Angularity Versus Curvature in Interior Design:

Effects on Aesthetic Preference, Stress Response, and Approach-Avoidance Tendencies

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Angularity Versus Curvature in Interior Design: Effects on Aesthetic Preference, Stress Response, and Approach-Avoidance Tendencies

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Summary

In the context of rapid urbanisation and growing mental health concerns, there has been an increasing focus on understanding how indoor environments, where humans spend the majority of their time, influence psychological well-being and mental health. It is now widely suggested that certain environmental features, such as geometry and forms, significantly shape individuals' affective and behavioural responses. Notably, a recurrent phenomenon in research highlights a seemingly consistent preference for curvature over angularity across various stimulus categories including simple lines and shapes as well as more complex everyday objects. This preference is believed to also extend to the built environment. Generally, the underlying reasons for this phenomenon are still debated. Some views attribute the preference effects to a threat elicited by angles while others ascribe them to a pleasant intrinsic effect of curves. Yet, the limited body of available research exploring architecture and interior design settings often relies on unrealistic or poorly matched stimuli, mainly presented as images, and focuses on the aesthetic dimension, neglecting other psychological domains. These limitations raise questions about the robustness and implications of the reported effects, especially given the variability in findings across some studies, underscoring the need for further investigation.

This dissertation comprises three publications aimed at systematically investigating the causal effects of short-term exposure to angular versus curved interior designs on affect, cognition, and behaviour, employing both virtual reality (VR) and images as presentation modes.

Paper I (Tawil et al., 2021) introduces a novel VR paradigm to assess the psychological impact of interior environments with angular versus curved features across various domains, including affective and spatial experience, momentary affect, cognitive performance, and perceived restorativeness. The study used two pairs of photo-realistic three-dimensional living spaces, exclusively differing in form (angular versus curved) and style (modern versus classic). Out of 33 variables assessed, only two revealed differences, favouring rooms with angular features on the "order" and "novelty" dimensions. Further Bayesian analysis supported the results from the initial frequentist approach, challenging the preference for curvature and suggesting that psychological responses to angularity versus curvature in close-to-reality architectural settings may entail greater complexity.

Paper II (Tawil et al., 2022) focuses on the effects of interior environments with angular versus curved features on aesthetic preference (i.e., liking and beauty) and stress ratings (i.e., restfulness and stressfulness), using 20 images derived from the virtual rooms used in *Paper I*,

controlled for low-level image features. Additionally, style and sex effects were examined to account for potential interactions. Results indicated that participants reported higher aesthetic preference and lower stress in response to images of curved compared to angular interiors. Notably, effects on stress responses were consistent, whereas aesthetic preference for curves was context- and sex-dependent, being limited to modern style and the female subgroup. These findings suggest that the impact of angular versus curved interiors appears to extend more widely to psychological and potentially physiological stress responses than to aesthetic evaluations that may be influenced by person-specific preferences, perhaps based on differential experiences and cognitive processes.

Paper III (Tawil et al., 2024) examines the preference for curves more implicitly, employing a battery of four reaction time paradigms that particularly focus on approach-avoidance behaviour, aligning with the different accounts regarding the source of the effect. The study aimed to capture attentional, motoric, as well as associative-semantic and -motoric biases towards angular versus curved interior designs. Results confirmed implicit effects with two paradigms, establishing links with approach-avoidance tendencies using experimental tasks and according reaction times. Participants semantically associated curvature with approach and angularity with avoidance, with stronger effects in women. Moreover, biases in motoric representations were identified, with participants exhibiting faster approach and slower avoidance responses to curvature, while no differences in responses to angularity were observed. These effects were intensified for interiors with the modern style. The findings may hint at (partially) automatic responses to curvature in interior design settings.

In conclusion, this thesis presents empirical evidence supporting the potential positive effects of interior spaces with curved features, particularly when presented as images, rather than in a dynamic spatial experience (i.e., VR). It underscores significant impacts on explicit (i.e., self-reported aesthetic preference and stress) as well as implicit responses (i.e., semantic and motoric representations relating to approach-avoidance tendencies). Furthermore, it highlights the importance of accounting for contextual (e.g., style) and person-specific (e.g., participant sex) factors when exploring the effects of angular versus curved designs on human psychology and physiology. Ultimately, this research contributes to the expanding fields of environmental and architectural psychology. Its findings hold promise for evidence-based design strategies aimed at considering affective and behavioural human responses. This may be particularly relevant to spaces intended to promote mental health and well-being, but also everyday environments, fostering a more informed approach to architecture and interior design.

Zusammenfassung

Vor dem Hintergrund der raschen Urbanisierung und der ansteigenden Besorgnis über die psychische Gesundheit wird zunehmend untersucht, wie Innenräume, in denen Menschen den größten Teil ihrer Zeit verbringen, das psychische Wohlbefinden und die mentale Gesundheit beeinflussen. Es wird angenommen, dass bestimmte Umgebungsmerkmale wie Geometrie und Formen die affektiven und verhaltensbezogenen Reaktionen von Individuen erheblich beeinflussen. Ein in der Forschung immer wiederkehrendes Phänomen ist die scheinbar konsistente Vorliebe für runde gegenüber eckigen Formen bei verschiedenen Kategorien von Stimuli, darunterfallen sowohl einfache Linien und Formen als auch komplexere Alltagsobjekte. Es wird angenommen, dass sich diese Präferenz auch auf die von Menschen geschaffene Umwelt erstreckt. Die Gründe für dieses Phänomen sind noch umstritten. Einige Auffassungen basieren auf der Annahme, dass die Effekte auf eine Bedrohung, die durch Winkel hervorgerufen wird, zurückzuführen ist, bei anderen wird von einem angenehmen intrinsischen Effekt, der durch Rundungen evoziert wird, ausgegangen. Die wenigen vorhandenen Forschungsarbeiten, die sich mit Architektur und Inneneinrichtung befassen, basieren häufig auf unrealistischen oder unzureichend kontrollierten Stimuli, die hauptsächlich als Bilder präsentiert werden. Zudem konzentrieren sie sich primär auf die ästhetische Dimension, wobei andere psychologische Bereiche vernachlässigt werden. Diese Einschränkungen werfen Fragen bezüglich der Robustheit und den Implikationen der berichteten Effekte auf, insbesondere angesichts der Variabilität der Ergebnisse zwischen einigen Studien, was die Notwendigkeit weiterer Untersuchungen verdeutlicht.

Diese Dissertation umfasst drei Publikationen, die darauf abzielen, systematisch die kausalen Auswirkungen einer kurzzeitigen Exposition gegenüber eckigen bzw. runden Innenraumgestaltungen auf Affekt, Kognition und Verhalten zu untersuchen, wobei sowohl virtuelle Realität (VR) als auch Bilder als Form der Darbietung verwendet werden.

In *Paper I* (Tawil et al., 2021) wird ein neuartiges VR-Paradigma vorgestellt, welches die psychologischen Auswirkungen von Innenräumen mit eckigen bzw. runden Merkmalen in verschiedenen Bereichen untersucht. Die untersuchten Bereiche umfassen affektive und räumliche Wahrnehmung, momentane Affekte, kognitive Leistung und wahrgenommene Erholungseffekte. Für die Studie wurden zwei Paare von fotorealistischen dreidimensionalen Wohnräumen verwendet, die sich ausschließlich in Form (eckig versus rund) und Stil (modern versus klassisch) unterschieden. Von den 33 untersuchten Variablen zeigten lediglich zwei

Unterschiede, wobei die Räume mit eckigen Merkmalen in den Kategorien "Ordnung" und "Neuartigkeit" bevorzugt wurden. Bayes-Analysen stützten die Ergebnisse des ersten frequentistischen Ansatzes, was die Präferenz für Rundungen in Frage stellt und nahelegt, dass psychologische Reaktionen auf Ecken gegenüber Rundungen in realitätsnahen architektonischen Umgebungen eine höhere Komplexität aufweisen.

