender of the avatar and that of the actor, we found that the avatar/actor gender incoherence spoils the difference between male and female avatar in terms of emotional expressiveness. A recent study reported a similar result using point-light stimuli representing emotional walking. The authors demonstrated that by depriving the participants of the structural cues of the walker gender, stimuli were perceived as equally emotionally expressive (Halovic & Kroos, 2018b).

As to arousal, male avatar with body postures extracted from female actresses were perceived in a lower arousing state than female avatar (with male postures) in the low body dynamicity condition. On the contrary, participants perceived the female avatar as less arousing than the male one in the middle condition. As in the first experiment, when considering the arousal dimension – regardless of the gender of the avatar – female postures were rated over a broader range compared to male ones. These results testify that the higher female expressiveness revealed in the arousal scores depends on gender-specific kinematic characteristics. These findings align with previous studies, where virtual puppets were more emotionally expressive when animated with female gestures (Yang & Ryu, 2021). However, these outcomes also show the importance of the avatar's aesthetic characteristics, represented by the two genders, for arousal judgments. Participants judged the female body postures differently if applied to a male or female avatar, highlighting that also the gender of the avatar influences the subject's judgment on arousal perception. In fact, in the second experiment, participants distinguished three levels of body dynamicity for female avatar, while in the first one, they confounded the middle with high body dynamicity. Similar results also emerged in previous research, showing that the same emotional postures were perceived as more emotionally expressive when represented by female virtual avatars (Cheng et al., 2020; Zibrek et al., 2015).

5. Conclusion

This study provides a new method that enables researchers to design body postures of virtual avatars with varying affective states, transferring affective information from dynamic walking to body postures. With this procedure, we created a set of virtual static stimuli potentially useful for studies exploring time-locked cognitive processes such as event-related potentials with electroencephalography, evoked-potentials with transcranial magnetic stimulation, and reaction times in all those studies which aim to investigate the perception of emotional body postures.

Two online experiments proved the reliability of the proposed methodology and revealed that male and female avatar are differently perceived when their body posture derives from kinematics recorded on coherent or incoherent gender actors. Therefore, to prevent perceptual biases caused by individual characteristics, it is worth considering the "actor behind the avatar" when creating the virtual character with affective postures, i.e., the physical characteristics of the actor when transposing affective information to a virtual avatar. For instance, the height of the actor and his/her size could be relevant information that should also be considered to model the virtual avatar representative of the actor's affective postures.

Further experiments could extend the validity of the presented methodology considering a more extensive set of kinematics comprising additional emotional gestures other than walking. Finally, exploiting 3D game engine software and virtual reality technologies, this methodology could be used in many experimental settings allowing researchers to resemble different social real-life situations to ultimately reach a deeper comprehension of how we perceive the affective states of others.

Chapter III – Study 2: The Affective Characterization of Virtual Architectures

The built environment represents the stage surrounding our everyday life activities. To investigate how architectural design impacts individuals' affective states, we measured subjective judgments of perceived valence (pleasant and unpleasant) and arousal after the dynamic experience of a progressive change of macro visuospatial dimensions of virtual spaces. To this aim, we developed a parametric model that allowed us to create 54 virtual architectural designs characterized by a progressive change of sidewalls distance, ceiling and windows height, and color of the environment. Decreasing sidewalls distance, ceiling height variation, and increasing windows height significantly affected the participants' emotional state within virtual environments. Indeed, such architectural designs generated high arousing and unpleasant states according to subjective judgment. Overall, we observed that valence and arousal scores are affected by all the dynamic form factors which modulated the spaciousness of the surrounding. Showing that the dynamic experience of virtual environments enables the possibility of measuring the emotional impact of macro spatial architectural features, the present findings may lay the groundwork for future experiments investigating the effects that the architectural design has on individuals' mental state as a fundamental factor for the creation of future spaces.

1. Measuring arousal and valence generated by the dynamic experience of architectural forms in virtual environments

A crucial but largely unexplored issue of human experience concerns how affective states are influenced by the dynamical change of spatial features when walking through a built environment. Previous studies using static 2D representations showed that several architectural features massively impact the observer affective states, typically measured in valence and arousal (I. Bower et al., 2019).

Valence represents the extent to which an architectural space makes an occupant feel good or bad. In recent studies, participants reported higher beautiful judgments for 2D representations of architectures with high ceilings and open spaces (Vartanian et al., 2013, 2015), which were also perceived as more pleasant (Coburn et al., 2020). The presence of windows is also typically linked to pleasant sensation (Higuera-Trujillo et al., 2021), enabling an outdoor view and creating a more spacious perception of the environment (Acosta et al., 2019; Ozdemir, 2010). Moreover, cold colors typically receive higher valence ratings than warm ones, thus moving people's preferences towards cold environments (Palmer & Schloss, 2010; Wilms & Oberfeld, 2018; Yildirim et al., 2011).

The arousal level can be modulated by the amount of light penetrating through the windows, which promotes circadian rhythms and contributes to people's overall well-being, diminishing their stress level (Kaye & Murray, 1982). Furthermore, cold-colored environments were associated with a peaceful sensation, while warm colors generated higher arousing states (Jalil et al., 2012; Yildirim et al., 2011). Previous research also reported that enclosed spaces increase vulnerability to stress and prolong the occupant's stress response (Fich et al., 2014), while spaces with low ceilings were found to generate a sense of confinement, thus being associated with higher arousing states (Meyers-Levy & Zhu, 2007; Stamps, 2011).

However, most of the studies mentioned above referred to 2D representations of the architecture, i.e., pictures of architectures shown on a monitor screen, which barely generate a realistic architectural experience. Nowadays, virtual reality technologies are gaining importance to recreate immersive scenarios (Sanchez-Vives & Slater, 2005; Slater & Sanchez-Vives, 2016), thus increasing the ecology of the architectural experience. Among such devices, head-mounted displays (HMDs) permit to visually explore the surrounding space through a subjective camera that follows the head movement and consequently updates the sensory perception in real-time. This mechanism creates a place illusion (Slater, 2009), generating realistic affective and behavioral responses in people, thus effectively providing a "reality simulator" (Slater & Sanchez-Vives, 2016). Compared with 2D stimuli, immersive virtual reality simulates the environment in a realistic and possibly interactive modality (Higuera-Trujillo et al., 2021), ameliorates the spatial perception (Paes et al., 2017), and can generate neurophysiological responses as it was a real scenario (Kisker et al., 2021; Schultheis et al., 2002). Nowadays, virtual reality is considered a powerful device for evoking emotions in laboratory settings (Marín-Morales et al., 2018, 2019; Riva et al., 2007; Rodríguez et al., 2015) compared to the presentation of passive stimuli (Marín-Morales et al., 2020). Indeed, virtual reality potentiates emotion and attention processes compared to conventional 2D stimulation, ensuring a deeper emotional experience (Schubring et al., 2020; Visch et al., 2010; Voigt-Antons et al., 2020). In architecture, virtual reality has been exploited to investigate the occupant emotions exposed to different architectural features (Cha et al., 2019; Franz et al., 2005; Marín-Morales et al., 2018). Also, immersive virtual environments generated similar behavioral outcomes compared to physically built environments (Heydarian et al., 2015; Heydarian & Becerik-Gerber, 2017; Latini et al., 2021). Hence, by adopting this technology, it is possible to effectively investigate the emotional perception of architecture under controlled laboratory conditions (Chiamulera et al., 2017; Franz et al., 2005; Higuera-Trujillo et al., 2021).

In particular, previous studies showed that walking within immersive 3D spaces significantly modulated individuals' emotional states. Ziegelman and colleagues found that different virtual scenarios elicited changes in state anxiety during walking (Ziegelman et al., 2021). Walking within virtual parks with different emotional contents elicited the intended emotions and a high sense of presence (Felnhofer et al., 2015). Also, immersive scenarios induced relaxing states while participants could freely navigate around (Baños et al., 2013; Colombo et al., 2021).

Although virtual reality has gained significant interest in investigating the architectural experience in the last years, only a few studies exploited its potential to permit a dynamic perception of the surrounding space (Djebbara et al., 2019, 2021). However, these works test the perception of affordances through the design of several architectural transitions (i.e., walking through a door of different dimension) comparing static versus dynamic condition not revealing emotional aspects, or investigate the emotional impact of static architectural forms not generating a dynamic perception of the surrounding (Banaei et al., 2017).

To overcome these limitations, we exploited the virtual reality technology to make subjects dynamically experience a set of immersive environments, conceived as a progressive modulation of the surrounding space only characterized by macro spatial dimensional changes, thus without any extraneous element.

Considering that exploring the space is fundamental for a comprehensive perception of the environment (Gramann, 2013), we exploited the HMD to enable an immersive, dynamic architecture experience. The subjective camera moves within the virtual architecture to dynamically perceive the surrounding space, thus generating a walking sensation. Indeed, previous research found that moving the user's view from one point to another can provide a compelling sense of self-motion (Harris et al., 2002; Hettinger, 2002; Nilsson et al., 2018). Such strategy allowed subjects to look around and see the space from different perspectives and positions, which is fundamental for visually exploring and perceiving the environment in a natural way (Banaei et al., 2017). Also, we minimized the presence of contextual elements within the virtual architectures. Indeed, they were conceived as a progressive modulation of the surrounding space, with no extraneous elements, thus only characterized by macro spatial dimensional changes. Furthermore, such dimensional changes were varied in a controlled way, thus creating 54 different environments where specific architectural parameters were manipulated either separately or in a combined way. Specifically, we manipulated the progressive variation of architectural elements such as sidewall distances, ceiling height, sill height, and color. Subjects made a virtual promenade within the architecture and then rated their experienced valence and arousal level.

This study demonstrates that a progressive modulation of spaciousness impacts the dynamic experience of architectural forms, thus influencing the subjective affective states (Gallese & Ruzzon, 2016; Ruzzon, 2017). In line with permeability theories (Stamps, 2010), our results show that moving towards narrow spaces with a reduced possibility to look around and visually explore the surrounding generates anguishing sensations. Showing that the dynamic perception of macro spatial architectural changes influences individuals' affective states, this study contributes to fostering a design approach that posits human affective states at the core of the creation of future spaces. We conclude with several possible future perspectives and implications, showing how the proposed experimental framework could be exploited to acquire a more generalizable knowledge of the architectural experience.

2. Material and methods

2.1. Stimuli

A parametric model was designed on Grasshopper (https://www.rhino3d.com/6/new/grasshopper/) and imported on the online platform ShapeDiver (https://shapediver.com/) to generate 27 different virtual architectural designs. Each design is a combination of three consecutive nuclei, the first of which had fixed dimensions: 4m x 4m x 7m (width x height x length) with 1m x 6.8m (height x length) windows located at the middle height of each sidewall. Then, the other two nuclei could vary architectural factors such as the distance between the sidewalls (SideWalls), the height of the ceiling (Ceiling), and the height of the windows sill (Windows), which refers to the location of the windows relative to the ceiling height. Specifically, the parametric model allowed increasing, decreasing, and keeping such architectural factors constant between one nucleus and the next. Thus, we realized variations of ± 0.8 m for the factors SideWalls and Ceiling. The sill height changed as a function of the ceiling height of the third nucleus: in the increasing sill height condition, windows were located close to the ceiling; in the decreasing condition, windows were located close to the floor; in the constant condition, windows were located in the middle of the sidewalls. The sill height of the second nucleus was defined considering the middle point between the sill height of the first and third nucleus. All virtual architectures were endowed with two doors: an opened one in the first nucleus as entrance and a closed one at the end of the third nucleus. Such configuration enhanced the realism of the dynamic experience of the architecture, giving the subject the impression of being inside an environment suitable for a promenade, providing an entry and an exit point. The dimensions of the architectural designs are shown in Appendix B.

The 3D architecture designs generated in Shapediver were imported into Unity (2019.1.0f2, https://unity.com/). Here, parameters such as texture and lighting were manipulated to transform the 3D object into a realistic architecture. Hence, each architecture was proposed in two colors: a warm reddish one and a cold bluish one. A specific lighting setting was implemented to generate realistic enlightenment of the virtual scene. The light was a directional one 4 m high, located 2.5 m to the right and 4.5 m before the entrance door outside the architecture. The light was also inclined towards the door, 18° around the x-axis (width) and -17° around the y-axis (height), making the lighting assume different shapes depending on architectural factors. In this way, 54 architecture designs were created to implement a 3x3x3x2 factorial model with factors SideWalls x Ceilings x Windows (each with conditions decreasing, constant, increasing) x Colors (warm, cold). Panel A of Figure 8 provides a view of the architectural factors from the entrance perspective.

2.2. Participants

Twenty-nine subjects were recruited for this experiment (27.35 ± 3.7 years, 16 female). All subjects were Italian master's or postgraduate students, they had no particular familiarity in using virtual reality, and none of them was an architect, studied architecture or was in any way familiar with the study of architecture, internal design and related disciplines. The sample size was determined using a power analysis computed through the G*Power software (Faul et al., 2007), considering the 2x3x3x3 within-subject design with the "as in SPSS" option and setting the significance level (α) at 0.05, the desired power (1- β) to 0.95, the number of groups to 1, the number of repetition to 54 and the non-sphericity correction ε to 1. The value of the ηp2 was set to 0.03 based on previous research (Coburn et al., 2020). All subjects reported normal or corrected-to-normal vision and no previous history of neurological disorders. The study was approved by the local ethical committee (Comitato Etico dell'Area Vasta Emilia

Nord, (https://www.aou.mo.it/ComitatoEticoAVEN) and conducted according to the principles expressed in the Declaration of Helsinki. Each participant provided written informed consent before participating in the experiment.

2.3. Experimental setup

The experiment was performed in a virtual reality environment realized with the HTC Vive Pro Eye HMD to provide a highly immersive experience. It is equipped with two AMOLED screens, with a resolution of 1440 x 1600 pixels per eye, a refresh rate of 90 Hz, and a field of view of 110°. Unity was integrated into the HMD via the Steam VR asset to control the experimental procedure and collect data. The experiment ran on a laptop equipped with Windows 10 Home (64-bit), Intel Core i7 -9750H, 32 GB RAM, and the NVIDIA GeForce RTX 2070 graphics card.

2.4. Experimental procedure

Subjects read written instructions explaining the experimental procedure and the concepts of valence and arousal. Valence is the pleasantness state generated by a given experience: unpleasant states are associated with bad feelings or a negative state of mind, while pleasant states to good feelings or a positive state of mind (Colibazzi et al., 2010; Colombetti, 2005; Hamann, 2012; Posner et al., 2005; Ramirez & Vamvakousis, 2012; Russell, 2003). The arousal dimension is the state of activation generated by a given experience, resembling a change of the individual's physical and psychological assets. A deactivated state is associated with a low heartbeat, sweating decrease, slow breathing, absence of energy, and decreased attentional and decisional capability. Instead, an activated state is associated with a high heartbeat, sweating increase, fast breathing, feelings of vigor, energy, tension, and increasing attentional and decisional capability (Colibazzi et al., 2010; Gomez et al., 2016; Russell, 2003). The Vive Pro Eye HMD was placed over the subject's head and arranged comfortably, providing a clear view of the virtual environment. Through the movement of a first-person perspective camera, subjects experienced the feeling of walking within the architecture. Specifically, the navigation within the environment was realized by moving the camera's position from the entrance door to the beginning of the third nucleus. Hence, the subjective camera was moved within the virtual environment, simultaneously following the subject's head rotation and displacement (6 degrees of freedom), thus ensuring the elicitation of the place illusion. The camera speed was set to 1.25 m/s, considering the average male and female gait speed (Bohannon & Williams Andrews, 2011). Also, a smoothing function was applied to avoid rough speed changing at the beginning and the end of the navigation, thus limiting and preventing motion sickness.

Thus, each experimental trial consisted of a virtual promenade (12.5 s) inside the architecture, followed by the presentation of two consecutive grey panels with an approximation of a visual analog scale (VAS) where subjects could rate the architectural experience in terms of arousal and valence. The lower and higher bound of the two VAS were 0 and 1, respectively. With the first scale, subjects answered the question: "This environment makes me feel…", ranging from "Deactivated" to "Activated". With the second scale, subjects answered the question: "This environment provides me … feelings", ranging from "Unpleasant" to "Pleasant". Subjects used the Vive controller to move the VAS cursor with no time limits to provide their judgments. The 54 architectures were randomly presented, divided into three blocks of 18 architectures each, thus subjects experienced each architecture once. Blocks were separated by a pause in which subjects were permitted to take the HMD off and have some rest. At the beginning of the experiment and during each pause, the experimenter made sure that subjects did not feel any motion sickness effects. No subjects reported motion sickness during the experiment. Panel B of Figure 8 depicts the timeline of an experimental trial.

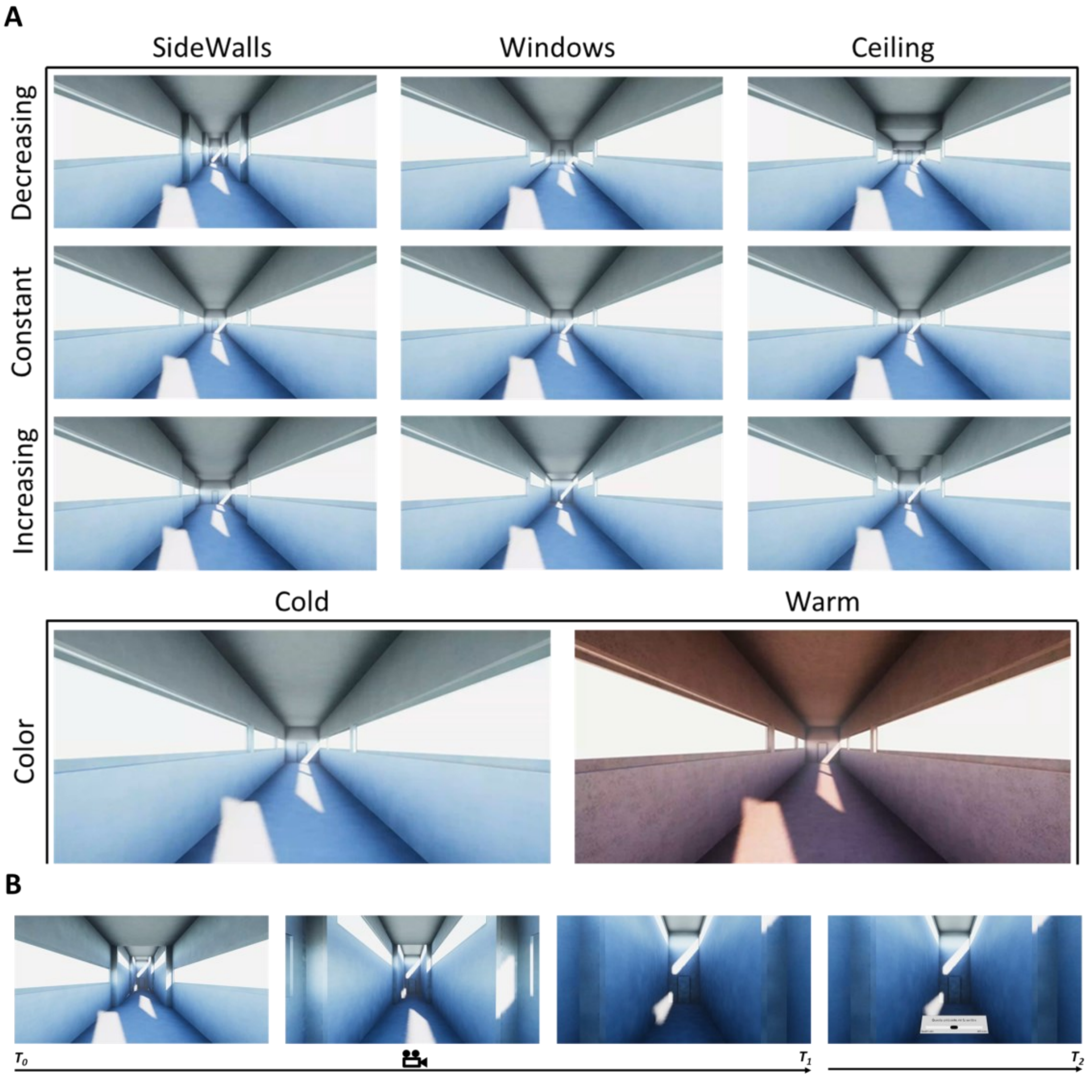


Fig. 8. Panel A: Perspectives of virtual environments for each architectural factor (SideWalls, Ceiling, Windows, Color) for the corresponding experimental conditions (decreasing, constant, increasing; cold, warm). Panel B: schematic representation of one experimental trial: subject made a virtual promenade between the first two nuclei of the architecture (T0-T1) and then rated the experienced level of arousal and pleasantness (T2).

2.5. Statistical analysis

Subjective valence and arousal ratings were z-scored and analyzed via two distinct 3x3x3x2 repeated measures (rm) ANOVA with SideWalls, Ceiling, Windows (decreasing, constant, increasing), and Colors (warm, cold) as within-subject factors. Pearson's correlation coefficient was used to compute the correlation between arousal and valence scores. K-means clustering (k=2) was used to group the environments in the space defined by the arousal and valence dimensions. For each of the four environmental factors, we computed the prevalence of the architectural design for each experimental condition. Finally, the statistical difference of the observed frequencies distribution was assessed by chi-squared tests. Data analysis was performed with Matlab 2018b (The Mathworks, Inc., Natick, MA, USA) and Statistica 7 (StatSoft Europe) software.