Paper II (Tawil et al., 2022) befasst sich mit den Effekten von Innenräumen mit eckigen bzw. runden Merkmalen auf die Bewertung der ästhetischen Präferenz (d.h. Gefallen und Schönheit) und der Stressreaktion (d.h. Ruhe und Stress). Die verwendeten 20 Bilder wurden aus den in *Paper I* virtuellen Räumen abgeleitet und hinsichtlich einfacher Bildmerkmale kontrolliert. Zusätzlich wurden Stil- und Geschlechtseffekte überprüft, um mögliche Wechselwirkungen zu berücksichtigen. Die Ergebnisse zeigten, dass die Teilnehmer eine höhere ästhetische Präferenz und geringeren Stress als Reaktion auf Bilder von runden im Vergleich zu eckigen Raumgestaltungen angaben. Insbesondere die Auswirkungen auf die Stressreaktion waren konsistent, während die ästhetische Präferenz für Rundungen kontext- und geschlechtsabhängig war und sich auf den modernen Stil und die weiblichen Teilnehmenden beschränkte. Diese Ergebnisse deuten darauf hin, dass sich die Auswirkungen von eckiger gegenüber runder Raumgestaltung offenbar stärker auf psychologische und potenziell physiologische Stressreaktionen auswirken als auf ästhetische Bewertungen, die möglicherweise durch personenspezifische Präferenzen beeinflusst werden, welche auf unterschiedlichen Erfahrungen und kognitiven Prozessen beruhen.

Paper III (Tawil et al., 2024) untersucht implizit die Vorliebe für Rundungen, indem eine Reihe von vier Reaktionszeitparadigmen eingesetzt wird, die sich insbesondere auf das Annäherungs-Vermeidungs-Verhalten konzentrieren und mit den verschiedenen Auffassungen über die Ursache des Effekts übereinstimmen. Die Studie zielte darauf ab, aufmerksamkeitsbezogene, motorische sowie assoziativ-semantische und -motorische Verzerrungen (Bias) gegenüber eckigen und runden Innenraumgestaltungen zu erfassen. Die Ergebnisse bestätigten die impliziten Effekte von zwei Paradigmen, wobei anhand experimenteller Aufgaben und entsprechender Reaktionszeiten Zusammenhänge mit Annäherungs- und Vermeidungstendenzen hergestellt wurden. Semantisch assoziierten die Teilnehmenden Rundungen mit Annäherung und Ecken mit Vermeidung, wobei die Effekte bei Frauen stärker ausgeprägt waren. Darüber hinaus wurde ein Bias bezüglich motorischer Repräsentation beobachtet: Teilnehmende reagierten auf Rundungen schneller mit Annäherung und langsamer mit Vermeidung, während keine Unterschiede in der Reaktion auf Ecken beobachtet werden konnte. Diese Effekte verstärkten sich in Innenräumen im modernen Stil. Die Ergebnisse könnten auf (teilweise) automatische Reaktionen gegenüber Rundungen in der Innenarchitektur hindeuten.

Zusammenfassend werden in der folgenden Arbeit empirische Belege für die potentiellen positiven Effekte von Innenräumen mit runden Merkmalen dargelegt, insbesondere wenn diese in Form von Bildern und nicht als dynamische räumliche Erfahrung (d.h. VR) präsentiert werden. Sie unterstreicht die signifikanten Auswirkungen auf explizite (d.h. selbstberichtete ästhetische Präferenzen und Stress) sowie implizite Reaktionen (d.h. semantische und motorische Repräsentationen in Bezug auf Annäherungs- und Vermeidungstendenzen). Darüber hinaus wird ersichtlich, dass es von essentieller Bedeutung ist, kontextuelle (z. B. Stil) und interindividuelle (z.B. Geschlecht der Teilnehmenden) Faktoren bei der Untersuchung möglicher Effekte von eckigen und runden Designs auf die menschliche Psychologie und Physiologie, zu berücksichtigen. Letztendlich trägt diese Forschung zu den expandierenden Bereichen der Umwelt- und Architekturpsychologie bei. Die Ergebnisse sind vielversprechend für evidenzbasierte Designstrategien, die darauf abzielen, affektive und verhaltensbezogene menschliche Reaktionen zu berücksichtigen. Dies kann insbesondere für Räume relevant sein, die die psychische Gesundheit und das Wohlbefinden fördern sollen, aber auch für alltägliche Umgebungen, die einen kompetenteren Ansatz der Architektur und Innenarchitektur fordern.

List of included papers

This doctoral dissertation is based on the following three original papers:

Paper I

Tawil, N., Sztuka, I. M., Pohlmann, K., Sudimac, S., & Kühn, S. (2021). The living space: Psychological well-being and mental health in response to interiors presented in virtual reality. *International Journal of Environmental Research and Public Health*, *18*(23), Article 12510. https://doi.org/10.3390/ijerph182312510

Paper II

Tawil, N., Ascone, L., & Kühn, S. (2022). The contour effect: Differences in the aesthetic preference and stress response to photo-realistic living environments. *Frontiers in Psychology, Article 13*, 933344. https://doi.org/10.3389/fpsyg.2022.933344

Paper III

Tawil, N., Elias, J., Ascone, L., & Kühn, S. (2024). The curvature effect: Approach-avoidance tendencies in response to interior design stimuli. *Journal of Environmental Psychology, Article 93*, 102197. https://doi.org/10.1016/j.jenvp.2023.102197

List of abbreviations

AAT	Approach-avoidance task
ACC	Anterior cingulate cortex
ASD	Autism spectrum disorder
DPT	Dot probe task
EEG	Electroencephalography
fMRI	Functional magnetic resonance imaging
IAT	Implicit association task
mOFC	Medial orbitofrontal cortex
RT	Reaction time
SES	Socio-economic status
SRCT	Stimulus-response compatibility task
VE	Virtual environment
VR	Virtual reality
WEIRD	Western, educated, industrialised, rich, democratic

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1. General theoretical and empirical background

In an era marked by unprecedented urban expansion, the rapid growth of cities and the corresponding rise in mental health challenges (Krabbendam et al., 2021; Peen et al., 2010) necessitate a deeper exploration of the intricate relationship between human experiences and the built environment. As urban dwellers, we spend 90% of our day immersed in various architectural landscapes (Klepeis et al., 2001), be it our homes, learning environments, workplaces, or areas of relaxation, underscoring an undeniable impact of these indoor spaces on us. Each environment, with its distinct physical and aesthetic characteristics, holds the potential to affect our well-being (Coburn et al., 2020; Evans & McCoy, 1998). This connection between our physical surroundings and our mental states emphasises the need for a deeper exploration into how our daily environments shape our psychological well-being.

Environmental psychologists have long highlighted the beneficial effects that a supportive environment can exert on our emotions, cognitive functions, and behaviour, thereby underlining profound implications for mental health (Evans, 2003; Gifford, 2002). This insight into the influence of our surroundings propels us into a broader discussion on the role of physical environments in brain plasticity. Over the past decades, a growing body of research utilising animal models has increasingly illustrated the significant impact of physical environments on brain plasticity (Kempermann, 2019), reinforcing the critical role of enriched environments in this process. This research has paved the way for a parallel understanding in the human context, where architecture and interior design are increasingly recognised for their potential to significantly shape behaviours and influence neural pathways (Eberhard, 2009). This potential of the built environment opens promising avenues for interventions aimed at enhancing mental health and well-being through evidence-based design strategies.

Recognising the complex relationship between the built environment and mental health outcomes is crucial for the fields of architecture and interior design. Traditionally, architectural design has primarily focused on fulfilling physical needs by adhering to standards for measurements, natural lighting, acoustics, thermal comfort, and indoor air quality (Albright, 2015). These elements have served as the foundation for creating spaces that are both functional and liveable. However, the growing understanding of human psychology highlights the urgent need to broaden this perspective. Contemporary architecture has yet to systematically incorporate considerations of psychological needs into its planning and design processes (Robinson & Pallasmaa, 2015). For instance, it is now evident that architectural design can support cognitive performance in learning environments (Llinares et al., 2021), or reduce anxiety in healthcare and psychiatric facilities benefiting both patients and staff (Norouzi et al., 2023; Ulrich et al., 2010). By understanding the holistic interaction between humans and their man-made environments, designers can proactively create spaces that not only meet the basic requirements of physical comfort, but also actively promote positive emotional states, cognitive development, and overall mental well-being (Evans, 2003). This approach contributes to the development of healthier, more supportive spaces, and also emphasises the significance of thoughtful, evidence-based design in improving the quality of urban life.

In this context, a variety of architectural features and parameters have been identified as influential in eliciting specific psychological and neurological responses within indoor settings. Those include forms (Banaei et al., 2017; Vartanian et al., 2013), ceiling height and enclosure (Vartanian et al., 2015), colours (Bower et al., 2022; Llinares et al., 2021), materials and textures (Zhang et al., 2017), lighting (Mostafavi et al., 2023; Shin et al., 2015), and the integration of natural elements (Jung et al., 2023; Rhee et al., 2023). For instance, a functional magnetic resonance imaging (fMRI) study on interior environments observed a preference for spaces with curvilinear rather than rectilinear features (Vartanian et al., 2013), which not only appeal aesthetically but also seem to influence activity in the medial orbitofrontal cortex (mOFC)—termed as anterior cingulate cortex (ACC) in the publication—which has been previously associated with positive valence and pleasantness (Kühn & Gallinat, 2012). However, while the study established links between specific environmental features and brain activity, it had some limitations. First, the sample size was relatively small (N = 18). Second, it presented static image stimuli that were not well-matched in the sense that a curvilinear stimulus was matched with a rectilinear stimulus that differed in more than just the shape thereby containing a considerable number of confounding variables. Hence, the investigation into forms necessitates further exploration, highlighting the need for a more nuanced understanding of how architectural and interior design influences psychological and neural responses.

1.1 Angular versus curved stimuli

Among the many visual parameters, the configuration of contours has been suggested as a core aspect of visual perception, fundamental in detecting and representing environmental stimuli

(Chuquichambi et al., 2022; Loffler, 2008). Contour is defined as “the edge or line that defines or bounds a shape or object” (Dictionary.com, 2024). Indeed, the shape of an object often serves as the primary descriptor when identifying or discussing it, usually taking precedence over colour, volume, or material quality (Dorsey et al., 2010; Pinna & Deiana, 2015). This emphasis on contours is underscored by phenomena such as the so-called “Maluma-Takete” effect, where different shapes evoke distinct contour attributes and a spectrum of contrasting properties (Köhler, 1929; Ramachandran & Hubbard, 2001). Specifically, the effect illustrates how people universally associate soft, rounded sounds with curvy shapes and sharp, harsh sounds with spiky shapes, demonstrating an intuitive link between auditory and visual perceptions.

The significance of contours has been recognised across various disciplines, including the arts, aesthetics, visual cognition, and social psychology, which have documented perceptual differences between angular/edgy/rectilinear and curved/rounded/curvilinear stimuli. Curved shapes and lines have been historically significant in Western philosophical, psychological, and evolutionary perspectives on aesthetics (Hogarth, 1753; Spencer, 1881; Valentine, 1913). These forms are often seen as more harmonious, relaxing, and pleasant than straight or broken lines, aligning more closely with natural forms (Gómez-Puerto et al., 2016). Early observations acknowledged the influence of contour on emotional response (Gordon, 1909), claiming that curves are perceived as more beautiful than straight lines due to their graceful and pliable nature, which contrasts with the harshness sometimes associated with straight lines. Experimental research from the early 20th century related specific lines and configurations to corresponding feelings (Hevner, 1935; Lundholm, 1921; Poffenberger & Barrows, 1924). In these experiments, participants often associated straight or sharp lines with unfavourable “feeling tones”, indicating intense motor expressions (e.g., agitating, hard, furious, and serious). Conversely, curved lines were linked with adjectives conveying relatively more pleasantness and less movement (e.g., gentle, quiet, and lazy). This early link between visual form and affect laid the groundwork for investigating the impact of contour on hedonic evaluation.

Follow-up studies explored the hypothesis that conditions involving curved or rounded shapes are more aesthetically appealing to humans compared to angular or edgy ones. This preference for curvature was validated across various stimulus categories. Those encompass abstract or geometrical shapes and lines (Bertamini et al., 2016; Chuquichambi, Corradi, et al., 2021; Corradi, Belman, et al., 2019; Fantz & Miranda, 1975; Palumbo et al., 2015, 2021;

Poffenberger & Barrows, 1924; Silvia & Barona, 2009), artistic elements like typeface (Kastl & Child, 1968; Velasco et al., 2015) and paintings (Munar et al., 2023; Ruta et al., 2021), as well as everyday objects (Bar & Neta, 2006, 2007; Chuquichambi, Palumbo, et al., 2021; Corradi, Belman, et al., 2019; Gómez-Puerto et al., 2018; Sinico et al., 2021) and consumer products including cars (Carbon, 2010; Leder & Carbon, 2005) and packages (Pombo & Velasco, 2021; Westerman et al., 2012). Stimuli have been typically presented as photographic images (Bar & Neta, 2006, 2007; Westerman et al., 2012), hand-sketched (Bertamini & Sinico, 2019; Chuquichambi, Palumbo, et al., 2021; Leder & Carbon, 2005), or computer-generated displays (Bertamini et al., 2016; Chuquichambi, Palumbo, et al., 2021; Corradi, Belman, et al., 2019; Ruta et al., 2021; Silvia & Barona, 2009).

To assess the psychological responses to angular versus curved stimuli, research has employed diverse outcome measures. For instance, studies exposed participants to images of either curved or edgy stimuli, for which they were required to make a like/dislike forced-choice decision based on their immediate "gut" reaction. Such forced-choice tasks have shown efficacy in finding a preference for curved objects (Bar & Neta, 2006) and abstract shapes (Palumbo & Bertamini, 2016). A large number of studies used rating/visual analogue scales (Belin et al., 2017; Bertamini et al., 2016; Chuquichambi, Palumbo, et al., 2021; Cotter et al., 2017; Kastl & Child, 1968; Leder & Carbon, 2005; Palumbo et al., 2021; Palumbo & Bertamini, 2016; Silvia & Barona, 2009; Sinico et al., 2021; Velasco et al., 2015; Westerman et al., 2012). Rating scales were tagged by terms relating to different constructs but were mainly focused on aesthetic preference, especially in more recent studies. For example, participants rated the images on liking (Bertamini et al., 2016; Palumbo et al., 2021; Palumbo & Bertamini, 2016), attractiveness (Leder & Carbon, 2005; Palumbo & Bertamini, 2016), or pleasantness (Cotter et al., 2017; Silvia & Barona, 2009). Moreover, some studies investigated additional variables such as complexity (Bertamini et al., 2016; Cotter et al., 2017; Leder & Carbon, 2005; Silvia & Barona, 2009), innovativeness (Carbon, 2010; Leder & Carbon, 2005), purchase likelihood (Westerman et al., 2012), and typicality (Leder & Carbon, 2005; Westerman et al., 2012) in an attempt to understand whether they influenced the perception and evaluation of angularity and curvature.

Beyond rating formats, more objective measures have also been employed. Specifically, some studies have used selection procedures that relate to the approach-avoidance construct in their design (Chuquichambi, Palumbo, et al., 2021; Corradi, Belman, et al., 2019; Gómez-Puerto et al., 2018; Munar et al., 2015). In these paradigms, participants are asked to choose one item from a pair shown on the screen, without employing in their instructions terms related to the semantic fields of liking, preferring, or wanting, thereby ensuring that participants are not influenced towards a specific direction. Based on participants' choice, the selected image enlarges on the screen to simulate an approach effect. Investigations also utilised association tasks (Hevner, 1935; Poffenberger & Barrows, 1924; Velasco et al., 2015), as well as the implicit association task (IAT; Palumbo et al., 2015; Velasco et al., 2016) and the stimulus-response compatibility task (SRCT; Bertamini et al., 2016; Palumbo et al., 2015), two paradigms widely used in social psychology research. Additionally, research has examined reaction and/or viewing time (Corradi, Belman, et al., 2019; Cotter et al., 2017; Hopkins et al., 1976; Jadva et al., 2010), and observed postural behaviour (Belin et al., 2017). In terms of neuroimaging studies, one study used fMRI to test the preference for curves in everyday objects and found that the amygdala, a region responsible for fear processing, was significantly more active when perceiving images of sharp-angled everyday objects compared to their curved counterparts (Bar & Neta, 2007). Interestingly, another fMRI study investigated curvature processing in human visual cortical areas, demonstrating that patches of neurons in specific brain regions, including V3, V4, lateral occipitotemporal cortex, and fusiform gyrus, show a preferential response to curvilinear contours (Yue et al., 2020). However, it is still unclear how the activity triggered by this network of neurons influences other neural systems.