3. Results

Results of the rmANOVA on valence ratings are illustrated in Figure 9. A significant effect was observed for the main factors SideWalls (F(2,56) = 29.933, p = 1.4*10-9, ηp2 = 0.516), Windows (F(2,56) = 4.941, p = .011, ηp2 = 0.149) and Ceiling (F(2,56) = 7.135, p = .002, ηp2 = 0.203). Specifically, Bonferroni corrected pairwise comparisons revealed lower valence ratings for those architectures with decreasing sidewalls distance when compared to those with constant (p = 6.6*10-6) and increasing (p = 1.3*10-9) one. Increasing windows sill height also resulted in lower valence scores compared to the constant (p = .016) and decreasing (p = .044) conditions. Finally, architectures with constant ceiling height were associated with higher valence ratings than those with increasing (p = .003) and decreasing (p = .008) one. No significant difference among valence scores was observed for the factor Color. The interaction SideWalls x Ceiling (F(4,112) = 6.219, p = 1.5*10-4, ηp2 = 0.182) was significant as illustrated in figure 4 (Panel A). Bonferroni corrected pairwise comparisons revealed that architectures with increasing sidewalls distance and constant ceiling height resulted in significantly higher valence scores than architectures with different combinations concerning the sidewalls distance and ceiling height. Contrarily, those architectures with decreasing sidewalls distance and increasing ceiling height received significantly lower valence scores than those with different combinations of such architectural elements. Also the interaction Windows x Ceiling (F(4,112) = 3.297, p = .013, ηp2 = 0.105) returned to be significant as presented in figure 10 (Panel B). Specifically, Bonferroni corrected pairwise comparisons revealed that subjects provided significant lower valence scores for those architectures with increasing windows height rather than decreasing (p = .022) or constant (p = 5*10-

5), but only when the ceiling of the architecture increased between one nucleus and the next one, and not in the decreasing or constant ceiling height condition.

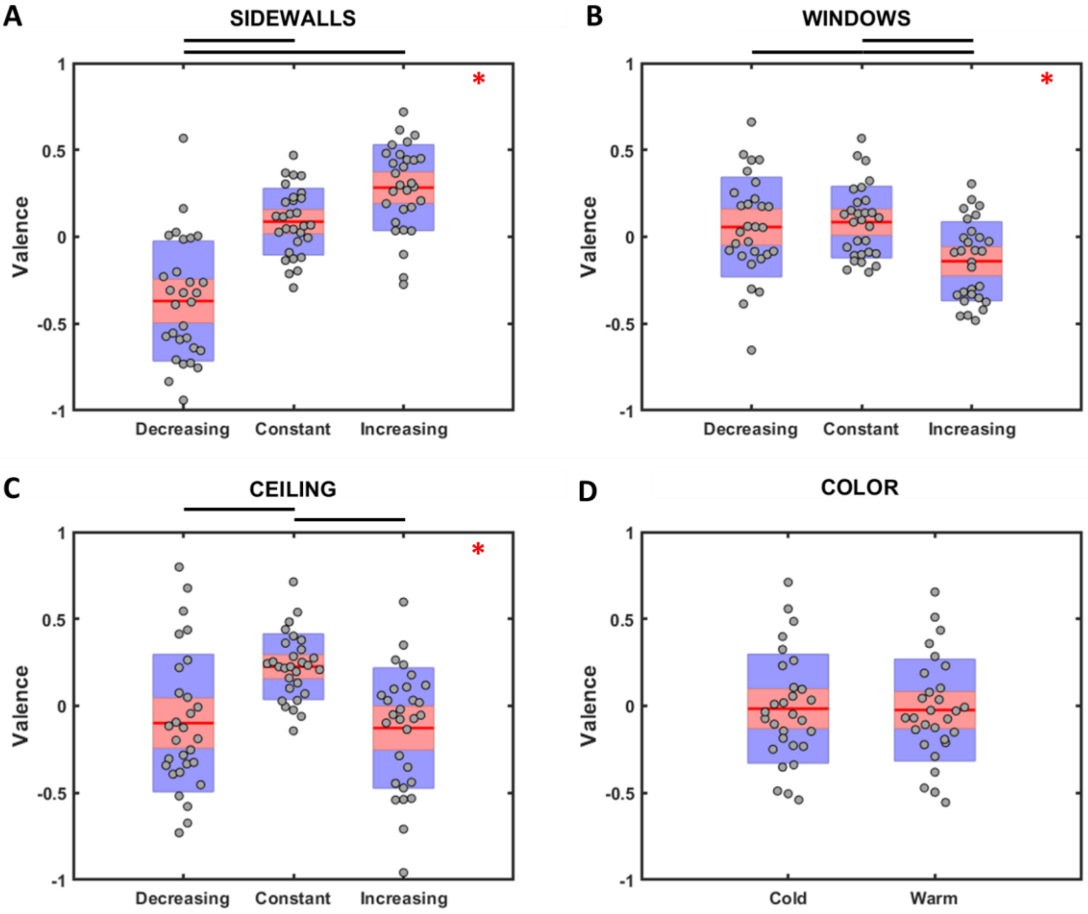


Fig. 9. Distribution of the valence scores for SideWalls, Windows, Ceiling, and Color are presented in panels A, B, C, D, respectively. Red lines represent the mean value; data are represented as dots laid over a 1.96 standard error mean (95% confidence interval) in pink and a 1 standard deviation in blue. Red asterisks indicate a significant main effect, and black lines show significant pairwise comparisons.

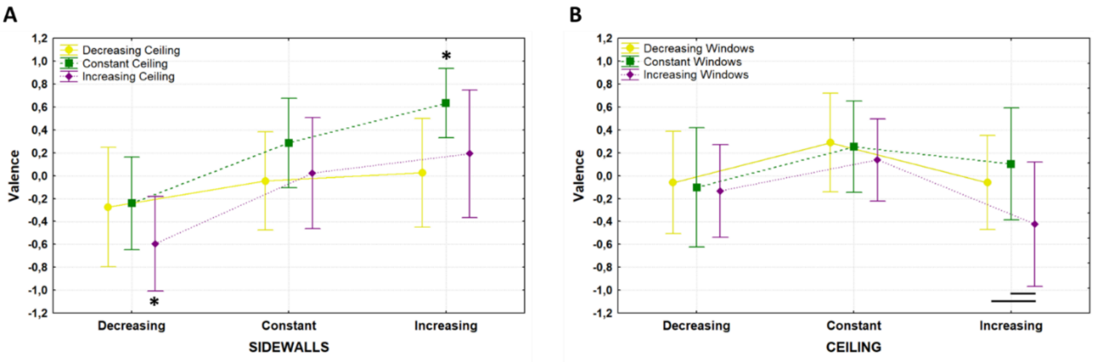


Fig. 10. Panel A: distribution of the valence scores for the two-way interaction SideWalls x Ceiling. Yellow, green, and purple lines represent decreasing, constant, and increasing ceiling height. Panel B: distribution of the valence scores for the two-way interaction Ceiling x Windows. Yellow, green, and purple lines represent decreasing, constant, and increasing windows height. Data are presented with their mean value with vertical lines representing the 95% confident interval. Black lines stand for significant pairwise comparison, while black asterisks remark an experimental condition which comparisons with the other conditions are all significant.

Results of the rm ANOVA on arousal ratings are illustrated in Figure 11. A significant effect was found for the main factors SideWalls (F(2,56) = 20.589, p = 1.9*10-7, ηp2 = 0.424) and Windows (F(2,56) = 6.812, p = .002, ηp2 = 0.196), with a trend for the factor Ceiling (F(2,56) = 2.519, p = .089). Specifically, Bonferroni corrected pairwise comparisons revealed that architectures with decreasing sidewalls distance resulted in higher arousal scores than those with constant (p = 2.2*10-4) and increasing (p = 1.5*10-7) sidewalls distance. Architectures with increasing windows sill height were perceived as more arousing than those with constant (p = .029) and decreasing ones (p = .002). No significant difference among the arousal scores was observed for the factor Color. A significant interaction of the factor Color x Ceiling (F(2,56) = 4.23, p = .019, ηp2 = 0.131) is illustrated in Figure 12 (Panel A). Bonferroni corrected pairwise comparison revealed that subjects perceived warm architectures more arousing than cold ones when the ceiling decreased between consecutive nuclei (p = .008). The interaction Windows x Ceiling (F(4,112) = 3.747, p = 0.007, ηp2 = 0.118) was also significant (Figure 12, Panel B), showing that higher arousal scores were collected in architectures with increasing windows height and increasing ceiling, compared to those architectures with different combination of such architectural features.

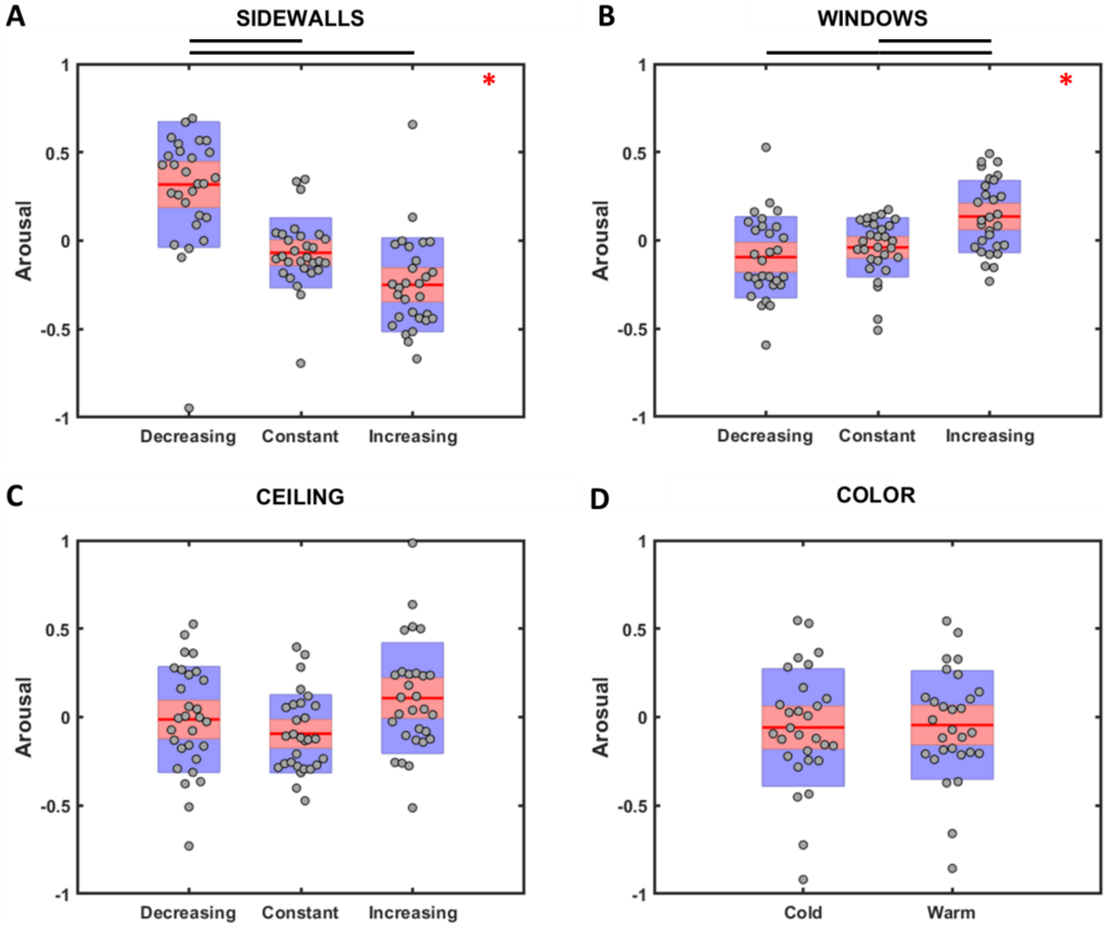


Fig. 11. Distribution of arousal scores for the main factors SideWalls, Windows, Ceiling, and Color are presented in panels A, B, C, D, respectively. Same color code as Figure 3.

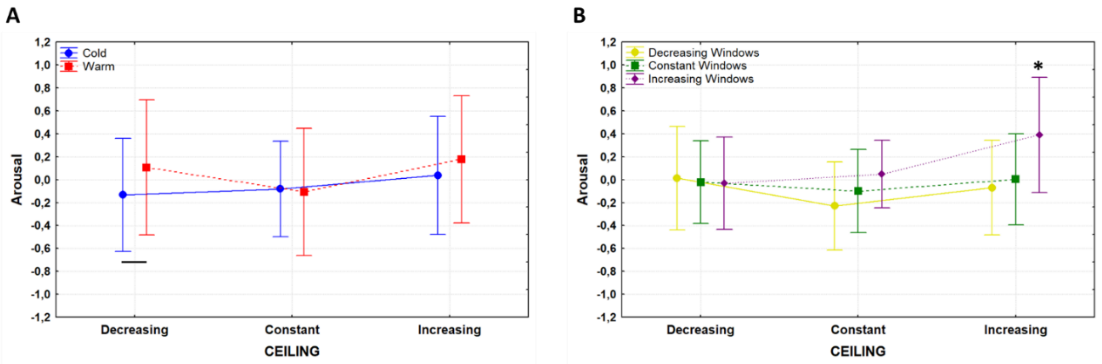


Fig. 12. Panel A: distribution of the arousal scores for the two-way interaction Color x Ceiling. Blue and red lines represent cold and warm architectures, respectively. Panel B: Distribution of the arousal scores for the two-way interaction Windows x Ceiling, same color code as Figure 4.

Results of the cluster analysis are illustrated in Figure 13. Architectures are distributed in the space defined by arousal and valence dimensions with a significant negative correlation (R = -0.85, p < .001). Hence, we applied the k-means algorithm (k=2) to segregate the architectures experienced with a high level of arousal and a negative level of valence (HANV) from those experienced with low arousal and positive valence (LAPV). The prevalence of architectures within the two clusters according to their experimental condition can be found in Table 1. Considering the factor SideWalls, we observed that architectures were largely unbalanced between the two clusters (χ2 = 20.05, p = 1.6 *10-5): the 89% of architectures with decreasing sidewalls distance belongs to the HANV cluster, while most of the constant and increasing sidewalls distance architectures belong to the LAPV cluster (72 and 83%). Furthermore, we found that the distribution of the architectures within the two clusters according to the ceiling height was close to being significant (χ2 = 5.85, p = .054): the 78% of architectures with constant ceiling belong to the LAPV cluster, while the 61% of architecture with decreasing ceiling belong to the HANV cluster. Clustering architectures according to the factors Windows and Color did not return statistically significant results.

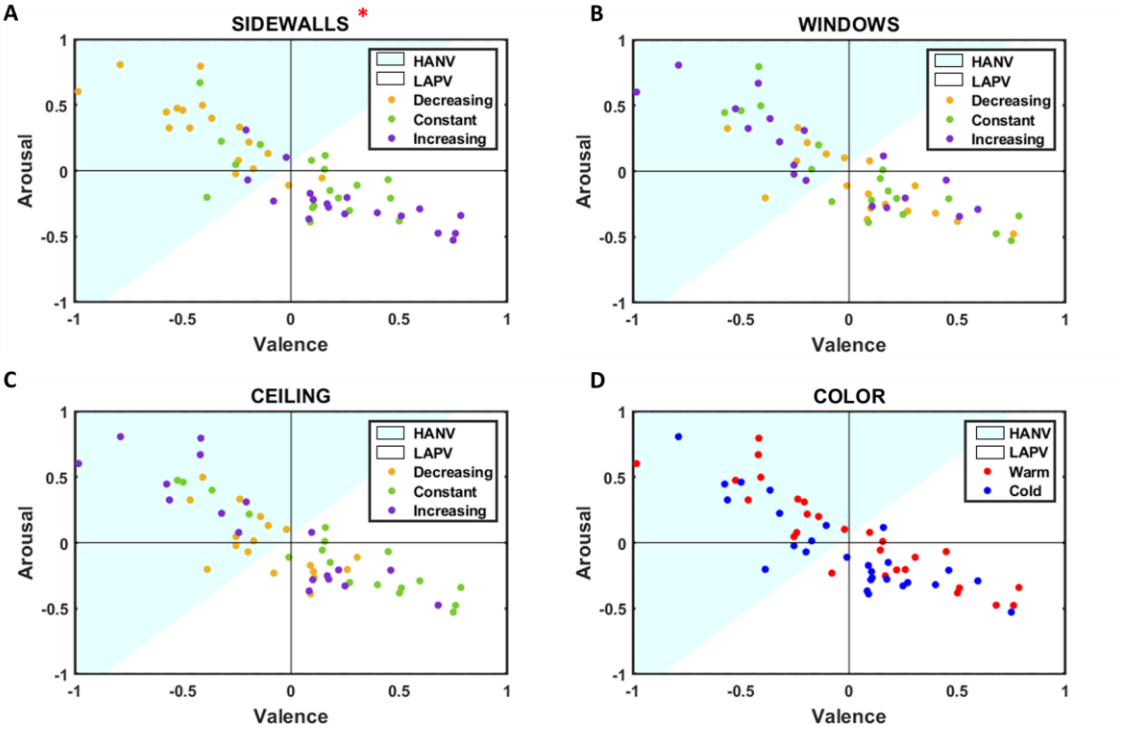


Fig. 13. For each panel, the blue section of the plane includes the architectures belonging to the HANV cluster, while the white one comprises architectures within the LAPV cluster. Panel A, B, C: yellow, green, and purple dots identify architectures with decreasing, constant and increasing conditions for SideWalls, Windows, and Ceiling factors, respectively. Panel D: blue and red dots identify architectures with cold and warm texture color, respectively. The red asterisk indicates statistically significant results.

Table 1. Percentage of architecture distribution within the clusters HANV and LAPV for each experimental condition.

		HANV	LAPV
SideWalls	Decreasing	88.89	11.11
	Constant	27.78	72.22
	Increasing	16.67	83.33

		HANV	LAPV
Windows	Decreasing	38.89	61.11
	Constant	33.33	66.67
	Increasing	61.11	38.89

		HANV	LAPV
Ceiling	Decreasing	61.11	38.89
	Constant	22.22	77.78
	Increasing	50	50

		HANV	LAPV
Color	Warm	48.15	51.85
	Cold	40.74	59.26

4. Discussion

Virtual reality technology created a virtual promenade experienced emotionally through macro spatial dimensional changes of the environments formed by three consecutive nuclei whose architectural features varied progressively. The proposed experimental framework allowed us to isolate the effects of macro spatial architectural changes on subjects' affective states, finding that negative-valenced feelings were generated by narrowing the sidewalls, increasing the windows sill height, or increasing/decreasing the ceiling height. In the first two cases, such modulations also significantly increased perceived arousal. Rm ANOVAs and cluster analysis revealed that the architectural feature that more strongly affected valence and arousal ratings was the sidewalls distance. Finally, we found that our architectural spaces generated either pleasant and low arousing states or unpleasant and high arousing states, possibly arguing that macro spatial architectural changes may be associated with relaxing or anguishing spaces and rarely with pleasant and exciting spaces or unpleasant and calming ones.

Our results showed a preference for the subjects to experience the virtual promenade within wide spaces rather than enclosed ones, arguing that the progressive reduction of the surrounding space was perceived as a constriction, thus leading to uncomfortable states of unpleasantness and high arousal (Gallese & Ruzzon, 2016; Ruzzon, 2017). These results are in line with enclosure and permeability theories, according to which enclosed spaces, characterized by a reduced possibility to move-through and see-through, are associated with uncomfortable states (Stamps, 2010). Previous studies also revealed that 2D stimuli of enclosed spaces were more likely to generate fear sensation and avoidance decisions and judged as less beautiful than open spaces (Im, 1987b; Vartanian et al., 2013, 2015). Furthermore, enclosed spaces are associated with situations perceived as less controllable and avoided by human beings because they increase the stress level for their inhabitants (Fich et al., 2014). Reasons can be found in survival motivation since enclosed spaces do not typically provide any possible way out (Stamps, 2005, 2010).

The virtual promenade characterized by decreasing ceiling height produced a progressive reduction of the surrounding space, thus leading subjects to report unpleasant judgments. We found a preference peak for the constant ceiling height of 4 m, resembling results favoring built environments with 3 m ceiling height that fosters exploration and visuospatial attention (Baird et al., 1978; Coburn et al., 2020; Vartanian et al., 2015). Such a 1 m difference concerning the reported literature could be due to general misperception effects generated by virtual reality (Armbrüster et al., 2008; Willemsen & Gooch, 2002). Findings suggest that egocentric distances in virtual environments are estimated as 75% of the modelled virtual distance (Renner et al., 2013). Instead, the over-increasing in the ceiling height led to perceiving the architectural space as less pleasant, as also reported by Baird and colleagues (Baird et al., 1978), possibly due to a decreased perception of the spaciousness (Stamps, 2011).

We report that virtual promenades with increasing windows sill height generated unpleasant and high arousing judgments. In such architectural spaces, light penetrated from progressively higher and less accessible points, leading subjects to move towards less enlightened areas where a possible outdoor view was more challenging to access. Previous research claimed that these aspects are fundamental for the well-being of the inhabitants(Nagy et al., 1995). Although we cannot measure the impact of the virtual simulation of sunlight on circadian rhythms, the realistic enlightenment we created within the virtual architecture contributed to creating the "place illusion," thus leading to the consequent modulation of affective states. In addition, access to outdoor views was found to reduce the stress level at the work office (Leather et al., 1998), provide restoration at home (Kaplan, 2001), and benefit post-operative patients during recovery (Ulrich, 1984). The presence of windows is also typically associated with an increased perception of the spaciousness of the environment (Moscoso & Matusiak, 2018; Ozdemir, 2010). In line with such findings, our results emphasize that moving towards spaces where the windows are closer to the subject height produced a more pleasant experience with lower arousal values, possibly due to an increased perception of the spaciousness (Kaye & Murray, 1982; Yeom et al., 2020; Yildirim et al., 2007). The proposed experimental design showed that participants felt an anguishing sensation within those architectural designs with increasing sill height relative to the roof location, regardless of the absolute height of the sill. However, further evidence is necessary to argue that the windows sill height relative to the eye level is crucial for modifying individuals' affective states.