It is important to note that the duration of exposure to angular versus curved stimuli varied across research studies, potentially affecting the outcomes. While some studies opted for brief presentation times (e.g., 84 ms in Bar & Neta, 2006; 90 ms in Maezawa et al., 2020, 120 ms in Palumbo & Bertamini, 2016), others allowed participants to respond without time constraints (Leder & Carbon, 2005; Palumbo & Bertamini, 2016; Silvia & Barona, 2009; Westerman et al., 2012). Experiments specifically assessing the impact of various presentation durations demonstrated that individuals exhibited a preference for objects with curved features exclusively during brief exposure periods (Corradi, Rosselló-Mir, et al., 2019; Maezawa et al., 2020; Munar et al., 2015). This preference was not observed when participants were allowed unlimited time to make their selection. Interestingly, concerning meaningless patterns, one study observed that the preference for curves increased under free viewing conditions (Corradi, Rosselló-Mir, et al., 2019), while another found a preference for angular shapes under these conditions (Palumbo & Bertamini, 2016). This suggests that choices made during free viewing may have been influenced by semantic content or a preference for other visual features.

Nonetheless, as mentioned above, several studies have consistently reported the presence of the curvature preference effect under free viewing conditions.

1.2 Angular versus curved everyday environments

In the fields of architecture and interior design, the significance of shapes and forms is paramount. A growing body of empirical research highlights the more positive effects of curved compared to angular designs on human psychological responses. This evidence spans various types of built environments, from outdoor spaces (Hesselgren, 1987; Li et al., 2022; Ruta et al., 2019) to indoor settings (Banaei et al., 2017; Küller, 1980; Madani Nejad, 2007; van Oel & van den Berkhof, 2013; Vartanian et al., 2013, 2019), and even extends to furniture design (Dazkir & Read, 2012). These studies consistently reveal the profound impact of the angular versus curved dichotomy on the perception of human-made environments, touching upon numerous psychological domains.

Research has predominantly utilised explicit rating formats to explore the affective responses to forms in built environments. For example, architectural designs featuring rounded edges have been shown to elicit more pleasure than those with square-edged forms (Küller, 1980). Similarly, a preference for object-orienting (i.e., curved walls) over spatially-orienting characteristics (i.e., squared walls) has been observed across various age groups (Shepley, 1981). In urban outdoor settings, a curved street was evaluated more positively than a straight one on most of the 34 bipolar dimensions used (Hesselgren, 1987). Comparing models of office spaces at a 1/20 scale in three geometric configurations, architects showed equal preference for triangular and circular conditions based on cumulative scores across 26 rating dimensions (Alp, 1993). Conversely, chemists preferred the circular condition the most, with both groups exhibiting the least preference for the rectangular condition. In a card-sorting task, non-architect participants favoured residential interiors more as they gradually shifted from rectilinear to curvilinear, judging them as pleasant, elevating, stress-reducing, friendly, personal, safe, complex, and mysterious (Madani Nejad, 2007). The study found a strong link between curvilinear spaces and perceived femininity, consistent across architects and non-architects. In furniture design, curvilinear forms evoked significantly greater pleasure than rectilinear ones and were associated with higher levels of pleasant-unarousing emotions such as relaxation, peacefulness, and calmness (Dazkir & Read, 2012). Within airport passenger areas, travellers preferred an area with a curvilinear roof and layout over an orthogonal roof and a straight layout (van Oel & van den Berkhof, 2013). Comparing virtual residential rooms with different forms, rooms that elicited lower pleasure and arousal levels were found to feature more linear shapes, whereas those rated higher in pleasure and arousal showed more curved features (Banaei et al., 2017). In the context of building facades, images of four architectural facades (curved, mixed, rectilinear, and sharp-angled) were presented using a projection screen, finding that the curved façade was preferred both in the two-alternative forced-choice and rating tasks (Ruta et al., 2019). A study analysing 200 photographs of interior spaces categorised as rectilinear or curvilinear found that spaces were more likely to be judged as beautiful if they had curvilinear features (Vartanian et al., 2013). However, further research using a subset of the same stimuli has shown mixed results. One study, using a small set of eight images, observed a preference for curvilinear spaces among experts but not non-experts in architecture and design (Vartanian et al., 2019). Interestingly, another study, using a larger set of 80 images, revealed that both quasi-experts in design and individuals with autism spectrum disorder (ASD) showed a preference for spaces with angular features, while neurotypical participants exhibited no significant preference (Palumbo et al., 2020).

Apart from impacting affective measures, the distinction between angular and curved designs has been proposed to influence behavioural responses, specifically in terms of approach-avoidance tendencies (Dazkir & Read, 2012; Vartanian et al., 2019). However, the scarce body of research in this domain has been limited to subjective, self-reported measures, which do not adequately capture actual motor responses. Additionally, the results have been inconsistent. For instance, one study focusing on furniture design reported that participants felt more inclined to approach images featuring curved furniture as opposed to their angular counterparts, as reflected in their ratings (Dazkir & Read, 2012). Conversely, another study observed no significant impact of rectilinear or curvilinear interiors on approach-avoidance self-reported decisions when participants were presented with 200 photographs of interior spaces (Vartanian et al., 2013). A subsequent study, which narrowed the focus to a smaller selection of eight images, revealed a significant preference among non-experts in architecture for entering curvilinear spaces over rectilinear ones, whereas this effect was not present among experts (Vartanian et al., 2019). A more recent study could not find any links between approach-avoidance ratings and the presence of angular versus curved spatial features, both in neurotypical individuals and those with ASD (Palumbo et al., 2020). Interestingly, the quasi-expert group showed a significant self-reported preference for entering spaces characterised by angular features. Thus, it becomes evident that further research is essential to unravel the effects of angularity versus curvature in interior design on human behaviour, particularly through the use of more objective measures that can better inform on any potential motoric tendencies.

Neuroimaging studies exploring the impact of forms in the built environment have been relatively scarce albeit insightful. One pioneering fMRI study examined architectural perception in images of interiors and found that curvilinear spaces, which were more likely to be judged as beautiful than rectilinear ones, activated the mOFC (specified as ACC in the publication), a brain region associated with reward and emotional salience (Vartanian et al., 2013). At the same time, rectilinear spaces did not elicit any activations in the amygdala. Notably, this is in contrast with a previous fMRI study on everyday objects that did find an activation in the amygdala as a response to sharp-angled objects (including furniture), suggesting a fear response to these objects (Bar & Neta, 2007). A subsequent electroencephalography (EEG) study further demonstrated that walking through virtual environments (VEs) depicting residential interiors with varying forms led to increased theta synchronisation in or near the ACC in response to curvature (Banaei et al., 2017). This area of the brain has been previously suggested to play a role in emotional (Etkin et al., 2011), aesthetic, and artistic experiences (Kawabata & Zeki, 2004; Vartanian & Goel, 2004). However, we note that these neuroimaging studies were particularly low in sample size (N = 18 in Vartanian et al., 2013, N = 16 in Bar & Neta, 2007, and N = 15 in Banaei et al., 2017), which may limit statistical power, increase error margins, and reduce the representativeness and generalizability of the findings. Another fMRI study, with a focus on healthcare environment with a relatively larger sample (N = 31), exposed participants to four categories of (unmatched) images featuring curved and sharp designs (i.e., interiors, exteriors, landscapes, objects) alongside control images. The findings indicated increased bilateral amygdala activation associated with sharp compared to curved conditions in the case of landscapes and objects images (Pati et al., 2016). Interestingly, images of hospital interiors and exteriors with curved features also showed higher bilateral amygdala activation. It was concluded that hospital designs may systematically influence fear reactions at the pre-cognitive stages of perception. These insights underscore the need for further neuroimaging research with larger sample sizes to fully understand the implications of angularity and curvature on the human brain in different functional settings.

In terms of stimulus material, research investigating this phenomenon in architectural and interior design settings has predominantly used photos of existing spaces (Palumbo et al., 2020; Vartanian et al., 2013, 2019), computer-generated three-dimensional images in both colour (van Oel & van den Berkhof, 2013) and greyscale (Dazkir & Read, 2012), sketches (Madani Nejad, 2007), and line drawings (Ruta et al., 2019), and even physical models (Alp, 1993). While investigations on everyday objects have managed to present a substantial number of matched stimuli through photographs (e.g., N = 140 in Bar & Neta, 2007) or drawings (e.g., N = 772 in Bertamini & Sinico, 2019, N = 90 in Chuquichambi, Palumbo, et al., 2021), research on built environments faces challenges with the stimuli used. Some studies have relied on a small (e.g., N = 4 in Dazkir & Read, 2012) and potentially unrealistic set of images (i.e., greyscale images or sketches), or a larger collection of photos of real environments categorised into rectilinear and curvilinear (e.g., N = 200 in Vartanian et al., 2013) but introducing many confounding factors. Moreover, studies typically confined stimuli to one image per environment, displaying them exclusively from one perspective. These methodological choices have implications for the generalizability and replicability of the findings. Notably, this area has seen limited experimental exploration beyond traditional image presentations, which contrasts sharply with how humans perceive architectural environments in the real world. Unlike the two-dimensional views often used in research, real-world environments are inherently three-dimensional (Coburn et al., 2017). Furthermore, the influence of human movement on spatial experience underscores a complexity that is not captured by conventional presentation methods (Gramann, 2013; Nasar, 1994). Only few studies employed virtual reality (VR) to create a more immersive three-dimensional experience. VR is known to enable the creation of experimental settings that can replicate real-world scenarios under controlled conditions while providing comparable responses (Kalantari et al., 2021). Yet, to the best of our knowledge, only two studies presented VEs to investigate forms in interior environments. Both studies immersed participants in empty, white virtual rooms where room shape was isolated from other architectural parameters such as colours, materials, and textures (Banaei et al., 2017; Shemesh et al., 2017), and only one of them allowed movement inside the VEs (Banaei et al., 2017). One other study presented rendered virtual spaces (Li et al., 2022), but focused on outdoor transition spaces such as a café and a plaza in a between-subject design. The limited use of immersive technologies such as VR highlights a significant gap in current research, suggesting that future studies should focus on developing experimental designs that more accurately reflect real-world environments.

1.3 The evolutionary perspective

Studies have documented the preference for curved over angular stimuli in different cultures (Gómez-Puerto et al., 2018), in infants and children (Fantz, 1961; Fantz & Miranda, 1975; Hopkins et al., 1976; Jadva et al., 2010), and even in non-human animals (Ebel et al., 2020; Fantz, 1961; Munar et al., 2015; Schneirla, 1966). This cumulative evidence has facilitated a conceivable notion of an evolutionary adaptive behaviour that might be driving this phenomenon.

Research across species, including chicks, primates, and great apes, has consistently shown a natural preference for curved over angular shapes (Ebel et al., 2020; Fantz, 1961; Munar et al., 2015; Schneirla, 1966). Early observations noted that newly hatched chicks, without any prior experience, favoured pecking at round rather than pyramid shapes, circles rather than triangles, and spheres rather than flat disks (Fantz, 1961). This innate ability of chicks to discern and exhibit a clear preference for shapes resembling potential food indicates a perceptual capability without prior learning. Another study presented evidence for the preference for rounded stimuli in infrahuman infants, including chicks (Schneirla, 1966). Similarly, in primate infants, such as chimpanzees, a systematic preference for certain objects was detected based on the duration of staring (Fantz, 1961). This was determined using a "looking chamber", a setup designed to comfortably observe the gaze behaviour of primate infants towards various objects. This method laid the ground for understanding visual preferences in non-human animals before extending these observations to human infants. A more recent study comparing humans and great apes (seven chimpanzees and two gorillas) found that, unlike humans, apes did not show a consistent preference for curvature in brief presentation conditions (Munar et al., 2015). However, when the viewing time was unrestricted, apes significantly preferred images of curved objects compared to their sharp-angled counterparts. This preference was also observed in captive Sumatran orang-utans, who favoured spherical over cuboid physical objects in play (Ebel et al., 2020). These findings highlight a broader biological inclination towards curved shapes, suggesting an evolutionary basis for this preference that transcends species boundaries.

Contrary to beliefs from the 1950s, research spanning several decades has shown that infants and children have sophisticated perceptual abilities, showing prolonged attention to or preference for curved stimuli, encompassing patterns (Fantz & Miranda, 1975), lines (Hopkins et al., 1976; Ruff & Birch, 1974), shapes (Jadva et al., 2010), geons (Amir et al., 2011), and even candies (Munroe et al., 1976). The use of the "looking chamber" enabled to demonstrate preferences for complex-patterned objects in infants (Fantz, 1961), indicating early form perception capabilities. Studies have found a preference for patterns with curves over those with straight lines in infants as young as three months (Ruff & Birch, 1974) and even those under seven days old, as long as the stimuli were not enclosed in a border (Fantz & Miranda, 1975). Using a habituation paradigm, 10-month-old male infants showed a pronounced initial dishabituation response to curvature, suggesting its distinctive attention-recruiting value (Hopkins et al., 1976). Additionally, a study on 4-12 year-old children's preferences for candies shaped like spheres or cubes found that both boys and girls tended to prefer sphere-shaped candies, with girls showing a stronger preference (Munroe et al., 1976). Further research involving the Gestalt principle of good continuation indicated that infants' spontaneous preference for curvature helps them to organise complex visual patterns into coherent forms (Quinn et al., 1997). More recently, a study examining preferences for toys, colours, and shapes across different infant age groups (12, 18, and 24 months) revealed that both girls and boys preferred rounded over angular shapes (Jadva et al., 2010). When 5-month-old infants were shown geons of different shapes, they tended to focus first on shapes that were not singular, which had tapered forms or distinct curved contours, rather than the straight contours of singular geons (Amir et al., 2011). However, unlike adults, infants displayed less interest in the non-singular geons, potentially due to the lengthy (5-second) presentation and their general disinterest in the stimuli. This body of evidence establishes a foundational role of curvature in shaping the perceptual preferences and cognitive development of infants and children from a very early age.

To explore the cross-cultural prevalence of the preference for curved stimuli, studies have investigated the phenomenon in participants with different cultural backgrounds (Dai et al., 2022; Gómez-Puerto et al., 2018; Maezawa et al., 2020). A study involved adults from Spain, Mexico, and Ghana, who engaged in a two-alternative forced choice task (Gómez-Puerto et al., 2018). The results consistently showed a preference for curved compared to sharp-angled objects across all three countries, suggesting a potentially universal aesthetic propensity. However, when non-Western, Asian observers were considered, different patterns of response emerged (Dai et al., 2022; Maezawa et al., 2020). Real objects and meaningless shapes were presented in four experiments testing preference (i.e., likeability and attractiveness) under different presentation times (i.e., 90 ms versus until response) and varied response measures (i.e., like/dislike versus 1–100 rating scale), finding that the preference for curved over sharp-angled objects was situation- and measurement-dependent in Japanese observers (Maezawa et al., 2020). More concretely, a preference for curved objects, and not meaningless patterns, was only detectable when images were briefly presented and preference was measured as a like/dislike choice. A reversed pattern, so a preference for sharp-angled objects and patterns, emerged when images were shown until response and preference was measured as ratings on attractiveness. In another vein, a study on the aesthetic judgment of interior spaces by Chinese participants, focusing on contours, ceiling height, and enclosure, found a preference for curvilinear contours only when the ceiling was low and the space enclosed, based on ratings of pleasantness and beauty for 200 photographs (Dai et al., 2022). While studies with Western samples show a seemingly consistent preference for curvature in both adults and children, recent research indicates varied aesthetic preferences between Western and non-Western populations, suggesting the need for further investigation.

1.4 Why is curvature preferred?

Although a large body of literature generally supports the preference for curved over angular or edgy stimuli, no consensus has been yet reached concerning its explanations (Corradi & Munar, 2019). An extensive historical review of various accounts seeking to explain this phenomenon categorised explanations into appraisal-based and sensorimotor-based (Gómez-Puerto et al., 2016). While some perspectives suggest evolutionary roots for the phenomenon, others propose that the preference for curvature might be acquired (Carbon, 2010).

One view, the “threat hypothesis”, attributes the effects to adaptive behaviours linked with appraisal mechanisms, possibly developed through the avoidance of potentially “threatening” edges (Bar & Neta, 2006, 2007). Indeed, it has been suggested that the human brain may have evolved to quickly detect edginess (e.g., thorns, pointed branches) and avoid it (Włodarczyk et al., 2018). Using a between-subject design, a seminal fMRI study with a small sample ($N = 16$) explored this hypothesis by exposing participants to either the sharp-angled or the curved version of 140 image pairs of matched real objects and meaningless patterns, as well as to 80 control objects (Bar & Neta, 2007). After a brief exposure of 85 ms, participants had to make a like/dislike forced-choice about each image within 1915 ms, based on their “gut” reaction. The percentage of “like” responses was computed for each condition by determining the ratio of “like” responses to the overall number of responses. Results revealed that images of curved objects were liked significantly more than control objects, while images of sharp-angled objects were liked significantly less than control objects. Moreover, images of curved patterns were liked significantly more than those with sharp ones. These results were in line with the neural responses showing a greater activation of the amygdala when perceiving sharp-angled as opposed to curved objects and patterns. More support on the evolutionary perspective is given by the findings outlined in the previous section that have shown the preference for curvature across cultures, in infants and children, as well as in non-human animals.