The environment's color modulation did not affect valence and arousal judgments at the end of the dynamic architectural experience. The specific bluish and reddish colors were selected to generate cold and warm sensations. To more deeply investigate how the chromatic aspect of the environment modulates the individual emotional state, we need to consider additional chromatic characteristics, such as the different values of hue, intensity, and saturation, possibly perceived in different modalities. For instance, one could introduce a dynamic component to the chromatic characteristics that could change across the nuclei, as done with the form factors, to investigate the role of a dynamic component of the color on emotional judgments. On the other hand, one could represent the environments statically to compensate for the dynamic component generated by changes in the macro spatial architectural dimensions, thus hypothesizing that a static color could mainly influence a static, not dynamic, perception of the environment.

These results suggest that modification of forms produces a variation of the extra-personal space, which the subject can visually explore, thus affecting the perception of spaciousness. Since it is known that space coding relies on both visual as well as motor circuits (Berti & Rizzolatti, 2002; Cléry et al., 2015, 2018; Rizzolatti et al., 1997), we may hypothesize that the emotional experience generated by the dynamic perception of progressive variation of architectural features could exploit the neural circuitry composed by parietal and premotor areas devoted to controlling and planning of voluntary movements (Jelić et al., 2016; Kravitz et al., 2011; Vecchiato, Jelic, et al., 2015; Vecchiato, Tieri, et al., 2015).

This study demonstrates the capability of Virtual Reality technologies to evaluate individuals' emotional response to key spatial architectural parameters experienced during a virtual promenade. On the one hand, virtual reality itself does have some caveats related to the limited sensorial stimulation and thus to the transferability of the results into real-world architectures. In fact, a comprehensive architectural experience is characterized by a larger variety of sensorial aspects, rather than only visual, that may interact to ultimately shape individuals' affective states. On the other hand, virtual reality has the unique advantage to allow the creation of ecologically valid experimental scenarios without confounding effects present in real-world investigations.

One challenge faced by virtual reality technology is reproducing a realistic perception of illuminance and colors. In earlier studies, real reference rooms were compared to their full-scale reconstructed virtual models. Virtual rooms presented incorrect light reflections on surfaces and several issues related to chromatic and color characteristics (i.e., achromatic shadows, limited contrast effects, and limited color variations) (Billger et al., 2004; Stahre Wästberg & Billger, 2006). In the last years, important steps forward have been made regarding color rendering in 3D virtual models, permitting to recreate a more realistic illuminance, pruned by color-related issues (Stahre Wästberg et al., 2015). Indeed, recent studies compared individuals' responses to real architectures and their virtual reproduction, finding no significant differences. In a study by Chamilothori and colleagues, they found that the use of immersive virtual environments is an adequate surrogate of real-world settings in daylight perceptual studies (Chamilothori, Wienold, et al., 2019). Latini and colleagues compared subjects' productivity and comfort between real and immersive virtual scenarios of an office considering different color layouts finding no statistical differences (Latini et al., 2021).

Architectural perception is a multisensory experience involving, for instance, visual sensations through the modification of form and color, tactile ones due to the combination of different materials, and acoustic phenomena produced by different kinds of sound wave reflections. However, the objective of the present study was to demonstrate that the only dynamic perception of macro visuospatial variations of forms could alter the affective experience of the environment, regardless of other sensorial variables. For this reason, we exploited the capability of VR that allowed us to render a series of environments with different visuospatial effects while keeping constant all the other architectural components, such as material, that would have impacted – without the possibility to test – the other sensorial channels. In addition, it could be also worth considering that vision is dominant over the other senses. In this regard, it was demonstrated that sensorial experiences of touch are negligible when coupled with visual stimulation to evaluate different materials and their warmth perception (Wastiels et al., 2012, 2013).

The generalizability of the present findings should be tested across different cultural backgrounds. Indeed, perception of spaciousness and color preferences may vary according to the cultures (Doherty et al., 2008; Mecklinger et al., 2014; Saulton et al., 2017). Generally, westerners are more focused on salient stimulus features independently of their surrounding spatial or social context (Nisbett et al., 2001; Nisbett & Miyamoto, 2005). Saulton and colleagues showed that German and South Koreans had different spatial volume perceptions of computer-generated rooms. Specifically, they found that Koreans were significantly less biased than Germans by room rectangularity and viewpoint, pointing to the necessity of further investigations to determine the exact reasons for the cultural differences in room size perception (Saulton et al., 2017). Also, color preferences may vary according to different cultures. For instance, Eastern Europeans were significantly more prone to green colors, while Western Europeans to dark greys (Serra et al., 2021). Similarly, Jonauskaite and colleagues found that the yellow-joy association was more frequent in participants who lived far away from the equator and in rainier countries (Jonauskaite et al., 2019). As a future perspective, our experimental framework offers the possibility to test cultural differences by ad-hoc manipulating forms and colors of the environment according to theories and findings reported in the literature, thus providing a valid approach to investigate why people from different ethnicities and cultures perceive architecture differently.

The adopted framework will also allow recreating immersive scenarios where the architecture is the context hosting our everyday activities and where individuals interact, thus resembling social scenarios. Indeed, humanoid avatars can be embedded within the virtual scenarios, thus reproducing those events that typically occur within built environments. In that case, one will be able to investigate how the architecture shapes social interactions, which are otherwise difficult to recreate with a standard laboratory setting or in real conditions.

In addition, behavioral and physiological measures could be coupled with explicit subjective reports to investigate the neural underpinnings and the corresponding actions emerging from the dynamic perception of architecture (Banaei et al., 2017; Chamilothori, Chinazzo, et al., 2019; Chiamulera et al., 2017). Eye-tracking systems could be embedded into the HMD to gather eye gaze and pupillometry for achieving a description related to the patterns of the visuospatial exploration. The recording of autonomic parameters could be synchronized with the virtual stimulation system to couple physiological measures related to emotional processes. Finally, electroencephalography can be recorded during the virtual reality experience to monitor cortical circuits underpinning the dynamic perception of architecture. In such a way, electrophysiological data would reveal the implicit correlates of the emotional experience elicited by the perception of a progressive modulation of the extra-personal space associated with the generation of relaxing and anguishing states.

5. Conclusions

The present study demonstrates that the dynamic experience of macro spatial variations of the architectural design influences the individuals' affective state. The visuospatial exploration of environments that progressively reduce the extra-personal space generated anguishing sensations. The resulting findings enlarge the understanding of how the dynamic perception of different architectural features influences and possibly supports appropriate emotional responses relevant for preparatory circulation spaces leading to meeting rooms, meditation spaces or sports halls, to mention a few exemplifying scenarios. Extending the proposed experimental framework to investigate physiological reactions to architectural changes will move towards a more generalizable knowledge of architectural perception. Thus, this approach will foster a design approach where individuals' affective states are fundamental for the creation of future spaces. The acquired knowledge would assist the design of built settings with features coherent with the social events expected to occur inside them, such as collaborative and social interactions in the workplace, patient-staff interaction in healthcare settings, and formation of social ties in public spaces.

Chapter IV – Study 3: Architectural Experience Influences the Processing of Others' Body Expressions

The interplay between space and cognition is a crucial issue in Neuroscience leading to the development of multiple research fields, including Neuroarchitecture. However, the relationship between architectural space, the movement of the inhabitants and their interactions has been too often neglected, failing to provide a unifying view of architecture's capacity to modulate social cognition broadly.

We bridge this gap by requesting participants to judge avatars' emotional expression (high vs. low arousal) at the end of their promenade inside high- or low-arousing architectures. Stimuli were presented in virtual reality to ensure a dynamic, naturalistic experience. High-density EEG was recorded to assess the neural responses to the avatar's presentation.

In line with previous evidence, observing highly aroused avatars increased Late Positive Potentials (LPP). Strikingly, 250 ms before the occurrence of the LPP, P200 increased due to the experience of low-arousing architectures regardless of the emotional expression of the avatar, paralleling increased subjective arousal reports and fixation times on the avatar's head. Source localization highlighted a contribution of the dorsal premotor cortex to both P200 and LPP.

In conclusion, the immersive and dynamic architectural experience modulates human social cognition. In addition, the motor system plays a role in processing both architecture and body expressions proving how the space/cognition interplay is rooted in common neural substrates. This study demonstrates that the manipulation of mere architectural space is sufficient to influence human behavior in social interactions.

1. The interplay between the architectural experience and the perception of emotional body expressions

The interplay between spatial and social environment is a fundamental aspect of daily life (Dorfman et al., 2021; Schafer & Schiller, 2018). The awareness that the amount of time we spend indoors could significantly influence human behaviour moved neuroscientists to explore human responses to the built environment, which can be considered the prototypic field for studying the interaction between space and social cognition (Eberhard, 2009; Gepshtein & Snider, 2019; Sternberg & Wilson, 2006). Previous studies demonstrated that the brain contains multiple, plastic, and dynamic space mappings accomplished by fronto-parietal networks characterized by visuomotor properties, mainly described in non-human primate studies and neglect patients (Berti & Rizzolatti, 2002; Cléry et al., 2018; Fogassi et al., 1992, 1996; Rizzolatti et al., 1997). These cortical regions engaged in space coding partially overlap with networks devoted to action and intention understanding, possibly indicating a functional binding between spatial and social processing (Arioli et al., 2021; Rizzolatti & Sinigaglia, 2010).

Several studies demonstrated that static architectural features modulate cerebral regions devoted to emotion perception (I. S. Bower, Clark, et al., 2022a, 2022b; I. S. Bower, Hill, et al., 2022; Vartanian et al., 2013, 2015; Vecchiato, Tieri, et al., 2015), and that the motor system is involved in processing affordable architectural transitions (Djebbara et al., 2019, 2021). From a theoretical point of view, Djebbara et al. provided a psychobiological framework describing the role of the pulvinar in integrating sensory processes, further affecting the higher visual cortex and the related cortico-cortical connections leading to sensorimotor responses integrating environmental features with attention and behavior (Djebbara et al., 2022). In addition, Jelic et al. proposed the enactive approach as a guide to study architectural experience, emphasizing the motor system's role and motivational factors as constituents of the body-architecture interactions (Jelić et al., 2016). Overall, it is recognized that the built environment where we live in fundamentally impacts human wellbeing at multiple temporal and spatial scales, affecting both the prevention and containment of infectious diseases (Pinter-Wollman Noa et al., 2018).

However, despite the increasing number of works in the field (Higuera-Trujillo et al., 2021; S. Wang et al., 2022), the presence and interactions among individuals, and their movement within the architectural space have been neglected so far, failing to provide a unified view of architecture's capacity to broadly modulate social cognition, such as the perception of other’s body expressions.

In this regard, a large body of evidence has shown that body expressions convey affective information, playing a fundamental role in social interactions (de Gelder, 2009; de Gelder et al., 2015; Van den Stock et al., 2007). From an electrophysiological point of view, the EEG offers great advantages in studying the mechanism underlying the processing of emotional body expressions, enabling the investigation of rapid dynamic changes of cortical activity both in the frequency and time domain. For instance, low frequency oscillations in the theta band (3 – 7 Hz) correlate with several cognitive and attentional mechanisms, showing an enhanced synchronization when orienting attention towards emotional salient stimuli at an early stage of processing (Aftanas et al., 2003; Balconi & Pozzoli, 2009; Bossi et al., 2020; Ding et al., 2022; Symons et al., 2016). Also, the processing of body expressions is reflected in an increased alpha desynchronization (7 – 15 Hz) when the posture convey emotional information requiring a greater load of attention to be evaluated (Jessen & Kotz, 2011; Siqi-Liu et al., 2018). In the time domain, cortical correlates of emotional body expressions processing show increased P200 when observing emotional rather than neutral body postures, pointing to greater attention to socially relevant cues (Conty et al., 2012). The observation of high-arousing body postures also generates higher Late Positive Potential (LPP) amplitude than low-arousing ones (Flaisch et al., 2011; Li & Wang, 2021). The modulation of such event-related potentials (ERPs) reflects a change in the level of exogenous attention captured by the stimulus (Carretié, 2014; Carretié et al., 2013) and greater attention allocation to motivationally relevant stimuli (Lang & Bradley, 2010; Leite et al., 2012; MacNamara et al., 2022; H. Schupp et al., 2004; H. T. Schupp & Kirmse, 2021), at an earlier and later stage respectively.

In natural viewing conditions, different stimulus categories carrying affective information, such as people and backgrounds, may all be relevant and processed together, and these information streams may interact. However, only a few studies focused on the effect of the environment in shaping the mechanisms underlying the perception of body expressions, and none of these consider architectural spaces. For instance, behavioural studies showed that the categorization of bodily expressions depends on the environment emotional content (M. E. Kret & de Gelder, 2010; Reschke & Walle, 2021). These results are supported by only one study showing that the affective information provided by the environment modulates the perception of body stimuli due to the changing activity of cerebral regions endowed with visual functions, and others involved in space and body processing (Van den Stock et al., 2014).

The present study bridges this gap by linking the judgment of emotional body expressions to the dynamic experience of architecture. We exploited virtual reality to ensure a naturalistic experience and requested participants to judge avatars' emotional expression (high vs. low arousal) at the end of their promenade inside high- or low-arousing architectures. The use of virtual reality is pivotal since it permits subjects to experience the architectural space in a dynamic and immersive way (Kokkinara et al., 2016; Presti, Ruzzon, Avanzini, et al., 2022; Sanchez-Vives & Slater, 2005; Slater, 2018), ensuring the same neurophysiological response as in a real scenario (Kisker et al., 2021; Schultheis et al., 2002). Because the processing of emotional body expressions is typically reflected in the modulation of brain components at different frequencies and latencies, high-density EEG was recorded to investigate the hypothesis that the dynamic experience of architectural spaces modulates neural responses to the avatar's presentation, thus affecting early or late stage of attention. Considering that spatial attention derives from the activation of brain maps transforming spatial information into motor representations (Craighero & Rizzolatti, 2005; Rizzolatti et al., 1987; Rizzolatti & Craighero, 1998), we expect to observe a different involvement of motor regions devoted to attention mechanisms and sensorimotor integration depending on spatial and social conditions.

In line with previous evidence, the observation of emotional avatars' body expressions – both low- and high-arousing body postures – produced a desynchronization of the alpha band. Also, highly aroused avatars increased the LPP amplitude. Strikingly, at an early stage of processing, an increase of the theta activity as well as of the P200 amplitude was elicited after crossing low-arousing architectures regardless of the emotional expression of the avatar, indicating that an immersive experience within different architectural spaces modulates early attentional mechanisms toward social stimuli. Moreover, source localization highlighted a contribution of the right dorsal premotor cortex to both P200 and LPP, reflecting the motor system's role in the preparation of an adaptive response to social interactions, as well as its modulation in relation to the surrounding architectural space. These results are corroborated by an additional behavioral experiment showing that participants judged more arousing those body postures presented within the low-arousing architecture, spending more time looking at the avatar head. These findings reveal a conceptual adaptation effect generated by the promenade within the architectural space and parallel the modulation of attentional mechanisms returned by neural evidence.

This study demonstrates that the immersive and dynamic architectural experience modulates human social cognition. Behavioral and electrophysiological evidence converge toward the involvement of attentional mechanisms at an early stage of body expression processing within architectural spaces. In addition, the motor system plays a role in processing both architecture and body expressions proving how the space/cognition interplay is rooted in common neural substrates. These findings reveal for the first time that mere architectural space is sufficient to influence human behavior in social interactions.

1.1. Experiment 1: EEG study

In the EEG study we compared the brain oscillatory activity, the ERPs and the corresponding pattern of cortical current density at an early and late stage of the emotional body posture presentation appearing at the end of the virtual promenade. If the processing of dynamical architectural features affects the attention to the avatar at a late stage, we would observe alpha and LPP modulations depending on the arousal level of the architecture. Alternatively, if the processing of the dynamical architectural features affects the attention to the avatar at an early stage, we would expect a modulation of the theta band and P200 specifically mediated by architectural forms as we hypothesized. Moreover, the source localization analysis would reveal whether the processing of emotional body posture and the surrounding architectural spaces is coded by common cortical areas.

1.2. Experiment 2: eye – tracking study

To corroborate Experiment 1 results with covert behavioral correlates of attention, we performed Experiment 2 to investigate how the fixation times to emotional body postures change according to the different dynamic experience of architecture. If the cerebral activations due to architecture characteristics depend on a modulation of attention mechanisms, we would observe changes in fixation times on salient avatar's body districts depending on the dynamic architectural experience.

2. Materials and methods

2.1. Participants

In Experiment 1, 24 participants were recruited (26.66 ± 4.02 years, 14 female). The sample size was determined using a power analysis computed through the G*Power software (Faul et al., 2007), considering the 2x3 within-subject design with the "as in SPSS" option and setting the significance level (α) at 0.05, the desired power (1- β) to 0.95, the number of groups to 1, the number of repetition to 6 and the non-sphericity correction ε to 1. The value of the $\eta p2$ was set to 0.19 based on previous research (M. E. Kret & de Gelder, 2010).

In Experiment 2, additional 32 participants were recruited (27.16 ± 4.16 years, 17 female). The sample size was determined using a power analysis computed through the G*Power 3 software (Faul et al., 2007) considering the 2x2x3 within-subject design with the "as in SPSS" option and setting the significance level (α) at 0.05, the desired power (1- β) to 0.95, the number of groups to 1 and the non-sphericity correction ε to 1. The value of the ηp2 was set to 0.07 based on previous research showing how participant's gaze on body postures was modulated by their affective state (M. E. Kret et al., 2017).

All participants were naïve to the purpose of the experiment and had normal or corrected-to-normal vision, with no history of psychiatric and neurological disorders. The study was approved by the local ethical committee (Comitato Etico AVEN) and conducted according to the principles expressed in the Declaration of Helsinki. Each participant provided written informed consent before participating in the experiment.

2.2. Stimuli

Architectures. Virtual architectures were selected from a database characterized in a previous study where participants rated the dynamic experience of the architecture on the emotional scales of arousal and valence (Presti, Ruzzon, Avanzini, et al., 2022). These architectures were conceived as a combination of three consecutive nuclei where the sidewalls distance, the ceiling, and the windows sill height could decrease, increase, or remain constant between consecutive nuclei. Specifically, for Experiment 1 and 2 we selected two different architectural forms associated to the lowest and highest level of arousal. The low-arousing architecture is characterized by constant ceiling, increasing sidewalls distance, and decreasing windows height. Conversely, the high-arousing architecture is characterized by decreasing sidewalls distance, increasing windows and ceiling height. Even though in the affective characterization of the architectures the color did not significantly impact on the affective state of the participants (Presti, Ruzzon, Avanzini, et al., 2022), the selected arousing architectures were used in the warm and cold colored versions to test whether the color could influence the perception of body postures. Figure 14B illustrates the experimental virtual architectures. Finally, we designed a control environment exploiting the custom scene of Unity 3D engine Software (2019.1.0f2), which is characterized by brown-colored ground and a blue sky, adding grey alternate vertical lines in the middle of the scene at the ground level.

Emotional Body Postures. Avatars' arousing body postures were selected from a database that was previously tested via an online experiment where participants scored the visual stimuli using the emotional scales of arousal and valence (Presti, Ruzzon, Galasso, et al., 2022). Three groups of 10 body postures each were created, representing low-, middle-, and high-arousal, respectively. Different levels of arousal scores across all the three groups were guaranteed ($F(2,27) = 102.93$ $p < .001$), as revealed by Bonferroni corrected pairwise comparisons (low < middle, $p < .001$; middle < high, $p < .001$; low < high, $p < .001$). Figure 14C presents an example of avatars with low-, middle-, and high-arousing body postures.

2.3. Experimental setup and procedure

We performed Experiment 1 and 2 in a highly immersive virtual reality environment realized with the HTC Vive Pro Eye head-mounted display (HMD). This device is equipped with two AMOLED screens, with a resolution of 1440 x 1600 pixels per eye, a refresh rate of 90 Hz, and a field of view (FOV) of 110°. Furthermore, the HTC Vive Pro Eye includes the Tobii eye tracking system, allowing the recording of eye data such as the eye openness and gaze origin and direction with an accuracy of 0.5° - 1.1° (within FOV 20°) https://www.vive.com/uk/product/vive-pro-eye/specs/. Unity was integrated into the HMD via the Steam VR asset to control the experimental procedure and collect data. The experiment ran on a laptop equipped with Windows 10 Home (64-bit), Intel Core i7-9750H, 32 GB RAM, and the NVIDIA GeForce RTX 2070 graphics card.

After reading written instructions, the HMD was comfortably arranged over the participant's head. Then, the eye tracking calibration was assessed, which consisted of centering the HMD at the eye level, calibrating the inter-pupillary distance, and finally asking participants to gaze at a central point that moved to four consecutive peripheral positions.

Each experimental trial started with 500 ms of static observation of the architectural space from the first nucleus. Afterwards, participants made a straight virtual promenade of 12.5 s crossing the first two nuclei of the architecture (for details see Presti, Ruzzon, Galasso, et al., 2022). Then, participants remained steady for 750±250 ms and finally a virtual avatar appeared in the middle of the scene for 3 s. Afterwards, participants judged the arousal level expressed by the avatar's body posture. To this aim, a grey panel was presented reporting the following sentence: "this person looks in a … state" ranging from "Deactivated" to "Activated". Participants used the Vive controller to answer this question. Figure 14A illustrates one experimental trial. The experiment counted 150 trials divided into 6 blocks. The first and the last blocks comprised 15 trials each, were 5 body postures with low-, middle- and high-arousal were presented within the control environment. Conversely, in the central blocks, 30 body postures (10 for each arousal level) were randomly presented within the low- and high-arousing architectures. At the end of each block, participants were allowed to take the HMD off and have some rest.