The view of the "threat hypothesis" was challenged by other researchers, who referred the effects to intrinsic properties of the "appealing" curves (Bertamini et al., 2016; Palumbo et al., 2015). On the one hand, potential evolutionary origins were suggested, however, relating the effects to neoteny—the retention of juvenile traits in adults resulting in salient curved configurations such as rounded face or eyes—which is attractive to both men and women and has undergone sexual selection (Bertamini et al., 2016). On the other hand, curved stimuli is assumed to directly interact with specific activation of sensorimotor mechanisms (Amir et al., 2011; Fantz & Miranda, 1975). This explanation is partly based on the processing fluency theory of aesthetic pleasure (Reber et al., 2004). Fluent processing of objects enhances aesthetic appeal, leading to a preference for curves over angles due to easier processing. Studies in this stream of reasoning demonstrated a "curvature effect" with a series of experiments based on explicit and implicit response paradigms (Bertamini et al., 2016; Palumbo et al., 2015). Among the implicit measures, an adapted version of the SRCT (De Houwer et al., 2001) was utilised in two experiments. In this task, participants moved a manikin towards or away from a stimulus based on the shape of the presented abstract patterns. It was assumed that if curved shapes were considered attractive, that would lead to faster movement towards them. Conversely, if angular shapes were perceived as threatening, as suggested by the "threat hypothesis", they would cause faster movement away from them. Thirty-six participants took part in the first experiment, finding patterns of approach towards curvature but no patterns of avoidance of angularity (Bertamini et al., 2016). In a second experiment with another sample of 36 participants, two types of reaction times (RTs) were analysed: RT1, reflecting the time between stimulus appearance and first key press, and RT3, reflecting the time between stimulus appearance and the manikin reaching edge of screen or shape (Palumbo et al., 2015). Both RTs revealed similar results, confirming the patterns observed in the first experiment. In terms of neuroimaging evidence, data from a study investigating images of interior spaces in 18 participants found no evidence for amygdala activity when responding to images of rectilinear spaces. At the same time, results showed an activation of brain areas previously linked with pleasantness and reward (i.e., mOFC), when perceiving images of curvilinear interiors (Vartanian et al., 2013). Taken together, such evidence suggests that the "threat hypothesis" cannot fully explain the phenomenon of curvature preference, and that curved shapes, per se, could be visually pleasant (Bertamini et al., 2016).

However, other research argues that the preference for curvature, although possibly pre-shaped by evolution, could also be learnt. According to this perspective, it is questionable whether the effect can be demonstrated in all domains and for all times, particularly when considering more complex human-made objects. A so-called "Zeitgeist effect", denoting time-specific worldviews, was proposed to be a confounding factor that modulates the preference, so the predominance of curvature in daily-used products of current modern life might have driven the observed effects (Carbon, 2010). In a set of four experiments, 38–40 participants assessed the curvature and their liking of car designs representing ten 5-year intervals from 1950 to 1999. The curvature of the cars was found to follow a parabolic pattern, with the designs from the 1980s showing the least curvature. The level of appreciation for the cars mirrored this parabolic curve, meaning that cars with curved designs were preferred exclusively during periods when such curved aesthetics were in vogue. The study identified adaptation effects as potential triggers for these shifts in preference. Overall, since the appreciation of curvature evolves over time, it was concluded that any research attempting to discover fixed and universal principles of preference related to curvature is confounded with Zeitgeist influences.

1.5 Interindividual differences in the response to angularity and curvature

The understanding of individual factors influencing the preference for curves remains limited (Cotter et al., 2017). It has been suggested that variables such as expertise in the arts and architecture may influence this phenomenon, although results are yet mixed and inconclusive with respect to abstract shapes as to built environments (Cotter et al., 2017; Palumbo et al., 2020; Silvia & Barona, 2009; Vartanian et al., 2019). When investigating geometric and abstract shapes in two experiments, the first experiment revealed a stronger preference for curvature in novices whereas the second one showed a stronger curvature preference in experts in the arts (Silvia & Barona, 2009). A more recent study showed that artistic expertise led to a greater preference for curvature (Cotter et al., 2017). Similar heterogeneous results were observed with interior environments. Specifically, one study observed that experts in architecture exhibited a stronger preference for curvilinear compared with rectilinear spaces (Vartanian et al., 2019), while another one revealed that quasi-experts in design actually preferred angular over curved spaces (Palumbo et al., 2020). Beyond expertise, factors such as personality traits (Banaei et al., 2020; Cotter et al., 2017) and cognitive styles (Cotter et al.,

2017) have also been explored, albeit less frequently. For instance, participants higher in openness to experience were found to prefer curved shapes more (Cotter et al., 2017). Interestingly, research on virtual indoor environments revealed that individuals with high openness to experience reported lower pleasure levels in spaces with linear geometries, whereas those with low openness to experience reported higher pleasure in spaces featuring curved geometries (Banaei et al., 2020). Further studies have investigated the impact of angularity and curvature on individuals with ASD and neurotypical adults, finding a shared preference for curved abstract shapes and lines across both groups (Palumbo et al., 2020). However, a distinct preference emerged among participants with ASD for angular features in images of interior environments, a contrast not observed in neurotypical participants who didn't have a particular preference. The evidence from abstract shapes contradicts an earlier study in which neurotypical children had a positive perception of a spiral stimulus, while children with ASD responded positively to the stimulus with jagged edges (Belin et al., 2017). Thus, while the influence of various interindividual factors on the preference for curves seem complex and multifaceted, there are clear first indications for the importance of specific factors, yet, demanding further investigation.

Recent research indicates that other factors such as gender and academic qualifications may also influence the curvature preference phenomenon (Palumbo et al., 2021). This study emphasised that the majority of previous research has predominantly focused on female psychology students, which might have biased the observed effects. Conducted with 80 undergraduate students in psychology and 80 in science, the findings revealed a stronger preference for smooth curvature among female psychology students. In fact, earlier research had identified sex differences, linking contour preference in candies to symbolic representations of the human body morphology (Munroe et al., 1976). Specifically, 175 children were presented with a choice between two types of wrapped candies: one spherical and the other cube-shaped. The findings revealed a preference for the spherical candy among both participant groups. Notably, a significant difference was observed in the choices of girls and boys, with 83% of girls opting for the spherical candy compared to 57% of boys. The authors concluded that selecting an edible object is more about a person's body concept than it is about a particular attraction or item choice. Given the age group of the study participants, ranging from 4 to 12 years old, one might argue that the findings more likely reflect "projected body ideals". This is because the body shapes of both boys and girls are generally considered to be alike until they reach adolescence. Subsequent research, however, has not identified any sex- or gender-based differences in preferences related to the shape of objects. For instance, in a more recent study investigating toys, colours, and shapes with 120 infants aged 12, 18, and 24 months, infants of both sexes spent more time looking at circles compared to squares, and rounded triangles over regular triangles (Jadva et al., 2010). The authors concluded that the similarity in shape preferences among infants of different sexes indicates that any differences in these preferences that emerge later might be attributed to social or cognitive influences related to gender, rather than innate biological factors. This mixed evidence suggests that while initial observations may point towards certain trends, the influence of socialisation and cognitive development in shaping preferences requires deeper investigation. Importantly, the exploration of sex or gender differences in the preference for curves within built environments remains an underinvestigated area, warranting further research to fully understand its implications.