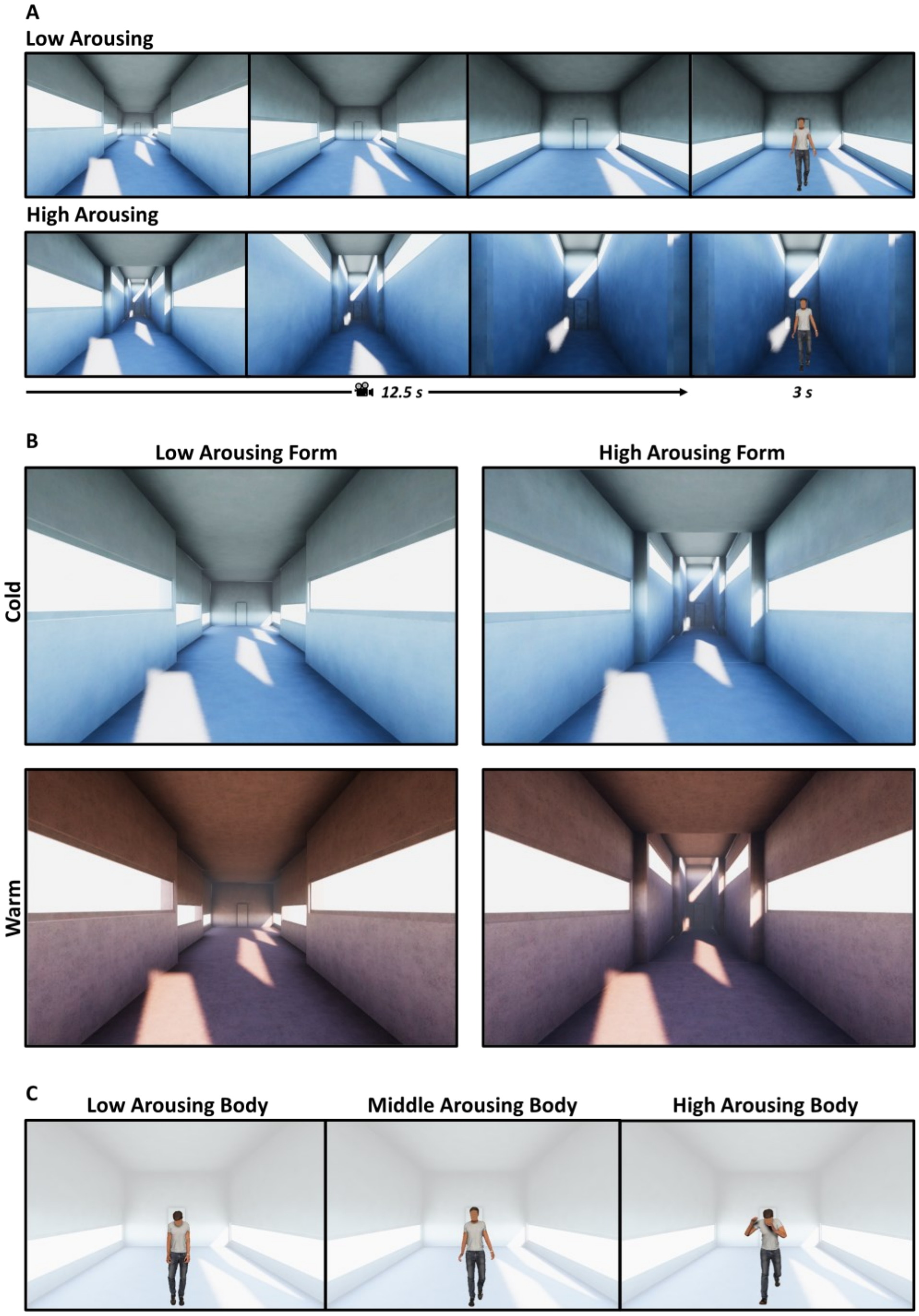


Fig. 14. Representation of the experimental trials and virtual stimuli. (A) Schematic representation of two experimental trials. The upper (lower) panels, from left to right, shows three first-person perspectives of the low (high) arousing architecture, corresponding to the participants' view at the start of the promenade, at the end of the first nucleus, and at the end of the second one. The last frame corresponds to the presentation of the avatar in the third nucleus. (B) Virtual environments with low/high arousing forms (columns) in the cold/warm colored version (rows). (C) Example of avatars with low, middle, and high arousing body posture, respectively. The transparent background is to highlight the body posture and represent the final nucleus of the low arousing architecture.

2.4. Behavioral data recording and analysis

Participants judged the avatar's arousal by using the Vive controller. Specifically, by pressing on the joypad trackpad button, the cursor of the corresponding panel moved by steps of 0.0083, ensuring a continuous-like movement of the cursor within the scale ranging between [0, 1], i.e. from deactivated to activated. Then, participants confirmed their choice by clicking the trigger button. Eye-tracking data were collected with a sample frequency of 90 Hz by means of the SRanipal (v1.3.0.9) plugin.

We discarded trials with possible dips of attention before any statistical data analysis. To this aim, for each participant we computed the blink rate of each trial and marked as bad trials the outliers of the relative distribution. Outliers were those trials corresponding to blink rates exceeding the 1.5 interquartile range above the 75° percentile. Using the degree of eye openness recorded by the Tobii eye-tracking system, a blink was identified with a value greater than 0.4 (1 stands for eye closed and 0 for eye opened) as in (Haq & Hasan, 2016), considering 300 ms of minimum distance between consecutive blinks (Caffier et al., 2003). This procedure led to the rejection of 2.39% ± 3.24 and 2.34% ± 2.20 of the trials for Experiment 1 and 2, respectively, thus ensuring a blink rate significantly lower after the rejection of trials with possible dips of attention (paired-sample t-tests for Experiment 1: $t(23) = 2.493$, $p = .020$, and Experiment 2: $t(30) = 4.862$, $p < .001$).

Then, subjective arousal ratings were z-scored. Outliers were defined as elements exceeding the threshold of $z=\pm2.5$ considering the distributions of z-scored arousal ratings across conditions. One and three participants resulted as outliers in Experiment 1 and 2, respectively, and then discarded from the following analyses.

2.4.1. Arousal ratings

Arousal ratings related to the low- and high-arousing conditions were normalized considering the mean $\bar{x}_e$ and standard deviation σ_e resulting from the scores provided in the empty scene:

$$x_z = \frac{x - \bar{x}_e}{\sigma_e} \tag{10}$$

Such normalized scores were then analyzed via a 2x2x3 repeated measures (rm) ANOVA, where the within factors were Form (Low-, High-Arousing), Color (Cold, Warm) and Body (Low-, Middle-, High-Arousing).

2.4.2. Fixation times

Data from one participant were discarded due to technical issues during the eye tracking recording, thus we analyzed data from 28 participants. We computed fixation times (FTs) during the observation of the emotional body postures over 4 different region of interests (ROIs) identifying the head, the trunk, the arms and the legs of the avatar, respectively (Kleinsmith & Semsar, 2019; Pollux et al., 2019). FTs were z-scored considering the corresponding ROIs in the empty control scene to avoid that possible low-level features, such as size and relative position of different body parts, could affect the statistics. Also, we discarded fixations that lasted less than 200 ms because any shorter dwell time is typically considered non-fixatory activity due to the presence of saccades and potential loss of signal (Juarez et al., 2019; Salthouse & Ellis, 1980; Salvucci & Goldberg, 2000).

To analyze important spatiotemporal dynamics of participant's gaze behaviour, we computed the time spent looking at each ROI within time slices of 100 ms each (Chaby et al., 2017). Then, we compared FT differences between the low- and high-arousing body postures as well as between low- and high-arousing architectures. To this purpose, we performed two separate non-parametric analyses based on Montecarlo statistics (5000 iterations, significance threshold 0.05) comparing FT between such experimental conditions across different ROIs and time bins. Considering the strongly correlated spatiotemporal structure of FTs, we adopted a cluster correction method to control for multiple comparisons. Finally a meta-permutation was performed, running the

Montecarlo permutation 20 more times and eventually computing the averaged p-value (Cohen, 2014).

2.5. EEG Data Collection and Analysis

The EEG was continuously recorded at a sampling rate of 500 Hz (vertex reference) using the 128-channels Geodesic EEG System (Electrical Geodesics Inc., Oregon) and the HydroCel Geodesic Sensor Net, which arrays 19 electrode sensors (AgCl-coated electrodes) in a geodesic pattern over the surface of the head at the equivalent 10–20 system locations. Consistent positioning was achieved by aligning the Sensor Net with skull landmarks (nasion, vertex and pre-auricular points). Using the Net Amps300 high-input impedance amplifier, low-noise EEG data was obtained guaranteeing sensor-skin impedances below 50 kΩ except for the reference one, which was kept below 10 kΩ.

2.5.1. EEG pre-processing

EEG data were exported in raw format using NetStation software (Electrical Geodesics, Inc., Eugene, OR, USA) and then imported into MATLAB to perform the following analysis with EEGLAB v2021.0 (Delorme & Makeig, 2004). We excluded the outermost belt of electrodes of the sensor net, prone to show residual muscular artefacts, thus discarding 19 peripheral channels located on the cheeks and nape (E43, E48, E49, E56, E63, E68, E73, E81, E88, E94, E99, E107, E113, E119, E120, E125, E126, E127, E128) (Michel et al., 2004). Data were subsampled at a sampling rate of 250 Hz, and the PREP pipeline was performed for line noise removal, identification and interpolation of bad channels, and data re-referencing to the common reference (Bigdely-Shamlo et al., 2015). To identify ocular, muscular and remaining channel noise, we chose to decompose data into independent components (ICs). In order to provide reliable ICs, data were firstly band-pass filtered ([2, 100] Hz) (Dimigen, 2020; Klug & Gramann, 2021; Winkler et al., 2015), segmented in epochs around the avatar presentations ([-1500, 4000] ms) removing the mean value across the epoch (Groppe et al., 2009; Zakeri et al., 2014), and visually inspected to remove corrupted trials (on average 5.46% ± 8.23 of the total number of trials). Then, we performed the independent component analysis (ICA) on the principal Components that explained the 99% of the data variance (55.50 ± 11.21) using the runICA algorithm available in EEGLAB v2021.0 (Delorme & Makeig, 2004). Bad ICs were identified using the ICLabel ((Pion-Tonachini et al., 2019)) (on average 16% ± 7.98 of the total components).

2.5.2. Time – frequency analysis

The computed ICA weights were applied to the dataset resulting from the Prep pipeline and then band-pass filtered between 2 – 45 Hz, i.e., the frequency range which can be reliable investigated through an EEG recording. EEG data were then segmented in epochs around the avatar presentation ([-1500, 4000] ms), and pruned of the bad components previously identified. Then, a final bad trial rejection was performed by visual inspection (on average 5.43% ± 6.57 of the total number of trials).

Time – frequency (TF) transform was performed exploiting the Matlab functions provided by Mike Cohen (https://github.com/mikexcohen/ANTS_youtube_videos). Spectral power was computed using a complex Morelet wavelet for each trial at each electrode location for the frequency range 2 – 45 Hz (60 frequency bins, logarithmic spaced). In order to provide a good trade-off between time and frequency resolution, the number of cycles defining the width of the wavelet changed (logarithmic increase) as a function of increasing frequency (ranging from 4 cycles for the lowest frequency (2 Hz) to 12 cycles for the highest frequency (45 Hz)) (Keil et al., 2022). The TF transform was dB normalized by dividing for the mean value relative to the time interval ([-400 -200] ms) before the presentation of the avatar (Keil et al., 2022) and data were subsampled at a frequency rate of 40 Hz (resulting in 142 time bins). Finally, trials belonging to the same experimental condition were averaged together.

To statistically evaluate differences of the oscillatory activity between the experimental conditions, two separate analyses were performed for the factor Body and Form using

Fieldtrip, an open source Matlab toolbox for script-based electrophysiological data analysis (Oostenveld et al., 2010). Specifically, nonparametric permutation-based (Montecarlo methods) ANOVA and t-tests were performed for the factor Body and Form, respectively. Statistics were performed for each time bin within the interval ([0 - 3000] ms) at each electrode position, averaging the spectral power for the EEG bands: theta ([3 – 7] Hz), alpha ([7 – 15] Hz), beta ([15 – 30] Hz), and gamma ([30 - 40] Hz). Hence, for both factors, for different analyses were performed, one for each frequency band. Corrections for multiple comparisons were performed through a cluster-based permutation approach. A cluster was defined along the dimension of time and electrodes, with the constraint that the cluster had to extend across at least 4 adjacent electrodes. The significance threshold was set to 0.05, the number of permutations to 1000 and the electrodes neighbour distance at 4 cm. Also, we visually inspected the channel x time panel of the resulting F-values (for the factor Body) and t-values (for the factor Form) to identify narrower time intervals showing the highest modulation. Then, for each time interval of the correspondent frequency band we performed a non-parametric statistic based on Montecarlo method, correcting for multiple comparisons with a cluster-based approach. For the factor Body, in case of significant cluster, pairwise comparisons were performed by means of permutation-based paired t-tests between conditions, considering the clusters' significant electrodes and time interval.

2.5.3. ERP analysis

The computed ICA weights were applied to the dataset resulting from the Prep pipeline, and then band-pass filtered ([0.1, 30 Hz]) because this type of filtering is the most appropriate for the ERP analysis (Acunzo et al., 2012; Luck, 2014; Tanner et al., 2015). EEG data were then segmented in epochs around the avatar presentation ([-1500, 1000] ms), and pruned of the bad components previously identified. Then, a final bad trial rejection was performed by visual inspection (on average 5.43% ± 6.57 of the total number of trials).

The ERP analysis was performed using the Factorial Mass Univariate ERP Toolbox (FMUT) (Fields & Kuperberg, 2020), which is a freely available set of MATLAB functions for performing mass univariate analyses of ERPs (Groppe et al., 2011). Advantages in using such an approach consist in reducing the need for a priori defined time windows/regions of interest and taking full advantage of the high temporal resolution of EEG. Firstly, trials were baseline corrected by subtracting the average of the 200ms before the avatar presentation. Then, two factorial analyses were performed with within factors Form and Body in separate time windows (0 - 400 ms and 300 – 1000 ms) so to investigate ERPs at both early and late stage of processing. Corrections for multiple comparisons were performed through a cluster-based permutation approach. Specifically, the significance threshold was set to 0.05, the number of permutations to 10000 and the electrodes neighbour distance at 4.03 cm. The FMUT analysis revealed significant spatiotemporal clusters pointing to specific ERPs. Hence, we finally performed cluster mass permutation tests on the mean ERP amplitudes within the significant time windows.

2.5.4. ERP source analysis

We localised ERP sources by solving the inverse problem with the Tikhonov-regularised minimum norm (Baillet et al., 2001). The minimum norm estimate (MNE) is an inverse method for reconstructing the primary current that underlies an extra-cranially recorded time-locked brain potential (Keil et al., 2002). We implemented this procedure in Brainstorm computing the cortical current density map with dipole orientations that are normal to the cortex (Tadel et al., 2011). As the forward model, we adopted a Boundary Element Method (BEM) volume conduction model of the head from the open-source software OpenMEEG (Gramfort et al., 2010; Kybic et al., 2005) using three realistic layers (scalp, 1082 vertices, 1 conductivity; inner skull, 642, 0.0125; outer skull, 642, 1) based on the head model provided by the FreeSurfer template (ICBM152). We computed the noise covariance from the concatenated pre-stimulus baseline. Then we aligned the electrode locations to the scalp of the head model. As source model, we adopted a cortical mesh surface with 15002 vertices available in Brainstorm. Statistical analysis was conducted at the source level to unveil the cortical generators of the ERPs emerged at the scalp level. Specifically, for the P200, we averaged the cortical activity within a 60 ms time-windows centred on the P200 peak and then compared the conditions low- vs high-arousing Architecture by computing paired t-test (two-tailed) between each dipole. Instead, considering that the LPP is a slow tonic component, we averaged the cortical activity elicited within sliding windows of 60ms each, with a 50% of overlapping between consecutive windows. For each time window we then computed paired t-test (two-tailed) between each dipole, comparing the activity elicited by high- vs low-arousing body. To correct for multiple comparisons, the significance threshold (alpha = 0.05) was adjusted using a false discovery rate (FDR) approach as implemented in Brainstorm.

3. Results

3.1. Experiment 1: EEG study

3.1.1. Arousal Ratings

The repeated-measures analysis of variance returned that participants coherently judged the emotional body postures according to their arousal level (main factor Body: F(2,48) = 115.13, $p < 0.001$, ηp2 = 0.833). However, these subjective arousal scores were higher within the architectures characterized by low-arousing forms (main factor Form: (F(1,23) = 6.76, $p = 0.016$, ηp2 = 0.227). Bonferroni corrected pairwise comparisons revealed that arousal ratings were significantly different among the three levels of avatar's bodily arousal (low < middle, $p < 0.001$; low < high, $p < 0.001$; middle < high, $p < 0.001$). Instead, the main factor Color (F(1,23) =0.66, p =0.425, ηp2 = 0.027) and the interaction Form x Body (F(2,46) = 0.144, $p = 0.866$, ηp2 = 0.006) were not significant. Considering that the factor Color did not generate any behavioral effect, it has not been considered for the following EEG analysis.

3.1.2. Time – frequency analysis

Both the cluster analyses performed for the factor Body and Forms on the 3 seconds of avatar's presentation did not return any significant effect. By visually inspected the channel x time panel of the resulting F-values (for the factor Body) and t-values (for the factor Form) we identified narrower time intervals showing a trend towards significance. For the factor Body, we identified the time intervals ([600 - 1200] ms) and ([1500 - 2300] ms) for the alpha band and the time interval ([0 - 1000] ms) for the gamma band. For the factor Form, we identified the time interval ([0 - 700] ms) for the theta band.

Figure 15 shows the significant results of the time – frequency analysis. The permutation-based ANOVA for the factor Body revealed a significant cluster in the alpha band, only for the time interval ([600 - 1200] ms). Specifically, the significant cluster ($p = 0.029$) ranged between 776 – 968 ms from the avatars' presentation and comprised the centro-parietal electrodes E41, E42, E46, E47, E51, E52, E53, E59, E60. Then, considering such electrodes and time interval, pairwise comparisons revealed two significant clusters when comparing the power spectrum of low- vs middle-arousing ($p = 0.001$) and high- vs middle-arousing ($p = 0.005$) body postures. Specifically, the observation of low-arousing body postures generated a higher alpha desynchronization compared to middle-arousing ones over centro-parietal electrodes E41, E42, E46, E47, E51, E52, E53, E59, E60 in the time interval 776 – 968 ms. Also, high-arousing body postures resulted in a greater alpha desynchronization compared to middle-arousing ones over the electrodes E41, E42, E46, E47, E52 in the time interval 896 – 944 ms. Figure 15A shows the topographic maps of the dB power spectrum averaged in the time (776 – 968 ms) and frequency (7 – 15 Hz) interval for the three arousing body conditions along with the power spectrum time course, averaged across common significant electrodes of the pairwise comparisons. For the factor Body, no significant clusters resulted for the late window ([1500 - 2300] ms) considering the alpha band (all p-values = 1) as well as the time window ([0 1000] ms) for the gamma band (all p-values > 0.055).

Strikingly, the dynamic experience of different architectures elicited a different synchronization in the theta band at an early stage of processing. In fact, we found a significant cluster in the time interval ([0 700]ms). Specifically, the cluster (p = 0.001) ranged between 224 – 368 ms after the presentation of the avatar and comprises the central electrodes E7, E31, E55, E106, Cz. For this cluster of electrodes, the synchronization in the theta band was higher after the virtual promenade within the low-arousing architecture rather than in the high-arousing one. Figure 15B shows the topographic maps of the dB power spectrum averaged in the time (224 – 368 ms) and frequency (3 – 7 Hz) interval for the low- and high-arousing architectures. On the right, the power spectrum time course, averaged across central electrodes of the significant cluster, is presented, comparing the oscillatory activity elicited by the presentation of the avatar after the dynamic experience of low- (blue) vs high- (red) arousing architectures.