2. Research questions

As cities grow and mental health concerns become increasingly prominent (Krabbendam et al., 2021; Peen et al., 2010), the significance of the built environment on mental health and well-being has emerged as a critical area of study. This exploration is especially pertinent as urban residents typically spend around 90% of their time indoors (Klepeis et al., 2001). Indeed, a growing body of evidence suggests that the architecture and design of our indoor spaces have a profound influence on our psychological states (Coburn et al., 2020; Evans, 2003; Gifford, 2002). Notably, it has been proposed that humans exhibit a preference for curved over angular designs, which are believed to induce higher positive emotions (Alp, 1993; Banaei et al., 2017; Dazkir & Read, 2012; Madani Nejad, 2007; Shepley, 1981; van Oel & van den Berkhof, 2013; Vartanian et al., 2013, 2019). Generally, the underlying reasons for this preference are still debated (Corradi & Munar, 2019; Gómez-Puerto et al., 2016), with explanations ranging from the perceived threat posed by sharp angles (Bar & Neta, 2007) to the inherent appeal of curves (Bertamini et al., 2016; Palumbo et al., 2015; Vartanian et al., 2013). Yet, understanding the psychological impact of architectural elements is essential for designing environments that promote mental well-being and enhance the quality of life for urban dwellers.

However, a thorough review of existing literature indicates that most studies comparing environments with angular versus curved features have relied on methodologies that utilise unmatched (Vartanian et al., 2013, 2019) or unrealistic/schematic stimuli (Dazkir & Read, 2012; Madani Nejad, 2007), often presenting environments as images. While recent studies have utilised VR to examine forms in indoor environments, they have not exclusively compared angular with curved designs. Instead, these studies have generally focused on form as an isolated variable and showcased empty, white VEs with various shapes along their boundaries (Shemesh et al., 2017; Banaei et al., 2017). These methodological constraints raise questions about the ecological validity of the reported results and their applicability to real-world settings. To the best of our knowledge, only one VR study has explored close-to-reality, rendered virtual settings (Li et al., 2022), focusing on transitional outdoor spaces in curved and linear conditions. This gap in research underscores the need for more comprehensive studies that employ realistic, immersive environments to accurately assess the psychological and physiological impacts of environments with angular versus curved features on human responses.

While earlier studies on environments with angular versus curved designs aimed to capture a broader spectrum of affective responses (Alp, 1993; Hesselgren, 1987; Madani Nejad, 2007), recent research has mainly focused on aesthetic preference measures such as liking (Palumbo et al., 2020), pleasantness/pleasure (Banaei et al., 2017; Vartanian et al., 2013), and beauty (Vartanian et al., 2013, 2019), with some investigations also examining arousal responses (Banaei et al., 2017; Dazkir & Read, 2012). It is noteworthy, however, that the bulk of evidence regarding the effect of angular versus curved stimuli stems from empirical aesthetics, a field primarily concerned with hedonic tones. This stands as a general limitation of the nascent research streams delving into the impact of the built environment, which primarily focus on aesthetics and neglect other facets of the cognitive-emotional dimension of architecture (Higuera-Trujillo et al., 2021). In addition to aesthetic preference and hedonic tones, environmental psychology has shown that the built environment plays a crucial role in regulating emotions, influencing mood (e.g., stress reduction; e.g., Ulrich et al., 1991), and consequently impacting human psychology and physiology. Thus, there is a need for a more holistic approach to fully understand the multifaceted impact of the built environment on human well-being.

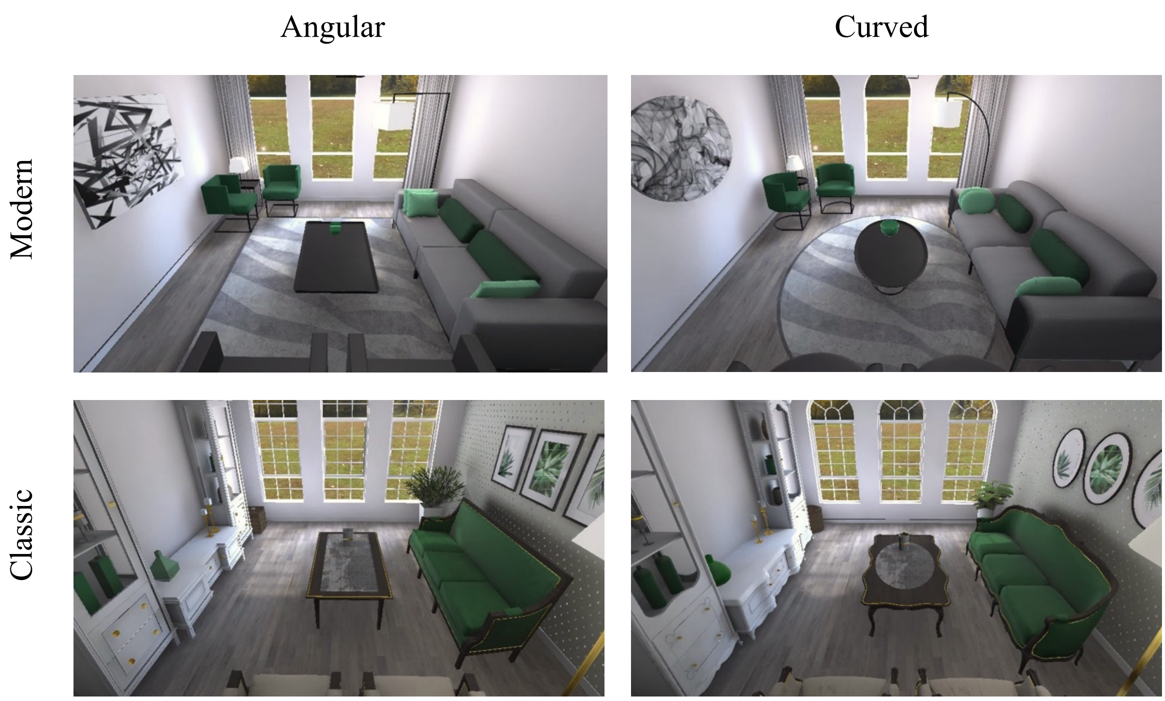

Figure 1. Virtual environments created for *Study I*. Images were generated from the Unity project for illustration purposes, with a perspective that does not represent a human eye view, but shows maximum coverage of the rooms.

To address these gaps, *Paper I* harnessed the potential of VR to examine the psychological responses to angular versus curved designs in indoor spaces, focusing specifically on residential environments. This setting is especially relevant as individuals typically spend about two-thirds of their daily time at home (Klepeis et al., 2001), including an average of 15.7 h for the German population (Brasche & Bischof, 2005). These figures have likely increased since the onset of the COVID-19 pandemic and the subsequent adoption of flexible work arrangements (i.e., home office). Therefore, we undertook an extensive investigation of the curvature preference phenomenon within three-dimensional VEs representing living spaces that were both well-matched and photo-realistic (Figure 1), exploring their effects on a broad spectrum of psychological domains. Specifically, with a sample size of 42 participants, *Paper I* sought to explore the following research question:

1. How does exposure to virtual interior environments featuring angular versus curved designs in a close-to-reality experience of space influence affective and spatial experience, momentary affect, cognitive performance, and perceived restorativeness?

Contrary to expectations, we observed no positive effects of curvature in *Paper I* on any of the 33 outcome variables measured. Given that the majority of the evidence on the effects of angular versus curved designs stems from studies that explored static image stimuli, we opted to test our environments in an online study, using the typical presentation paradigm. This approach aimed to determine whether presentation mode may influence the results. Recognising that research has yet to thoroughly investigate fully matched, yet realistic stimuli, we generated 20 images from our VEs ensuring insignificant differences in terms of low-level features such as edge density, hue, saturation, brightness, entropy (Figure 2). This step was crucial as studies have shown that low-level features affect how environments are perceived and evaluated (Berman et al., 2014; Kardan et al., 2015), with a noted effect of, for example, brightness on participants' preference responses (Beute & de Kort, 2013). Thus, with a sample size of 198 participants, *Paper II* attempted to answer the following research question in an online study:

2. How do well-matched images of photo-realistic interior environments featuring angular versus curved designs influence explicit affective responses, such as aesthetic preference and stress response?

In addition to exploring explicit evaluations, our interest also encompassed the investigation of implicit responses related to behavioural outcomes, specifically approach-avoidance tendencies. Notably, prior studies have proposed that individuals exhibit an inclination to approach environments with curved as opposed to angular features (Dazkir & Read, 2012; Vartanian et al., 2019). However, not only the findings in existing literature have shown inconsistencies (Palumbo et al., 2020; Vartanian et al., 2013), but these behavioural tendencies have only been assessed through explicit evaluations, such as self-reports. While explicit measures offer valuable insights and have the ability to capture conscious personal experiences and perceptions, they are susceptible to biases such as social desirability or other expectancy biases, including experimenter bias. Therefore, *Paper III* introduced an implicit testing strategy to explore the following research question in an online study, with an initial sample of 217 participants:

3. How do well-matched images of photo-realistic interior environments featuring angular versus curved designs influence implicit behavioural responses related to approach-avoidance behaviour?