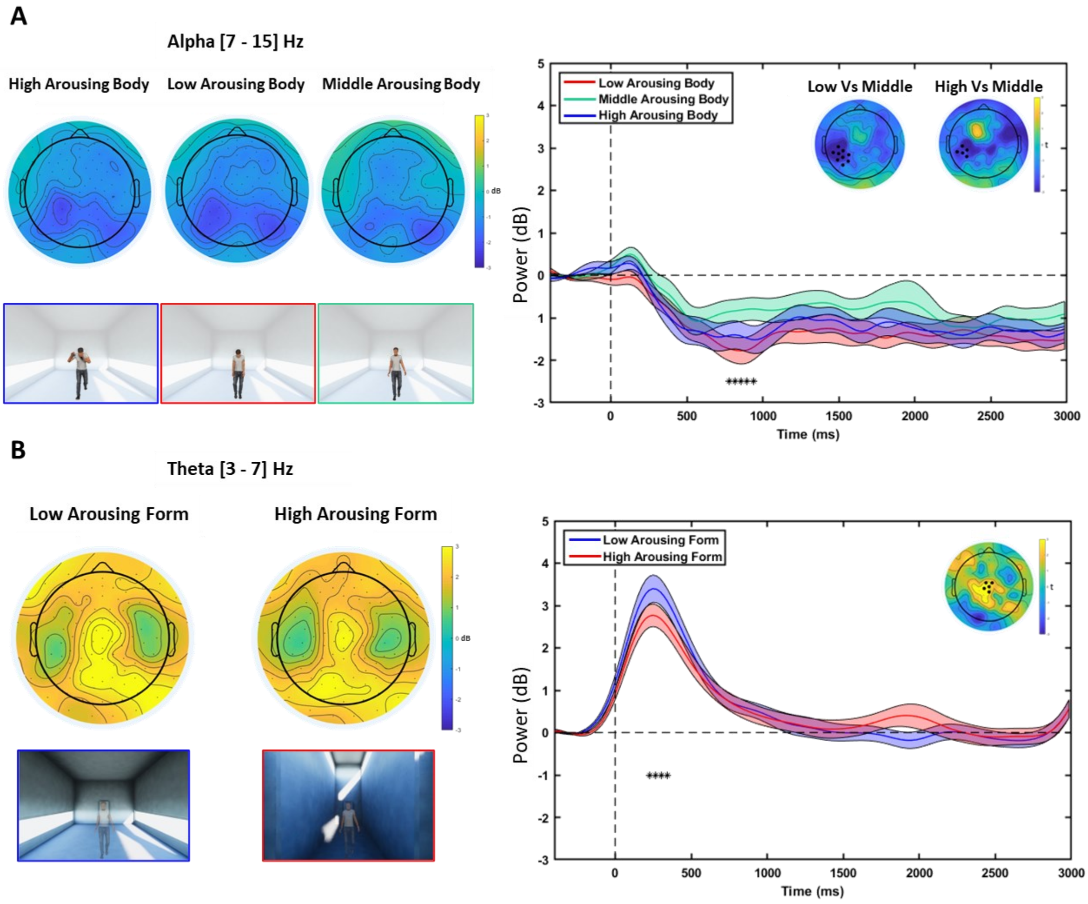


Fig. 15. Topographic and time course oscillatory activity of alpha and theta bands related to the processing of body and architecture characteristics. (A) The left pictures represent the topographic desynchronization in the alpha band averaged within the time interval (776 – 968 ms) elicited by the processing of avatars with high-, low-, and middle-arousing body postures. The right pictures represent the power spectrum time course for the high- (blue), low- (red), and middle- (green) arousing body posture conditions. These were averaged across common

electrodes comprised in the two clusters referring to the comparison between low- vs middle- and high- vs middle-arousing body postures. Significant clusters are highlighted with black dots on the topographic map in the figure inset (colormap codes the t-statistic, cluster-based corrected). The standard error is presented as light shadows of the corresponding color. The significant time interval is defined by black asterisks. (B) The left pictures represent the topographic synchronization in the theta band averaged within the time interval (224 – 368 ms) elicited by the processing of the avatar after the dynamic experience of low- and high-arousing architectures. The right pictures represent the power spectrum time course for low- (blue) and high-arousing (red) architecture conditions, averaged across the electrodes defining the significant cluster, highlighted with black dots on the topographic map in the figure inset (colormap codes the t-statistic, cluster-based corrected). The standard error is presented as light shadows of the corresponding color. The significant time interval is defined by black asterisks.

3.1.3. ERP analysis

Figure 16 shows the topographic maps and ERPs related to significant neural activations for the body and form characteristics. We performed a factorial mass univariate analysis in a late and early ERP window. In the late window, the factorial analysis returned a significant modulation of the LPP amplitude related to the arousal level represented by body characteristics as expected. In fact, we report a significant cluster of electrodes for the factor Body (p = .006) within a time interval of 452 - 1000 ms from the avatar presentation. However, no significant clusters were found for the main effect Form (all p-values > .67) and interaction Form x Body (all p-values > .156). Then, pair-wise comparisons within the main effect Body were conducted through cluster mass permutation tests on the mean ERP amplitudes in the 452 - 1000 ms time window. Specifically, we found a cluster of fronto-central electrodes (E5, E6, E7, E13, E30, E31, E37, E55, E80, E105, E106, E111, E112, Cz) with higher LPP amplitude elicited by avatars with high-arousing body postures compared to avatars with low-arousing characteristics (p = .005). Figure 16A presents the topographic maps of voltage distribution averaged in the 452 - 1000 ms interval for the high- and low-arousing body conditions, showing that the LPP amplitude was mainly located at centro-parietal electrodes. On the right, the grand average ERP of centro-frontal electrodes of the significant cluster is presented, comparing the LPP elicited by the presentation of avatars with high- (blue) vs low- arousing (red) body postures. Also, a different cluster of frontocentral electrodes (E5, E6, E7, E12, E13, E30, E80, E87, E105, E106, E112, E118, Cz) showed a significantly higher LPP amplitude (p = .014) when avatars had high-arousing body postures rather than middle ones. No significant differences were found comparing avatars with low- and middle-arousing body postures (all p-values > 0.154).

Strikingly, in the early window of analysis, the factorial analysis returned a significant modulation of the P200 amplitude during the observation of avatars related to the differences of the architectural forms. In fact, we report one significant cluster for the factor Form (p = 0.023) spanning the time range between 168 - 384 ms after the presentation of the avatar. Figure 16B shows the topographic maps of voltage distribution averaged in the 168 – 384 ms time interval for the two arousing form conditions and the grand average ERPs of significant electrodes. Specifically, we found a cluster of electrodes in centro-parietal areas with greater activity elicited by the presentation of the avatar within the low-arousing architecture compared to the high-arousing condition (E31, E54, E55, E78, E79, E86, E87, E91, E92, E93, Cz). The higher difference between the two conditions was reached around 250 ms after the avatar onset. No significant clusters of electrodes were found for the main effect Body (all p-values > .481) as well as for the interaction Form x Body (all p-values > .559). These results show that the dynamic experience of architecture affects the processing of body postures at an early temporal stage, thus anticipating the classic late neural modulation related to the observation of mere body characteristics.

These results show that the dynamic experience of architecture affects the processing of body postures at an early temporal stage, thus anticipating the classic late neural modulation related to the observation of mere body characteristics.

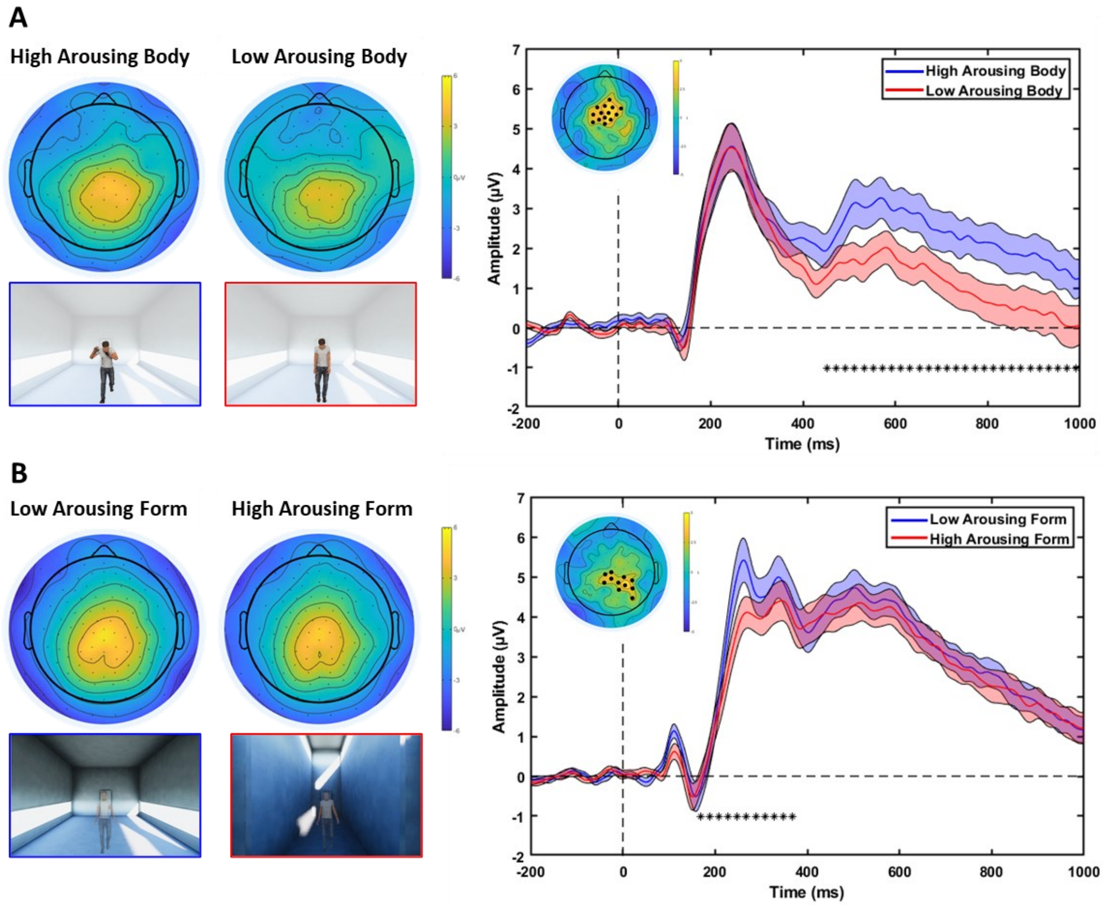


Fig. 16. Topographic and ERP activations related to the distinct neural temporal dynamics processing architecture and body characteristics. (A) The left pictures represent the topographic voltage distributions of the LPP (452 – 1000 ms) to the presentation of avatars with high- and low-arousing body postures. The right pictures represent the grand average ERPs for the high- (blue) and low-arousing (red) body posture conditions. (B) The left pictures represent the topographic voltage distribution of the P200 (168 – 384 ms) to the presentation of avatars within low- and high-arousing form. The right pictures represent the grand average ERPs for low- (blue) and high-arousing (red) architecture conditions. Figures within the blue and red frames below the scalp maps highlight the corresponding experimental conditions. The ERPs were averaged across the electrodes defining the significant cluster, highlighted with black dots on the topographic map in the figure inset (colormap codes the t-statistic, cluster-based corrected). The standard error is presented as light shadows of the corresponding color. The significant time interval is defined by back asterisks.

3.1.4. ERP Source analysis

Figure 17A shows the cortical currents density elicited by the presentation of high-arousing body postures, significantly higher compared to low-arousing ones in the time window between 600 – 660 ms, and the corresponding statistical cortical map. To the dipole with the current density peak within the right dorsal premotor cortex corresponds a tp = 5.038 (p = 4.24*10-5, lower than the FDR corrected alpha threshold 4.29*10-4, MNI coordinates: X = 30.6, Y = 7.3, Z = 65). In the subsequent 630 – 660 ms time interval we found another significant cluster of activation (tp = 4.625, p = 1.18*10-4, lower than the FDR corrected alpha threshold 1.86*10-4, MNI coordinates: X = 30.6, Y = 7.3, Z = 65).

Figure 17B shows the cortical generators of the P200 peak, and the significant statistical difference in the right dorsal premotor cortex corresponding to the observation of body postures presented in low-arousing architectures when compared to the same stimuli presented in high-arousing architecture. Specifically, in the 220 – 280ms time window centered on the P200 peak, we found a significant cluster of activation with tp = 4.861 (p = 6.58*10-5, lower than the FDR corrected alpha threshold 2.77*10-3, MNI coordinates: X = 18.4, Y = 21.5, Z = 67.1).

These results show that the motor system is activated by architecture and body characteristics at different time intervals during the observation of body postures. Overall, findings returned from the EEG Experiment indicate an early-stage modulation of attention mechanisms to the observation of body postures due to the dynamic experience of low-arousing architecture. This process is driven by the activation of premotor areas.

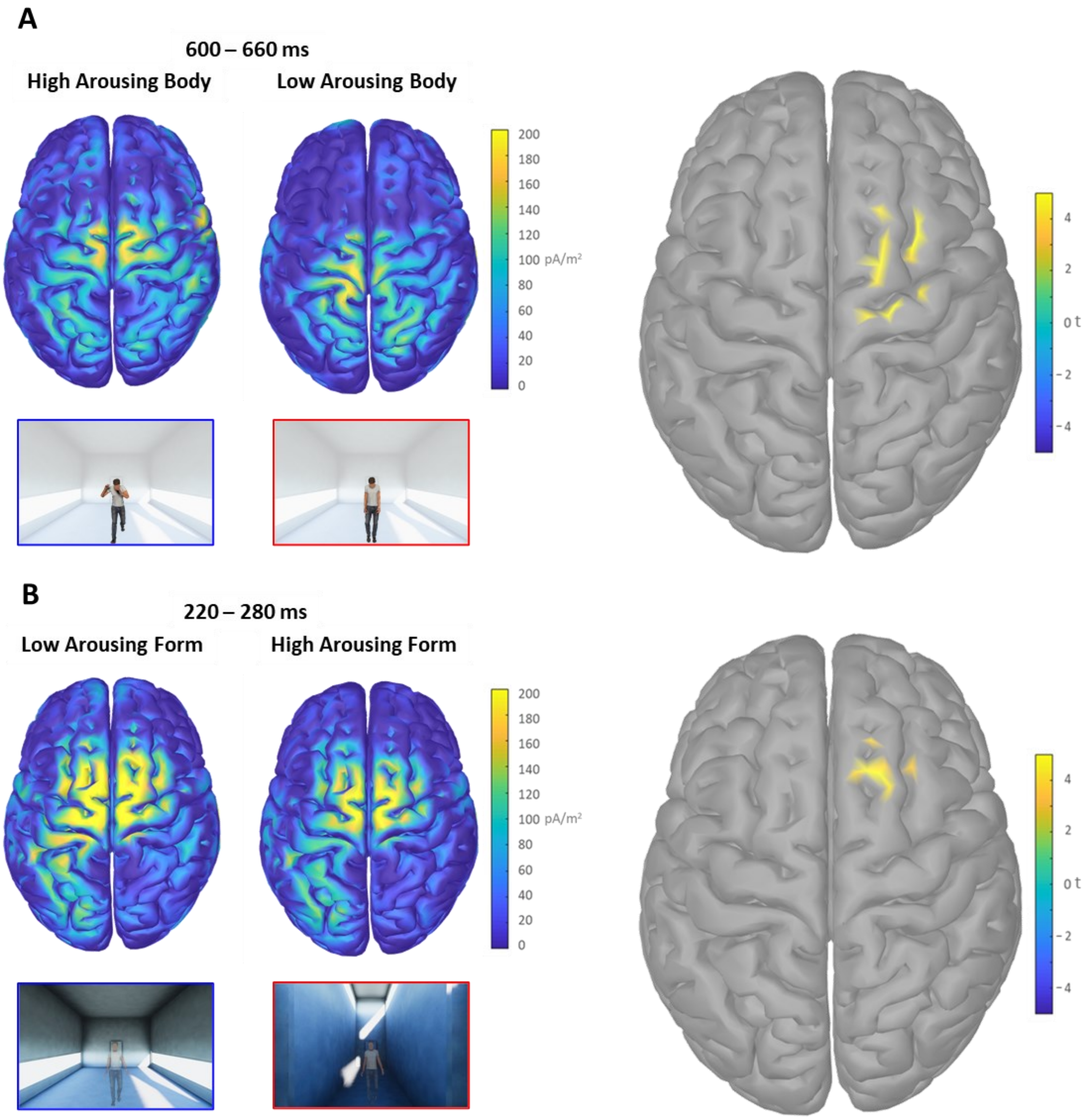


Fig. 17. Cortical maps related to the common motor activation for architecture and body characteristics. (A) The left pictures represent the two cortical maps of current density averaged in the 600 – 660 ms interval elicited by the presentation of avatars with high- and low-arousing body postures. The right picture shows the significant dipoles revealed by the corresponding statistical comparison within the cortical map. (B) The left figures represent the two cortical maps of the current density averaged in the 220 – 280 ms interval elicited by the presentation of avatars within the low- and high-arousing architecture. The right picture shows the significant dipoles revealed by the corresponding statistical comparison. The colormaps code the distribution of current density and the corresponding t statistic.

3.2. Experiment 2: Eye-tracking study

3.2.1. Arousal ratings

Figure 18A shows the results of the rm ANOVA on arousal ratings. As we reported for Experiment 1, despite the emotional body postures were coherently judged (main factor Body: F(2,56) = 92.046, p < .001, ηp2 = .767), we found increased arousal ratings to body postures observed after the dynamic experience of low-arousing architecture (main factor Form: F(1,28) = 5.864, p = .022, ηp2 = .173). Bonferroni corrected pairwise comparisons revealed that arousal ratings were significantly different among the three levels of the avatar's bodily arousal (low < middle, p < .001; low < high, p < .001; middle < high, p < .001). The main factor Color (F(1,28) = 2.041, p = .164, ηp2 = .068) and the two-way interaction Form x Body (F(2,56) = 1.599, p = .321, ηp2 = .039) did not result in any significant effect.

3.2.2. Fixation times

Figure 18 panel B and C present the results of the time-varying analysis comparing FTs between low- and high-arousing body postures across different ROIs and time bins. The Montecarlo analysis returned two significant clusters, one for the legs region between 400 and 2800 ms (p < 0.001, cluster corrected) and one for the arms from 1900 to 2600 ms (p = 0.011, cluster corrected) after the presentation of the avatar. Specifically, participants spent more (less) time looking at the arms (legs) of avatars with high arousing body postures compared to avatars with low arousing ones. Figure 4C shows the results of the Montecarlo analysis comparing the FTs according to the different architectural experience. We found two significant clusters, one for the head region between 700 and 1400 ms (p = 0.002, cluster corrected) and one for the trunk from 1000 to 1600 ms (p = 0.018, cluster corrected) after the presentation of the avatar, revealing that participants spent more (less) time looking at the head (trunk) after the virtual promenade within low-arousing architectures.

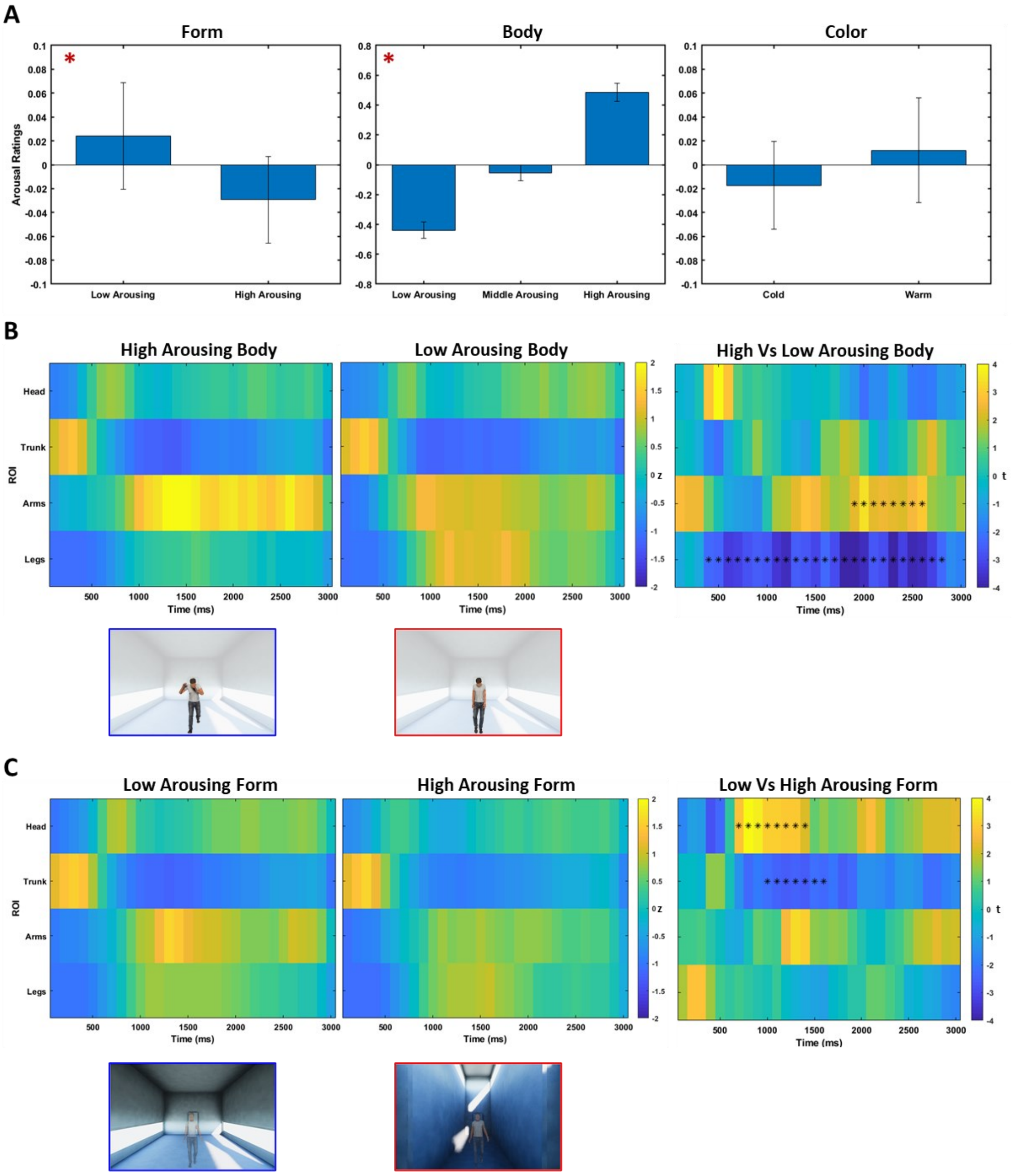


Fig 18. Increased arousal ratings and fixation times to body postures after the dynamic experience of low-arousing architecture. (A) Results of the rm ANOVA on arousal ratings for the main factors Form (on the left) and Body (on the middle) and Color (on the right). Results are presented with their mean and standard error, significant effects are highlighted by a red asterisk. (B) Time course of fixation times on avatar's ROIs with high- (left panel) and low-arousing (middle panel) body postures. (C) Time course of fixation times on avatar's ROIs within the low- (left panel) and high-arousing (middle panel) architecture. For the left and central panels, the color of each time bin codes the time spent staring at the ROI, z-scored with respect to the empty control condition. In the right panel, the statistical comparison between the two condition is presented: the color of each time bin represents the t-statistic and black asterisks identify the significant cluster related to the head region.

4. Discussion

The present work explored the interplay between spatial and social cognition by investigating electrophysiological and behavioral reactions to expressive avatars within an immersive and dynamic architectural experience. The EEG study revealed the involvement of late and early attentional mechanisms differently triggered by emotional body expressions and architectural spaces. As widely reported in the literature, the observation of emotional – both low- and high-arousing – postures elicited a greater alpha suppression, whereas the observation of high-arousing body postures generated an increased LPP amplitude. Strikingly, we found a modulation of the theta activity and P200 amplitude in response to the avatar presentation, depending on the dynamic experience of different arousing architecture: the more relaxing the architectural experience is, the higher the theta synchronization and P200 potential. The source localization highlighted a contribution of the right dorsal premotor cortex to both LPP and P200 generation, pointing to common neural substrates within the motor system processing spatial and body characteristics. The eye-tracking study corroborated the neural findings revealing that differences in late attention discriminate the processing of low- and high-arousing body postures with a difference in fixation times across the avatar’s limbs. Interestingly, the dynamic experience of low-arousing architectures modulated early attention leading the participants to focus more on the avatar’s head. Finally, both the EEG and the eye-tracking studies revealed that the avatar's body was scored as more arousing after the dynamic experience of low-arousing architectures. Overall, our findings show for the first time that the dynamic experience of architecture modulates the perception of other’s affective states.

The processing of emotional body postures after the dynamic architectural experience was characterized by the modulation of brain oscillatory activity in alpha and theta frequency range as well as by different amplitude of LPP and P200 components. On the one hand, alpha de-synchronization is classically correlated to an increased attentional load resulting from the execution of cognitive tasks (Cona et al., 2020). When processing emotional body postures, the evaluative process of discrimination between emotional and neutral cues is associated with a suppression of the alpha rhythm over sensorimotor areas, possibly reflecting motor resonance mechanisms for the understanding of others' intentions (Jessen & Kotz, 2011; Perry et al., 2010, 2017; Siqi-Liu et al., 2018). We found that emotional expressions – both low- and high-arousing avatar's body postures – elicited a greater alpha desynchronization at centro-parietal electrodes compared to middle-arousing ones, i.e., neutral expressions with no emotional content. Hence, interestingly, we found that such alpha desynchronization was not positively correlate with the dynamicity expressed in the body posture, in fact low-arousing body postures (with the lowest degree of dynamicity) elicited a higher alpha suppression compared to middle ones. A possible explanation could be that low-arousing postures also contain a social meaning thus eliciting a greater alpha suppression over centroparietal electrodes than neutral ones which do not involve a social response by the observer (Dumas et al., 2012; Naeem et al., 2012; Urgen et al., 2013). Paralleling the higher alpha suppression, we also found a modulation of the LPP depending on the arousal level of the avatars' body posture. In fact, the LPP indexes sustained attention on arousing stimuli (Hajcak & Foti, 2020; Hajcak & Olvet, 2008; MacNamara et al., 2022), reflecting the evaluative process of the stimulus significance that may activate an approaching or aversive response. In line with previous research, our results revealed that the observation of arousing body postures increased LPP amplitude compared with low- and middle-arousing postures (Flaisch et al., 2011; Li & Wang, 2021). On the other hand, low frequency oscillations in the theta band correlate with several cognitive and attentional mechanisms, showing an enhanced synchronization when orienting attention towards emotional salient stimuli at an early stage of processing (Aftanas et al., 2003; Balconi & Pozzoli, 2009; Bossi et al., 2020; Ding et al., 2022; Knyazev et al., 2009; Spadone et al., 2021; Symons et al., 2016). Similarly, the P200 indexes an early capture of attention which facilitates a fast detection of biologically relevant stimuli stimuli (Carretié, Mercado, et al., 2001; Doallo et al., 2006). Strikingly, the dynamic experience of low-arousing architectures elicited a higher early theta synchronization and P200 amplitude when observing the avatars compared to the experience of high-arousing architectures. Hence, our results suggest that participants' early attentional process, involving the redirection of attentional resources from the processing of architecture to the avatar's body posture, was boosted due to the experience of low-arousing architectures and impaired in the high-arousing condition. One possible explanation could be that the dynamic experience of low- and high-arousing architectures generated respectively relaxing and anguishing states (Presti, Ruzzon, Avanzini, et al., 2022), thus varying the availability of attentional resources that can be redirected on the avatar's body postures when presented. In fact, previous research found that low-arousing positive states broaden attentional resources (P. Gable & Harmon-Jones, 2010), while high-arousing negative ones narrow the scope of attention (Fredrickson & Branigan, 2005). Also, anxiety traits are associated with a lower theta band synchronization (Gold et al., 2013; Schoenberg & Speckens, 2014) as well as with a reduced P200 amplitude (Rossignol et al., 2013; Zhang et al., 2018), whereas a greater reallocation of attentional resources is reflected in a higher theta synchronization (Spadone et al., 2021) and higher P200 amplitude (Ghani et al., 2020). Hence, we argue that the modulation of theta synchronization and P200 amplitude reflects a different attentional shift due to the greater availability of attentional resources generated by the relaxing architectural experience. Notably, considering that during the early processing stage we did not find any effect driven by the avatar's body characteristics, we argue that participants' fast allocation and redirection of attentional resources on the body postures was due to the previous dynamic architectural experience and not by the arousal level expressed by the avatar.

The source analysis revealed that the right dorsal premotor cortex (PMC) is the common neural generator of both LPP and P200, reflecting the modulation of attentional mechanisms involved in the early and late stages of processing emotional body expressions. Previous studies have suggested the role of the right dorsal PMC in supporting several cognitive functions, such as action preparation and attention (Genon et al., 2017). Rizzolatti and colleagues originally proposed the role of the PMC in attention mechanisms, arguing that attention systems are not separated from those for sensorimotor integration (Craighero & Rizzolatti, 2005; Rizzolatti et al., 1987; Rizzolatti & Craighero, 1998). Specifically, the activity of the PMC reflects the preparation of a motor program to respond to an external stimulus presented in the space, independently from its actual execution. Here, the PMC is more activated by the high arousal level expressed by the avatar's body compared to the low-arousing condition. This result is in line with previous findings showing that high-arousing body postures with socially relevant cues elicit a greater activity of the PMC compared to postures with low arousal levels (Conty et al., 2012). Also, the activity in the PMC may be related to the evaluative process of others' internal states and intention through a motor response that facilitates intersubjective empathy (Arioli et al., 2021; Calbi et al., 2017; Rizzolatti & Craighero, 2004). Thus, the emotional content of the observed posture elicits a different motor activation. (de Gelder, 2006; Grosbras & Paus, 2006; Pichon et al., 2009). Strikingly, our results revealed a stronger PMC activity after the dynamic experience of low-arousing rather than high-arousing architectures at an early stage of the emotional body processing. Hence, we argue that the relaxing state generated by the architectural experience may foster the preparation of an adaptative social response to the target avatar's body expression, thus eliciting a greater motor readiness in the PMC, directly linked to the reallocation of attentional resources (Craighero & Rizzolatti, 2005; Rizzolatti et al., 1987; Rizzolatti & Craighero, 1998). Over the last few years, researchers have already described the architectural experience in terms of sensorimotor integration, pointing to the modulation of sensorimotor brain areas depending on architectural affordances (Djebbara et al., 2019, 2021), as well as reflecting the involvement of the motor system during the processing of architectural elements within the surrounding space (Freedberg & Gallese, 2007; Jelić et al., 2016; Vecchiato, Tieri, et al., 2015). Here, the presence of an emotional avatar's body expression adds a social component to the architectural experience, which has been neglected so far. Our findings showed that the involvement of motor-related brain areas is related to the processing of spatial features and reflects attentional mechanisms describing how the architectural space influences the processing of others' affective states. Importantly, the difference in the PMC activity - depending on both body and architectural conditions - also corresponds to a different pattern of eye movements on the avatar's body districts as evidence of the role played by the motor system in integrating attention mechanisms and sensorimotor information.

Paralleling the involvement of early and late attentional mechanisms that emerged in the EEG study, the eye-tracking study revealed different patterns of fixation times on the avatar's body district depending both on the arousal level of the body posture and on the dynamic architectural experience. Specifically, results reveal a late allocation of attention on the arms of the avatars with high- compared to low-arousing body postures, showing that the position of the arms is a relevant cue for the recognition of high arousing states (Kleinsmith & Semsar, 2019; Pollux et al., 2019). Also, we found that participants drew less attention to the legs of avatars with high- compared to low-arousing postures, probably because this body district is not often identified as diagnostic for intensive emotional states (Dael et al., 2012a, 2012b; M. Kret, Stekelenburg, et al., 2013; Pollux et al., 2019). Strikingly, results revealed that after the virtual promenade within the low-arousing architectures, participants allocated greater attention to the avatar's head and less to the trunk at an early stage of processing. The head position has been found to provide useful information for emotion recognition (Dael et al., 2012a, 2012b; Fourati & Pelachaud, 2015; Pollux et al., 2019). Also, the higher attention directed at the head of the avatar could reflect the participants' lower anxiety state generated by the promenade within the low-arousing architecture. In fact, people tend to look at other's faces when they feel comfortable during social interactions (M. E. Kret et al., 2017). Thus, as already discussed for the brain activities, we argue that such dynamic architectural experience facilitated the initial reallocation of attentional resources on emotional-relevant body cues.

Finally, subjective arousal ratings from both the EEG and eye-tracking studies revealed that participants perceived the avatars' body posture as more arousing after the dynamic experience within the low-arousing architecture compared to the high-arousing condition. This result could reflect a conceptual adaptation effect. The virtual promenade within low- or high-arousing architectures represent the adapting stimulus that biases the perception of the arousal expressed by the avatars' body posture in the opposite direction. Considering the different nature of the two stimuli, the generation of a conceptual adaptation effect is only possible when the adapting and the target stimuli share some perceptual mechanisms (Halovic et al., 2020; Hedger et al., 2013), reflected here in the common activation in the PMC. Also, the color of the architecture did not affect the perception of the avatars' body postures. This result strengthens the idea that it is the arousing state generated by the progressive modulation of the surrounding space that modulates the participants' perception of the avatar's body posture. Indeed, the color did not influence the participants' affective state (Presti, Ruzzon, Avanzini, et al., 2022) and consequently did not have any impact on the way they perceive the avatar's body posture.

5. Conclusion

This study provides the first evidence of the interplay between the dynamic experience of architecture and human social cognition. We demonstrate that the emotional state generated by the architectural experience influences attentional mechanisms involved in the observation of emotional body expressions. Indeed, at an early stage of processing, reallocation of attentional resources is facilitated in low-arousing architectures, whereas at a later stage the attention depends on the emotional content expressed by the avatar. Hence, the processing of other's body expressions is firstly influenced by the architectural experience and then by the actual physical characteristics. Furthermore, the motor system was found to be elicited during both early and late processing of the other's body expression. This finding highlights the existence of neural substrates common to spatial and social cognition as evidence of their interplay, possibly enabling interactive mechanisms generating a conceptual adaptation effect. Overall, our findings reveal that mere architectural forms influence human behavior, thus suggesting that proper spatial design could facilitate everyday social interactions.

Chapter V – The Role of the Motor System in the Interplay Between Emotional Body Expression and Architecture

1. General discussion

During my PhD program I conducted three separate studies that eventually allowed me to characterize the mechanisms underlying the processing of emotional body expressions modulated by the dynamic experience of the surrounding architecture. Studies 1 and 2 built up the basis, characterizing both the avatar's body expressions and the virtual architectures in terms of their affective components. In Study 3, I investigated the interplay between the architectural experience and the processing of emotional body expressions by means of EEG and eye-tracking experiments.

In Study 1, I exploited specific body cues to transfer affective information from emotional walking to static body postures. Two separate online surveys highlighted the validity of the proposed methodology. As widely demonstrated in previous literature, the use of body pleasantness and body dynamicity well characterized the valence and arousal dimension of the emotional walking (Fourati & Pelachaud, 2018; Karg et al., 2010, 2013; Kleinsmith & Bianchi-Berthouze, 2007; McColl & Nejat, 2014; Paterson et al., 2001; Pollick et al., 2001; Poyo Solanas et al., 2020), thus enabling the selection of emotional frames in a reliable and time-efficient way. Overall, with this study I created a set of 180 avatars' body postures with different level of pleasantness (valence) and dynamicity (arousal) that can be exploited in a wide range of experimental studies investigating time-locked cognitive processes related to the perception of emotional body postures.

In Study 2, I evaluated how the dynamic experience of the surrounding architectural space impacts on participants' affective state. A head mounted display for virtual reality was exploited to make participants live an authentic and immersive experience of 54 different architectures, which was realized by means of a virtual promenade. In line with previous research (Coburn et al., 2017, 2020; Stamps, 2010; Vartanian et al., 2015; Yildirim et al., 2007), results revealed that the experience of a progressive modulation of spaciousness impacted on participants’ affective state. Specifically, moving towards narrow spaces with a reduced possibility to look around and visually explore the surrounding generates anguishing sensations whereas moving towards a more spacious environment resulted in relaxing sensations.

Finally, in Study 3, I combined avatars’ body expressions and virtual architectures to recreate a realistic social scenario. The arousal dimension was the common affective component of such different stimuli, being highly correlated with the dynamicity of the stimuli and linked to the activation of the sensorimotor system. The use of EEG and eye tracking allowed me, from a behavioral and neurophysiological perspective, to evaluate how the processing of emotional body expressions is influenced by the dynamic architectural experience.

Results of the EEG experiment highlighted that the evaluation of the affective state expressed by the posture of the avatar occurs at a late stage of processing. In fact, starting from 500 ms after the presentation of the avatar, both the activity in the alpha frequency range over centro-parietal electrodes as well as the LPP amplitude at centro-frontal electrodes varied according to the arousal level of the body postures. These modulations reflected the late allocation of attention on social relevant cues that serve the preparation of an approaching or aversive response toward the stimulus (Hajcak & Foti, 2020; Hajcak & Olvet, 2008; Jessen & Kotz, 2011; MacNamara et al., 2022; Perry et al., 2010, 2017; Siqi-Liu et al., 2018). Strikingly, at an early stage of processing, the fast reallocation of attentional resources from environmental to bodily features was modulated by the architectural experience. In other words, the shift of attentional focus from the architectural space to the processing of the emotional body postures was facilitated when participants experienced the low-arousing relaxing architecture and inversely impaired in the high-arousing anguishing architecture. Evidence were found in the early modulation – ranging between 200 – 380 ms from the presentation of the avatar – of the theta activity and P200 amplitude at central electrodes depending on the architectural experience, reflecting the rapid orienting of attention on salient emotional cues (Aftanas et al., 2003; Bossi et al., 2020; Carretié, Martín-Loeches, et al., 2001; Ding et al., 2022; Doallo et al., 2006; Spadone et al., 2021). A possible explanation is that the dynamic experience of low-arousing architecture generates a relaxing state thus broadening participants' scope of attention (Fredrickson & Branigan, 2005; P. A. Gable & Harmon-Jones, 2008), thus facilitating the reorienting of attentional resources on the emotional body expressions. Interestingly, the source localization analysis returned an involvement of the right dorsal premotor cortex for both the LPP and P200. According to Rizzolatti and colleagues, attention systems are not separated from sensorimotor integration. Hence the activity in the PMC can be considered as the preparation of a motor response towards an external stimulus that draw our attention (Craighero & Rizzolatti, 2005; Rizzolatti & Craighero, 1998). At a late stage of processing, participants' attention is focused on the physical characteristics of the avatar's body posture to detect emotional salient cues. Hence, the modulation of the PMC activity could reflect the preparation of a different motor program in response to the emotion perceived in the body of the avatar, as the observation of an angry posture fosters a flight or fight response whereas happy postures evoke a more affiliative response. Strikingly, the PMC was also greater activated at an early stage of processing emotional body expressions after the dynamic experience of low-arousing architecture. Hence, we argue that the relaxing state generated by the architectural experience may foster the preparation of an adaptative social response to the target avatar's body expression, thus eliciting a greater motor readiness in the PMC, directly linked to the reallocation of attentional resources (Craighero & Rizzolatti, 2005).

Results of the eye-tracking experiment further corroborated the involvement of attentional mechanisms. A late allocation of attention on the arms of the avatar distinguished between high- and low-arousing postures (Pollux et al., 2019) and an early allocation of attention on the head of the avatar emerged due to the dynamic experience of low-arousing architectures as evidence of a greater attitude towards social interactions (M. E. Kret et al., 2017).

Finally, arousal ratings provided in both EEG and eye-tracking experiment showed that after the dynamic experience of the low-arousing architecture participants judged the avatars' expression as more arousing compared to the experience of high-arousing architecture. Hence, a conceptual adaptation effect may be occurred due to processing of consecutive stimuli that involve common perceptual mechanisms identified here in common activation in the PMC (Halovic & Kroos, 2018b; Hedger et al., 2013).

2. Final conclusion

Overall, these studies highlight the influence of the surrounding architecture in the processing of emotional body expressions, demonstrating the interplay between space and social cognition. The processing of emotional body expressions is not independent from the surrounding context which instead plays a primary role at the very early stage of processing. In fact, EEG and eye tracking results clearly show that the reorienting of attentional resources on the presented avatar is influenced by the dynamic architectural experience. In this framework, the architectural experience modulates the inhabitant's initial attention: the more relaxing is the experience, the more attention is drawn to the incoming social stimulus. Reflecting the modulation of attention, the activity of the right dorsal PMC due to the architectural experience indexes the capability of the surrounding space to prompt the inhabitant motor planning in response to the emotional posture at the early stage of processing, whereas the late activity is modulated by the physical characteristics of the posture. Hence, the motor system represents the common neural substrate to both a spatial and social cognition, possibly enabling interactive mechanisms generating a conceptual adaptation effect.

These findings demonstrate that the perception of others' affective state is influenced by the surrounding architecture, highlighting the common activation of the motor system during the processing of both architectural and body characteristics. To deeply comprehend the role of PMC in this mechanism, future studies may investigate how the dynamic experience of arousing architectures influences the processing of emotional stimuli different from bodies. Whether we would still find an elicitation of PMC, then we may argue that the motor system activity could reflect the modulation of attentional mechanisms due to the architectural experience on the perception of emotional salient stimuli in general. In this direction, other behavioral tasks may be proposed to better investigate the specific role of the surrounding space in modulating the participants' availability of attentional resources and visuospatial attention (e.g., global-local visual processing paradigms, Posner paradigms). On the other hand, a silent PMC with emotional stimuli different from bodies would remark that the effect of the architecture is specific for social situations involving an interaction with another person. Hence the activity in the PMC may be more related to motor resonance mechanisms elicited by the observation of the others' body postures and to the preparation of an adaptative response facilitated by the architectural experience. In this direction, future line of research could also investigate how the architectural experience modulate the space perception in terms of interpersonal distance, i.e., the distance within we feel comfortable to interact with another person. Considering that previous studies demonstrated that do not exist a unitary representation of the space in the brain but contrarily there are numerous spatial maps representations with no fixed boundaries, then it is possible that contextual factors may modulate such brain maps representations. Whether on the one hand the modulation of the interpersonal distance due to the emotional state of the other person has been already demonstrated, on the other hand the role of the surrounding architecture in changing the interpersonal distance is still unknown. Considering that the architectural experience influences the perception of others' affective states, I hypothesize that it will also generate a modulation of the interpersonal distance, defining the dynamics of social interactions. Finally, exploiting immersive virtual reality technologies it will be possible to investigate these perceptual mechanisms considering a huge variety of different architectures (such as school, hospitals, and offices), adding also contextual elements, and recreating realistic social interactions. The final goal would be to know in advance, using behavioral and neurophysiological indexes, how the architecture influences affective states and human behavior in social interactions.

In conclusion, findings of the present dissertation highlight the straight link between space and social cognition, showing that the mere manipulation of the surrounding architectural forms is sufficient to influence human behavior in social interactions. Creating a bridge between neuroscience and architecture, such knowledge will set the basis for a new approach to the design which focuses on the social role of the environments, thus eventually improving humans' quality of life and wellbeing.

Appendix

A. The affective characterization of avatars' body postures

1. Stimuli selection procedure

Nine-hundred-twelve avatar's body postures were sorted according to their BP (BD) scores. Then, three equidistant groups were identified at the bottom (Low), middle (Middle) and top (High) of the distributions. We avoided selecting postures at the border of the distributions due to the non-linear trend. We discarded by visual inspection very similar postures and finally identified 30 (15 males) postures per condition. To assess differences among the identified groups, we performed two separate 2-way ANOVAs with main factors BP (BD) (Low, Middle, High) and Actor Gender (Male Actor, Female Actress) which represents the gender of the actor from which the posture was extracted. As concerns BP, the main factor Body Pleasantness ($F(2, 84) = 1151.3$, $p < .001$) was found to be significant. Bonferroni corrected pairwise comparisons highlighted significant difference across all levels (low < middle, $p < .001$; middle < high, $p < .001$; low < high, $p < .001$). The factors Actor Gender ($F(1, 84) = .272$, $p = .603$) and the interaction Body Pleasantness x Actor Gender ($F(2, 84) = .0419$, $p = .959$) did not return any significant difference. As concern BD, the main factor Body Dynamicity ($F(2, 84) = 1170.3$, $p < .001$) was significant. Bonferroni corrected pairwise comparisons highlighted significant difference across all levels (low < middle, $p < .001$; middle < high, $p < .001$; low < high, $p < .001$). The factors Actor Gender ($F(1, 84) = .572$, $p = .451$), and the interaction Body Dynamicity x Actor Gender ($F(2, 84) = .217$, $p = .805$) did not return any significant difference.

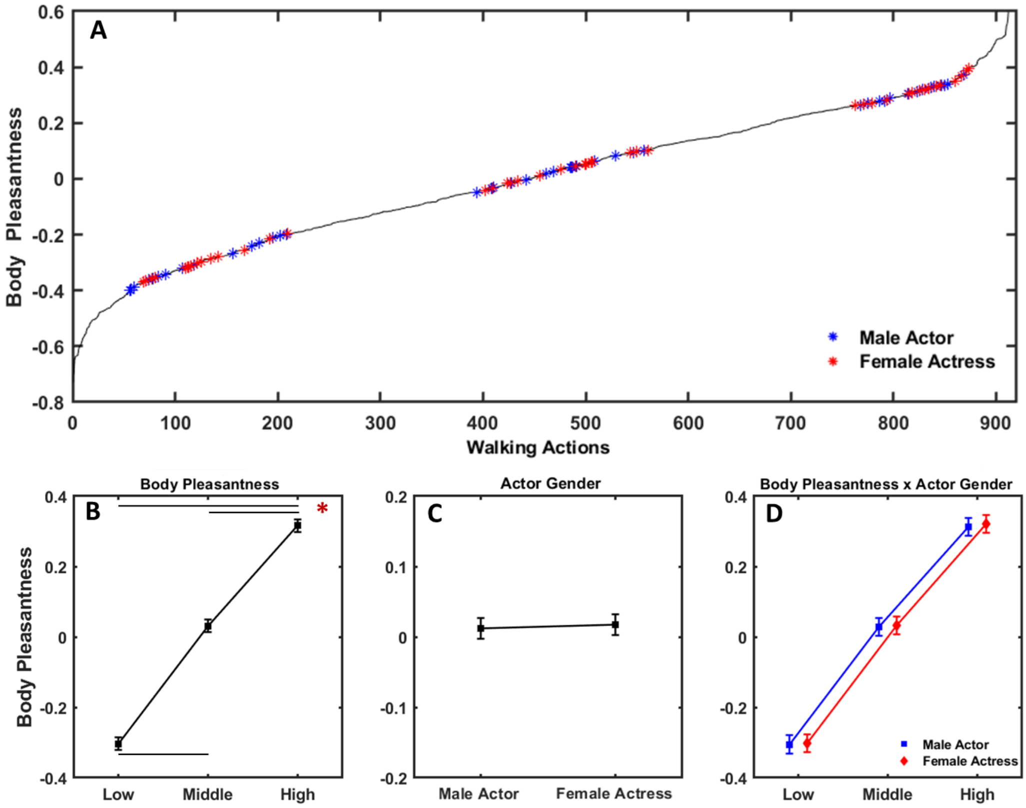


Fig. A1. Panel A shows the representative BP scores for all the 912 walking actions. The selected body postures are represented in three separate levels (low, middle, and high) with blue asterisks for male actors and red asterisks for female actresses. Bottom panels represent the results of the 2-way ANOVA computed on the selected BP values. Specifically, panel B presents the significance of the main factor Body Pleasantness (F(2, 84) = 1151.3, p < .001). Bonferroni corrected pairwise comparisons highlighted significant difference across all levels (low < middle, p < .001 ; middle < high, p < .001; low < high, p < .001). The factors Actor Gender (F(1, 84) = .272, p = .603) and Body Pleasantness x Actor Gender (F(2, 84) = .0419, p = .959) did not return any significant difference (panel C and D, respectively).

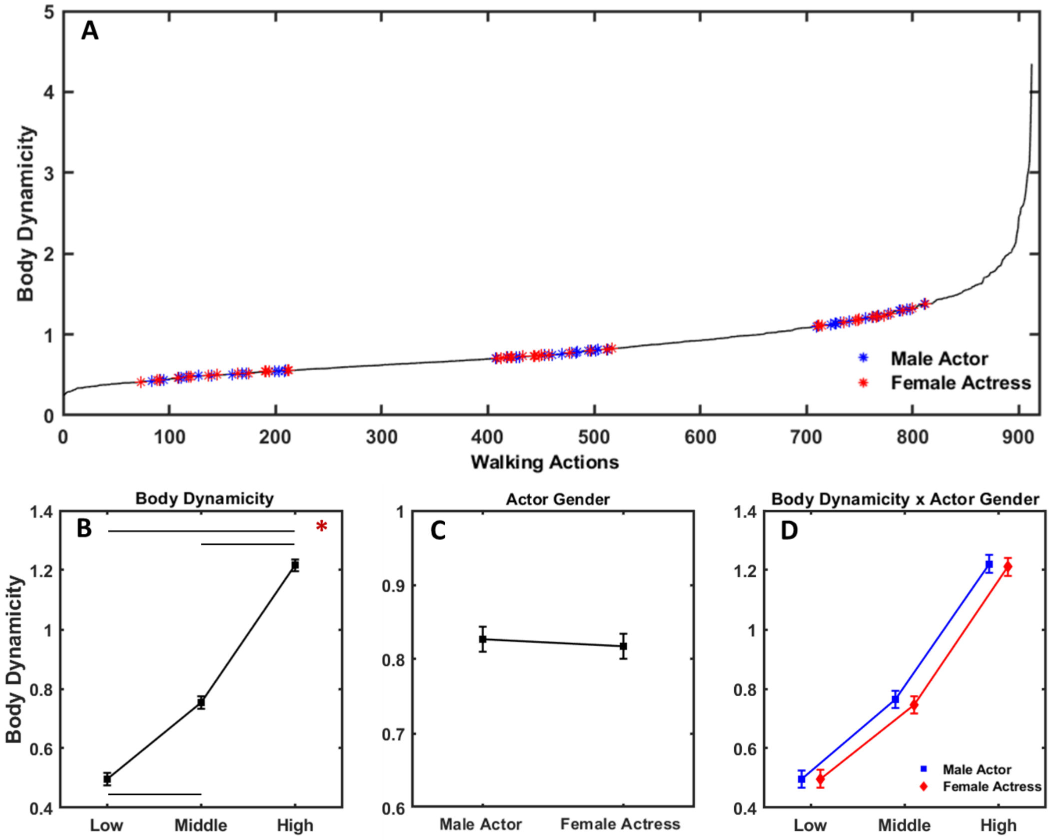


Fig. A2. Panel A shows the representative BD scores for all the 912 walking actions. The selected body postures are represented in three separate levels (low, middle, and high) with blue asterisks for male actors and red asterisks for female actresses. Bottom panels represent the results of the 2-way ANOVA computed on the selected BD values. Specifically, panel B presents the significance of the main factor Body Dynamicity (F(2, 84) = 1170.3, p < .001). Bonferroni corrected pairwise comparisons highlighted significant difference across all levels (low < middle, p < .001 ; middle < high, p < .001; low < high, p < .001). The factors Actor Gender (F(1, 84) = .572, p = .451), and Body Dynamicity x Actor Gender (F(2, 84) = .217, p = .805) did not return any significant difference (panel C and D, respectively).

2. Definition of valence and arousal as provided in the instructions of the online experiments

Arousal. With the first scale you will judge the state of ACTIVATION expressed by the body posture. The activation state of the organism is correlated to the change of the individual physical and psychological asset. A deactivated state is associated with a low heartbeat, sweating decrease, slow breathing, absence of energy, decreasing of attentional and decisional capability. An activated state is associated with a high heartbeat, sweating increase, fast breathing, feelings of vigor, energy and tension, increasing of attentional and decisional capability.

Valence. With the second scale you will judge the state of PLEASANTNESS expressed by the body posture. The pleasantness state of a body posture refers to the positive or negative character of the event that the body is experiencing. An unpleasant state can be associated with bad feelings or negative state of mind. A pleasant state can be associated with good feelings or positive state of mind.

3. Relationships between body cues, and subjective scores

We performed a correlation analysis considering the bodily indices extracted by the 180 postures used for the experiment to evaluate the relationship between BP and BD. Thus, for each body posture, we considered the BP at the time frame representative for the BD, and vice versa. Pearson's correlation coefficient was computed for the correlation analysis. As shown in panel A, the figure below illustrates a weak positive correlation between BP and BD scores ($R = 0.15$, $p= 0.04$). Then, we evaluated the relation between the subjective ratings of valence and arousal for each body posture, returning a positive correlation (Pearson's correlation coefficient $R = 0.84$, $p < .001$) (see panel B). This result reflects a tendency of participants to judge the avatar's posture in low arousal and negative valence state or in a high arousal and positive valence state, although the weak correlation between BP and BD. This result is in line with previous theories considering the affect spectrum ranging from low aroused negative affect to highly aroused positive affect (Pettinelli, 2007). This assumption may have its roots in the documented Western preference for highly aroused positive affect (Tsai et al., 2006). From this perspective, the prototype of a positive feeling is excitement (i.e., pleasure accompanied by high arousal), and its opposite is sadness and gloom (i.e., displeasure accompanied by low arousal). Kuppens et al. (2013) report that valence and arousal perceptions can result in six different relationships, regardless of the categorization of the stimuli: independence, a positive linear relation, a negative linear relation, a V-shaped relation, an asymmetrical

V-shaped relation, valence as a function of arousal. Although the relation mainly reported in the literature is the V-shaped one, we show that the perception of the stimuli we created falls into one of the main theories describing the relationship between valence and arousal.

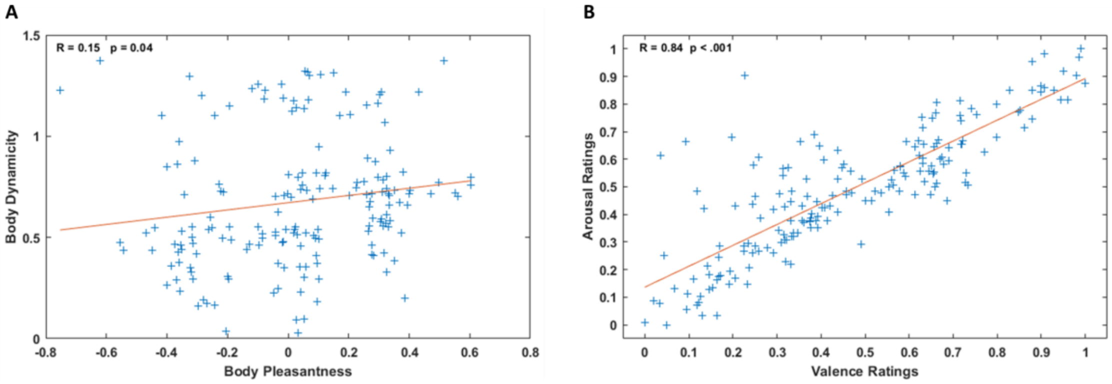


Fig. A3. Panel A shows the correlation between BP and BD. Panel B shows the correlation between valence and arousal ratings. valence (arousal) scores when subjects rated static postures and the movements from which they were extracted. The Pearson's linear correlation coefficient and the p-value are reported on the top of both panels. Red lines indicate the best linear fit (Panel A: y = 0.18x + 0.67; Panel B. y = 0.76x + 0.14).

B. The affective characterization of virtual architectures

1. Generation of virtual architectures

Figure B1 illustrates the macro spatial dimensions that we manipulated to create the 27 different architectural designs.

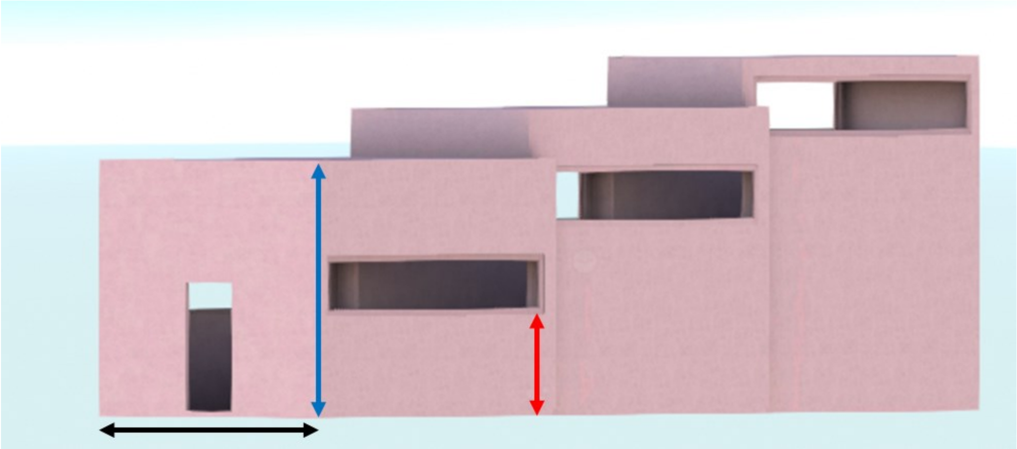
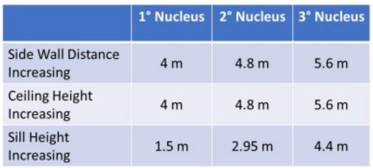
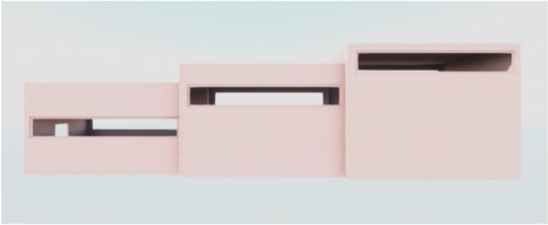


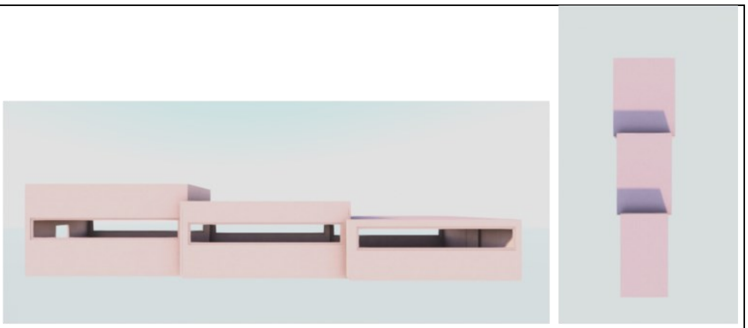
Fig. B1. The architectural design with increasing sidewalls distance, increasing ceiling height and increasing sill height is presented here as example. The black arrow indicates the sidewalls distance, the blue one the ceiling height and the red one the sill height.

Each of the architectural design is illustrated in supplementary Figure S2 where values of sidewalls distance, ceiling height and sill height are reported for each nucleus within a table. Furthermore, a lateral view and a view from the top are shown for each architectural design.

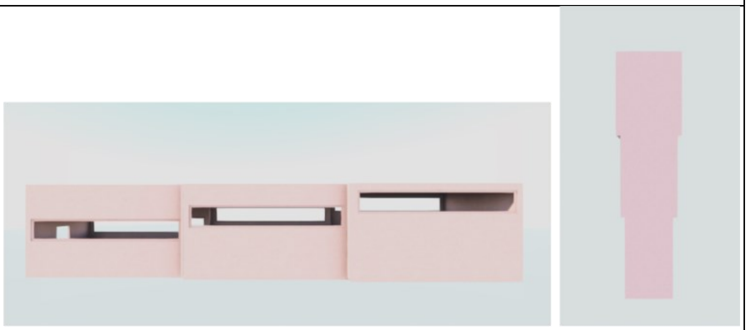
Nuceli Dimensions	Lateral View	Top View
		

	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Increasing	4 m	4.8 m	5.6 m
Ceiling Height Increasing	4 m	4.8 m	5.6 m
Sill Height Increasing	1.5 m	2.95 m	4.4 m

	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Increasing	4 m	4.8 m	5.6 m
Ceiling Height Decreasing	4 m	3.2 m	2.4 m
Sill Height Increasing	1.5 m	1.35 m	1.2 m



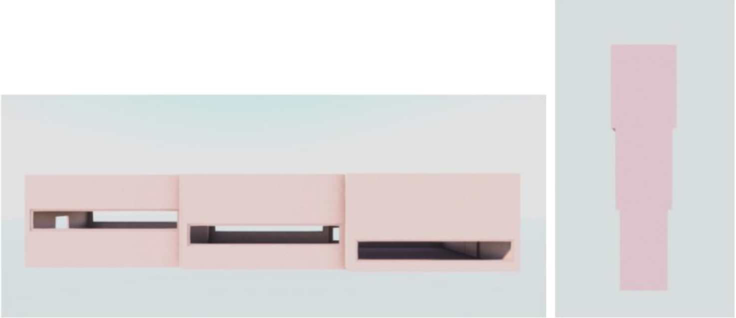
	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Increasing	4 m	4.8 m	5.6 m
Ceiling Height Constant	4 m	4 m	4 m
Sill Height Increasing	1.5 m	2.15 m	2.8 m



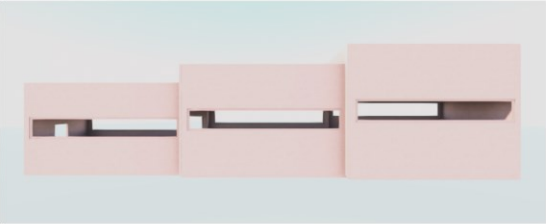
	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Increasing	4 m	4.8 m	5.6 m
Ceiling Height Increasing	4 m	4.8 m	5.6 m
Sill Height Decreasing	1.5 m	0.85 m	0.2 m

	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Increasing	4 m	4.8 m	5.6 m
Ceiling Height Decreasing	4 m	3.2 m	2.4 m
Sill Height Decreasing	1.5 m	0.85 m	0.2 m

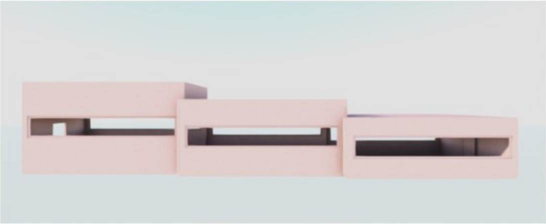
	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Increasing	4 m	4.8 m	5.6 m
Ceiling Height Constant	4 m	4 m	4 m
Sill Height Decreasing	1.5 m	0.85 m	0.2 m

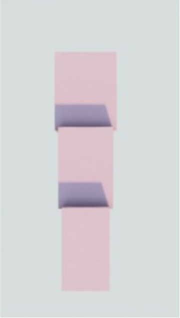


	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Increasing	4 m	4.8 m	5.6 m
Ceiling Height Increasing	4 m	4.8 m	5.6 m
Sill Height Constant	1.5 m	1.9 m	2.3 m

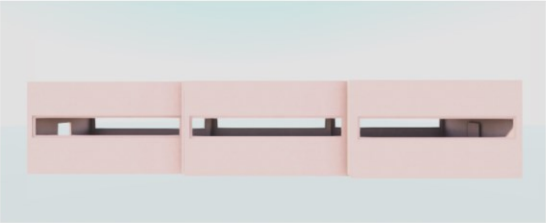


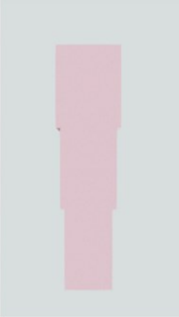
	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Increasing	4 m	4.8 m	5.6 m
Ceiling Height Decreasing	4 m	3.2 m	2.4 m
Sill Height Constant	1.5 m	1.1 m	0.7 m





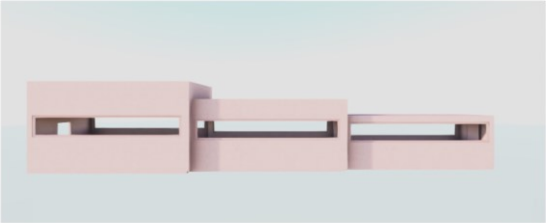
	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Increasing	4 m	4.8 m	5.6 m
Ceiling Height Constant	4 m	4 m	4 m
Sill Height Constant	1.5 m	1.5 m	1.5 m



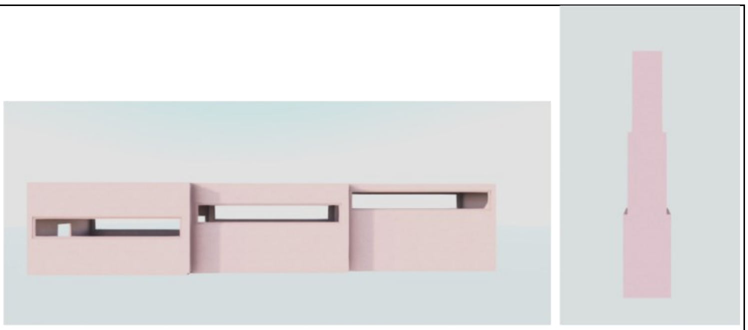


	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Decreasing	4 m	3.2 m	2.4 m
Ceiling Height Increasing	4 m	4.8 m	5.6 m
Sill Height Increasing	1.5 m	2.95 m	4.4 m

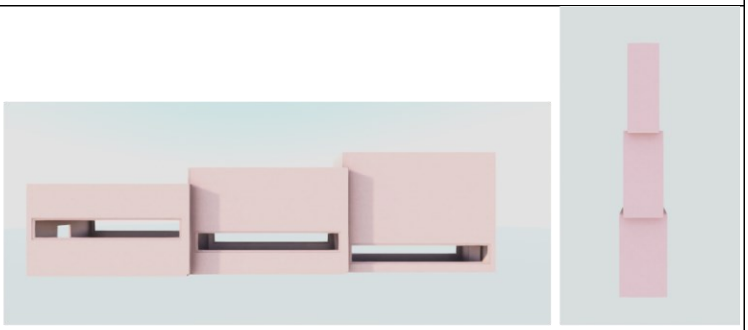
	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Decreasing	4 m	3.2 m	2.4 m
Ceiling Height Decreasing	4 m	3.2 m	2.4 m
Sill Height Increasing	1.5 m	1.35 m	1.2 m



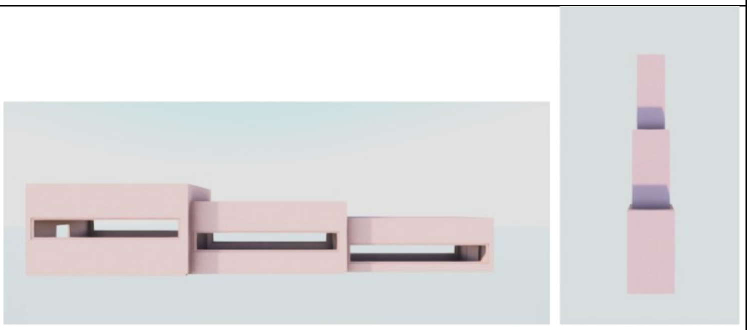
	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Decreasing	4 m	3.2 m	2.4 m
Ceiling Height Constant	4 m	4 m	4 m
Sill Height Increasing	1.5 m	2.15 m	2.8 m



	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Decreasing	4 m	3.2 m	2.4 m
Ceiling Height Increasing	4 m	4.8 m	5.6 m
Sill Height Decreasing	1.5 m	0.85 m	0.2 m

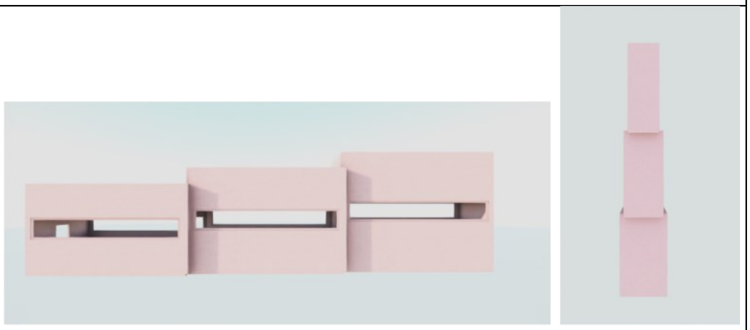


	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Decreasing	4 m	3.2 m	2.4 m
Ceiling Height Decreasing	4 m	3.2 m	2.4 m
Sill Height Decreasing	1.5 m	0.85 m	0.2 m

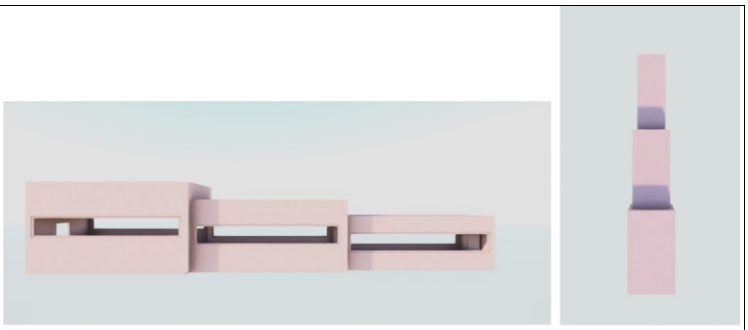


	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Decreasing	4 m	3.2 m	2.4 m
Ceiling Height Constant	4 m	4 m	4 m
Sill Height Decreasing	1.5 m	0.85 m	0.2 m

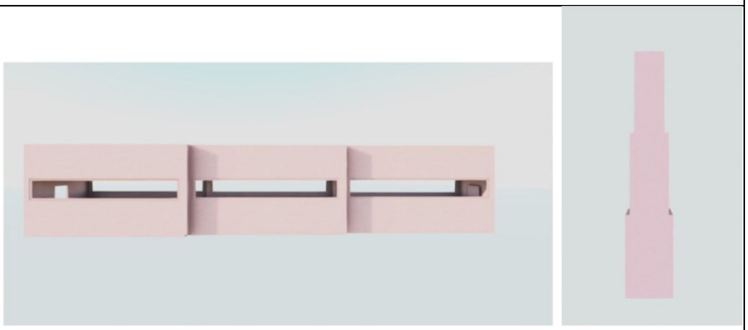
	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Decreasing	4 m	3.2 m	2.4 m
Ceiling Height Increasing	4 m	4.8 m	5.6 m
Sill Height Constant	1.5 m	0.9 m	2.3 m



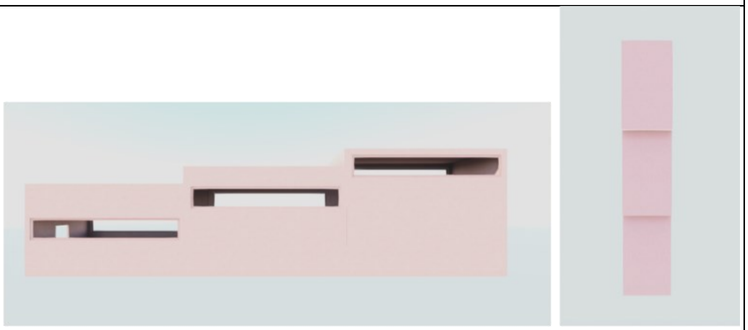
	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Decreasing	4 m	3.2 m	2.4 m
Ceiling Height Decreasing	4 m	3.2 m	2.4 m
Sill Height Constant	1.5 m	1.1 m	0.7 m



	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Decreasing	4 m	3.2 m	2.4 m
Ceiling Height Constant	4 m	4 m	4 m
Sill Height Constant	1.5 m	1.5 m	1.5 m

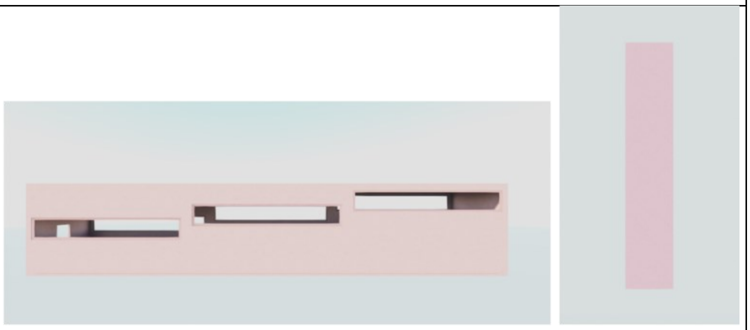


	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Constant	4 m	4 m	4 m
Ceiling Height Increasing	4 m	4.8 m	5.6 m
Sill Height Constant	1.5 m	2.95 m	4.4 m

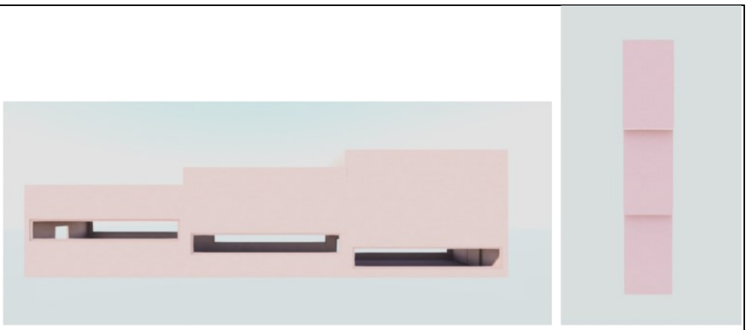


	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Constant	4 m	4 m	4 m
Ceiling Height Decreasing	4 m	3.2 m	2.4 m
Sill Height Increasing	1.5 m	1.35 m	1.2 m

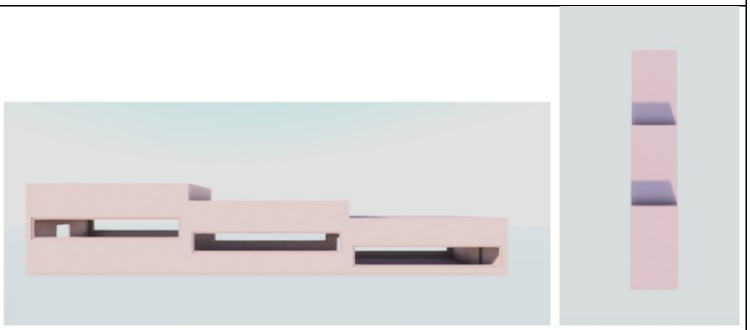
	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Constant	4 m	4 m	4 m
Ceiling Height Constant	4 m	4 m	4 m
Sill Height Increasing	1.5 m	2.15 m	2.8 m



	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Constant	4 m	4 m	4 m
Ceiling Height Increasing	4 m	4.8 m	5.6 m
Sill Height Decreasing	1.5 m	0.85 m	0.2 m

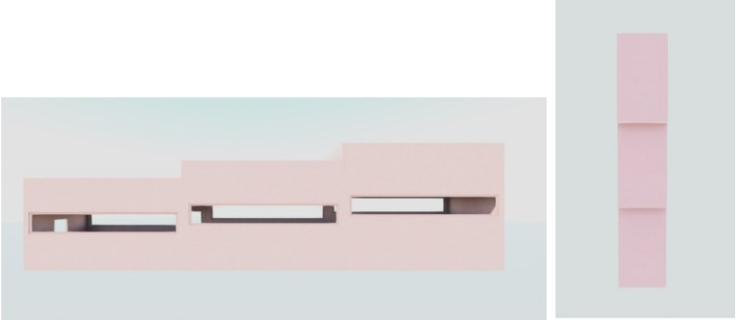


	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Constant	4 m	4 m	4 m
Ceiling Height Decreasing	4 m	3.2 m	2.4 m
Sill Height Decreasing	1.5 m	0.85 m	0.2 m

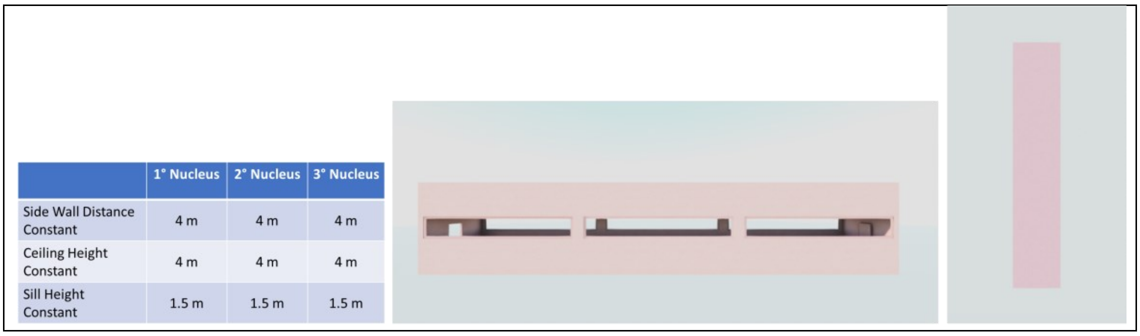


	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Constant	4 m	4 m	4 m
Ceiling Height Constant	4 m	4 m	4 m
Sill Height Decreasing	1.5 m	0.85 m	0.2 m

	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Constant	4 m	4 m	4 m
Ceiling Height Increasing	4 m	4.8 m	5.6 m
Sill Height Constant	1.5 m	1.9 m	2.3 m



	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Constant	4 m	4 m	4 m
Ceiling Height Decreasing	4 m	3.2 m	2.4 m
Sill Height Constant	1.5 m	1.1 m	0.7 m



	1° Nucleus	2° Nucleus	3° Nucleus
Side Wall Distance Constant	4 m	4 m	4 m
Ceiling Height Constant	4 m	4 m	4 m
Sill Height Constant	1.5 m	1.5 m	1.5 m

Fig. B2. The tested architectural designs are illustrated in the figure. Within each row we represent a different design. Specifically, from left to right, we show: i) a table with the dimensions of the sidewalls distance, ceiling height and sill height for each nucleus of the design; ii) a lateral view of the design; iii) a top view of the design.

2. Additional results

A preliminary correlation analysis was computed between the average brightness measured within the virtual architectures and subjective z-scored valence and arousal ratings. Indeed, due to differences in terms of colors and forms, virtual architectures were characterized by different brightness values. To compute the brightness of each architecture, we firstly recorded a digital video of the virtual promenade inside the architecture. Then, the brightness was computed as the mean value of the RGB triplets relative to each video frame. Hence, we performed two separate Pearson's correlation analyses to test the independence between the brightness and subjective scores of arousal and valence. Figure B3 showed the results of the correlation analysis between the brightness of the architectures and valence (R = -0.09, p = 0.52) and arousal (R = 0.07, p = 0.62) subjective ratings. No correlation was found, highlighting that the affective modulation generated by the architectural experience did not depend on such a low-level brightness factor.

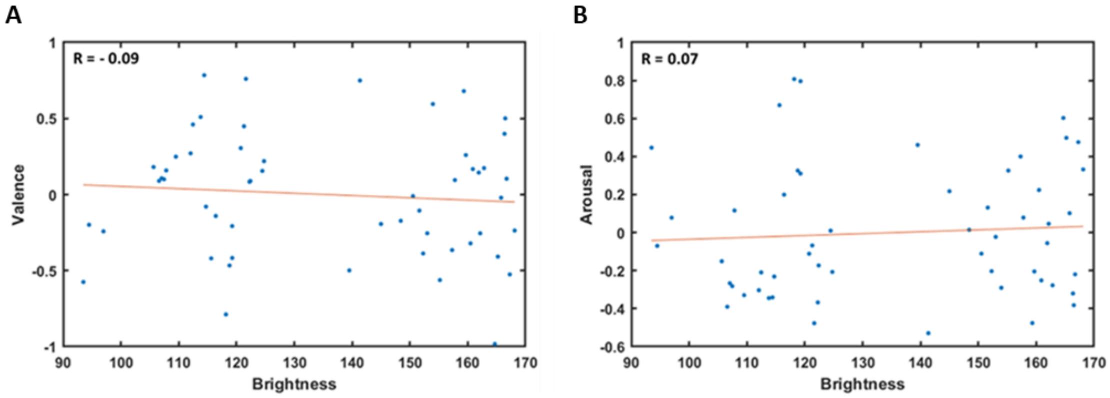


Fig. B3. Architectures distribution within the space of valence and brightness (Panel A) and arousal and brightness (Panel B). The Pearson's linear correlation coefficient is reported on the top of both panels. Red lines indicate the best linear fit between the subjective ratings of valence (Panel A) and arousal (Panel B) and the brightness value of the architectures.

Considering that a key parameter impacting on individual's affective state could be the relative sill height to the eye level of the participant rather than to the location of the roof, we performed a correlation analysis between subjective valence and arousal ratings and the sill height relative to the subject's eye level. We computed the relative sill height as the average between the sill height of the second and third nucleus, scaled by the average participants' eye level (1.60 m).

$$Relative\ Sill\ Height_i = \frac{Sill\ Height_{2°\ Nucelus,i} + \ Sill\ Height_{3°\ Nucelus,i}}{2} - 1.60$$

Where i identifies each of the specific architecture. The 54 combinations of architectural design resulted in 7 different relative sill heights (-1.075 m, -0.7 m, -0.325 m, -0.1 m, 0.5 m, 0.875 m, 2.075 m). Negative values indicated a sill height below the participant's eye level. Pearson's correlation coefficient was computed for the correlation analysis. The correlation between subjective ratings of valence and the relative sill height was found to be not significant (p = 0.11). Instead, subjective ratings of arousal and relative sill heights were found to be positively correlated (p = 0.004). However, the Pearson's correlation coefficient revealed a moderate effect (R = 0.385). Figures below illustrate the results.

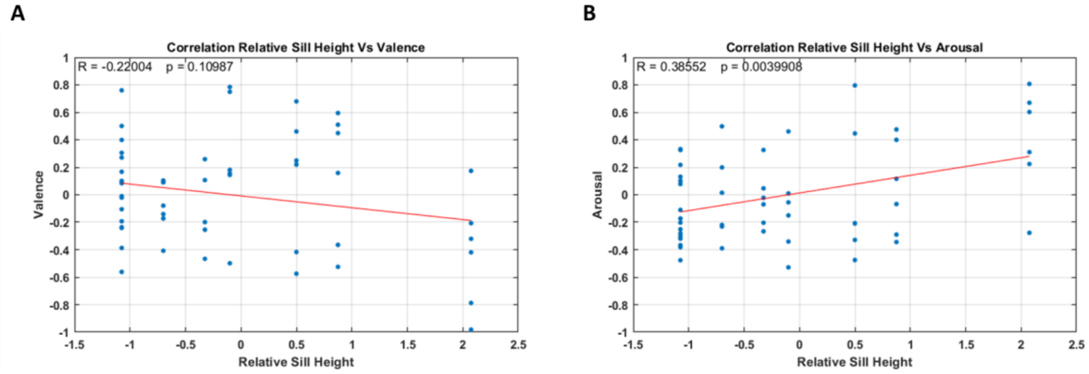


Fig. B4. Architectures distribution considering valence (arousal) ratings and the relative sill height are illustrated in Panel A (Panel B). The Pearson's linear correlation coefficient and the p-value are reported on the top of both panels. Red lines indicate the best linear fit between the subjective ratings of valence (Panel A) and arousal (Panel B) and the relative sill height.

We conducted two separate Kruskal Wallis tests to further evaluate possible differences in the subject’s preferences according to the relative sill heights. The null hypothesis was that subject’s valence (and arousal) ratings belonged to the same distribution, not depending on the relative sill height. Results showed no significant differences among the 7 levels of relative sill heights, for both valence ($\chi2(6) = 9.651$, $p = 0.14$) and arousal ($\chi2(6) = 6.932$, $p = 0.327$) ratings. Hence, although the present analysis returned a significant correlation between the relative sill height and the subjective arousal preference, we did not observe a clear preference for those architecture having windows vertically centred on, or slightly lower than, the eye-level of the participants, as hypothesized by the reviewer. In that case, we should have observed the highest (lowest) valence (arousal) subjective rating for the conditions where the relative sill height is close to zero (i.e., -0.325 m, 0.5 m). This condition is not verified. However, with our virtual stimuli is not possible to effectively disentangle the combined effect due to the progressive variation of the sill height between consecutive nuclei and their relative position to the eye level of the participants. For instance, conditions relative to constant sill height across nuclei are missing. Considering that valence and arousal ratings are not segregated in two sets but are distributed continuously between the two quadrants, it could be useful to make a more refined clustering. For this reason, we decided to perform an additional k-means cluster analysis, setting k = 3, thus identifying a new “Neutral” group of architectures. From the results it is possible to observe that the k = 3 cluster analysis confirmed the results obtained with k = 2, i.e., the sidewalls distance is still the only experimental condition according to which architectures were unbalanced between clusters (χ2 = 30.9, p = 3.2 *10-6): the 78% of architectures with increasing sidewalls distance belongs to the LAPV cluster, while the 55% of the decreasing sidewalls distance architectures belong to the HANV cluster. Clustering architectures according to the factors Windows, Ceiling and Color did not return statistically significant results. The prevalence of architectures within the two clusters according to their experimental condition can be found in the Table below, along with the Figure illustrating the results of the cluster analysis.

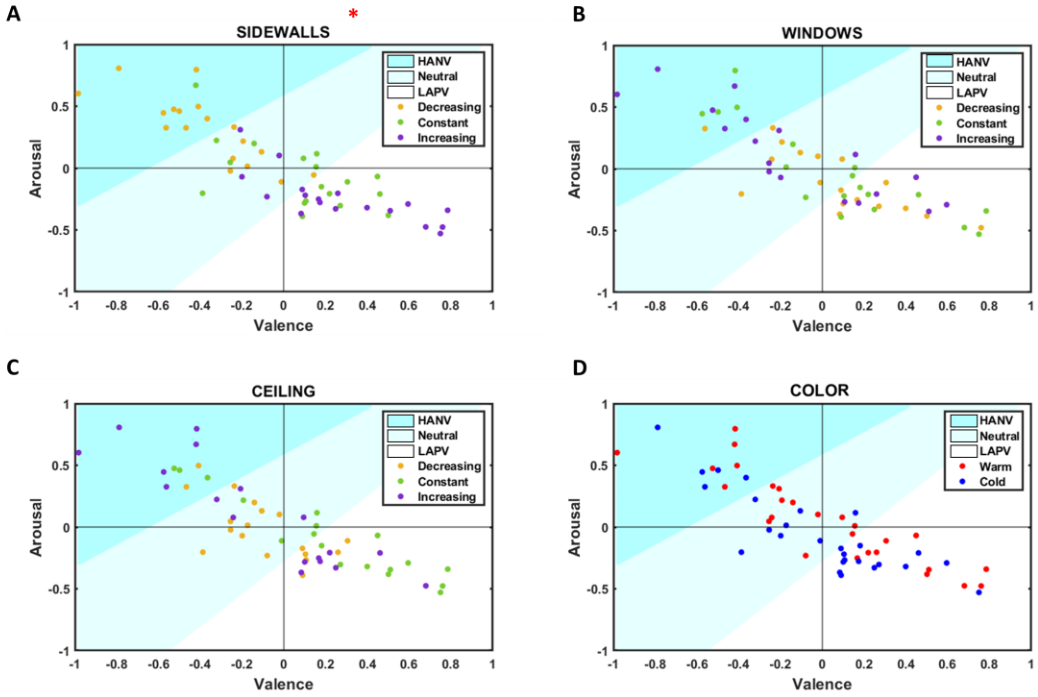


Fig. B5. For each panel, the darker blue section of the plane includes architectures belonging to the HANV cluster, the lighter blue one comprises architectures within the Neutral cluster and the white one includes architectures belonging to the LAPV. Panel A, B, C: yellow, green, and purple dots identify architectures with decreasing, constant and increasing conditions for SideWalls, Windows, and Ceiling factors, respectively. Panel D: blue and red dots identify architectures with cold and warm texture color, respectively. The red asterisk indicates statistically significant results

		HANV	Neutral	LAPV
SideWalls	Decreasing	55.56	44.44	0
	Constant	5.56	38.89	55.56
	Increasing	0	22.20	77.78

		HANV	Neutral	LAPV
Windows	Decreasing	5.56	44.44	50
	Constant	22.22	27.78	50
	Increasing	33.33	33.33	33.33

		HANV	Neutral	LAPV
Ceiling	Decreasing	11.11	55.56	33.33
	Constant	16.67	27.78	55.56
	Increasing	33.30	22.22	44.44

		HANV	Neutral	LAPV
Color	Warm	22.22	40.74	37.04
	Cold	18.52	29.63	51.85

Table B1. Percentage of architecture distribution within the clusters HANV, Neutral, and LAPV according to the experimental conditions.

Acknowledgments

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