Figure 2. Examples of the stimuli used in *Papers II* and *III* showing the same view according to the design factors contour (angular vs. curved) and style (modern vs. classic).

Besides the research questions outlined above, and considering the lack of consensus regarding the origins of the curvature preference phenomenon (Corradi & Munar, 2019; Gómez-Puerto et al., 2016), we aimed to explore whether the observed effects stem from a specific negative response to angular features (Bar & Neta, 2007) or rather a positive effect of curved ones

(Bertamini et al., 2016; Vartanian et al., 2013). Hence, we sought to answer the following research question:

4. Are the observed effects of angularity versus curvature in interior environments attributable to a positive effect of curvature (e.g., approach behaviour) or a negative effect of angularity (e.g., avoidance)?

Above and beyond investigating the distinct main effects of angular versus curved interior environments on affect, cognition, and behaviour, we also explored interaction effects. Firstly, we examined the interaction with style as another main aspect of architecture and interior design (Carbon, 2010). Secondly, given the previously reported evidence regarding sex- and/or gender-related differences in the evaluation of contours in edible objects and abstract shapes (Munroe et al., 1976; Palumbo et al., 2021), we assessed the interaction with participant-reported sex as a person-specific aspect. To note that we are using the term "sex" and not "gender" since we asked our participants to report on their biological sex. Therefore, we aimed to address the following research question:

5. How do other contextual (i.e., style) and person-specific (i.e., participant sex) factors influence the observed effects of angular versus curved interiors?

The following section provides an overview of three papers (see Appendix) that aimed to investigate the effects of short-term exposure to interiors featuring angular versus curved designs on affect, behaviour, and cognition from several perspectives. In *Paper I* (Tawil et al., 2021), we developed a photo-realistic VR paradigm to systematically assess the psychological effects of angularity versus curvature beyond mere preference. Contrary to expectations, our findings revealed no significant positive effects of curvature on 33 outcome variables measured. We opted for the typical presentation paradigm in *Paper II* (Tawil et al., 2022), so we presented images of the same stimulus set after controlling for insignificant differences in terms of low-level image features. Interestingly, we observed a significant effect of contour on self-reported aesthetic preference and stress ratings. Specifically, images of curved interiors scored higher on beauty, liking, restfulness, and lower and stressfulness. Notably, we also found interaction effects with interior design style and participant-reported sex in the aesthetic response: the preference effect was only observed for the modern style and in women. We tested this phenomenon implicitly in *Paper III* (Tawil et al., 2024), using a battery of RT paradigms. This approach confirmed effects of contours on approach-avoidance tendencies in two out of the four administered tasks. In particular, we detected semantic biases to associate curvature with approach and angularity with avoidance. Moreover, we observed biases in motoric representations, attributable to a faster approach and slower avoidance of curvature, rather than a specific response to angularity.

3. Overview of papers

3.1 Paper I

Tawil, N., Sztuka, I. M., Pohlmann, K., Sudimac, S., & Kühn, S. (2021). The living space: Psychological well-being and mental health in response to interiors presented in virtual reality. *International Journal of Environmental Research and Public Health*, *18*(23), Article 12510. https://doi.org/10.3390/ijerph182312510

Objective: In Paper I, we used VR to systematically test the effects of exposure to photo-realistic indoor environments with angular versus curved features on affective and spatial experience, momentary affect, cognitive performance, and perceived restorativeness.

Theoretical background: The influence of architecture and design on mental health and psychological well-being is currently receiving considerable attention. This focus is driven by the substantial amount of time individuals spend within indoor spaces (Klepeis et al., 2001). Studies have explored the psychological reactions to interior design elements, such as angular versus curved designs, and shown that these features can impact responses. Findings indicate that curved interiors, as opposed to angular ones, are generally regarded as more aesthetically pleasing and evoke more positive emotional responses (Dazkir & Read, 2012; Madani Nejad, 2007; van Oel & van den Berkhof, 2013; Vartanian et al., 2013, 2019). However, the majority of these findings are based on the use of two-dimensional images to represent three-dimensional real-life environments, thus overlooking the role of human movement in spatial experiences (Gramann, 2013; Nasar, 1994). To the best of our knowledge, only two studies have tested forms in virtual indoor environments, presenting white VEs differing in the shape of their bounding walls and ceilings (Banaei et al., 2017; Shemesh et al., 2017), without including furniture. To address these gaps, we conducted a VR study to systematically examine the effects of photo-realistic environments with angular versus curved features, in real human scale, on affect, cognition, and behaviour.

Main findings: The study found no evidence for a preference for, or positive effects of, curved interior designs on a multitude of psychological domains, including affective and spatial experience, momentary affect, cognitive performance, and perceived restorativeness. Out of the 33 assessed outcome variables, and after correcting for false discoveries, only two showed differences in favour of angular rooms, which were rated as more novel and ordered. In particular, we were surprised that differences in both “pleasantness” and “beauty” scores were not statistically significant. Additional analysis using the Bayesian framework supported the findings yielded by the frequentist approach. These results challenge the hypothesis of a preference for curvature in interior design, suggesting that the psychological response to forms in a close-to-reality three-dimensional setting is more complex than in two-dimensional static stimuli.

3.2 Paper II

Tawil, N., Ascone, L., & Kühn, S. (2022). The contour effect: Differences in the aesthetic preference and stress response to photo-realistic living environments. *Frontiers in Psychology, 13*, Article 933344. https://doi.org/10.3389/fpsyg.2022.933344

Objective: Given the null results observed in *Paper I*, *Paper II* adopted the typical presentation paradigm and aimed to test the effects of exposure to environments with angular versus curved features on explicit responses, in particular self-reported aesthetic preference and stress, using images depicting well-matched, photo-realistic living environments.

Theoretical background: In the past two decades, the exploration of contours and forms has seen renewed interest, revealing apparent evidence for a positive effect of curved versus angular stimuli (Bar & Neta, 2007; Palumbo & Bertamini, 2016; Vartanian et al., 2013). While this phenomenon seems to be consistent in studies involving abstract shapes and objects, there is a variability in the results observed in studies examining architecture and interior design (Palumbo et al., 2020; Vartanian et al., 2013, 2019). For instance, our attempt to replicate these effects in a VR study was unsuccessful, as seen in the findings of *Paper I*. However, we note that most of the available evidence for this phenomenon relates to studies that used static architectural and interior design image stimuli that were either not well-matched (i.e., involving a number of confounding variables), or not truly realistic (e.g., greyscale, line drawings). *Paper II* further explores the effects of angular versus curved interiors on self-reported aesthetic preference and stress response, using the typical presentation paradigm, i.e., static image stimuli. After controlling for insignificant differences in terms of low-level image features, the online study presented 20 stimuli generated from the VEs tested in *Paper I*, exclusively manipulated in terms of contours (angular versus curved) and style (modern versus classic). In addition to our primary investigation into angularity and curvature, we explored the potential interactions effects with style and participants' self-reported sex.

Findings: Our research revealed significant effects of contour on subjective aesthetic preferences and stress responses. In particular, images featuring curved interiors scored higher on the liking and beauty scales, whereas images showing angular interiors scored lower on restfulness and higher on stressfulness. Regarding interactions with style, curvature was aesthetically preferred over angularity only within images depicting modern interiors, however, effects on stress ratings remained significant irrespective of the interior design style.

Furthermore, we observed sex differences in aesthetic but not in stress evaluations, with the preference for curves only found in participants who reported their biological sex as female. The impact of contour on aesthetic preference appears to be influenced by contextual (i.e., style) and person-specific (i.e., participants' sex) factors. In contrast, the consistent effects on stress responses, which are particularly relevant for designs aimed at promoting mental health, suggest a more general characteristic of contours. The results indicate that the influence of contours in images of indoor environments extends beyond conscious aesthetic evaluations potentially shaped by experience and cognitive processes, encompassing psychological and physiological responses more broadly.

3.3 Paper III

Tawil, N., Elias, J., Ascone, L., & Kühn, S. (2024). The curvature effect: Approach-avoidance tendencies in response to interior design stimuli. *Journal of Environmental Psychology, 93*, Article 102197. https://doi.org/10.1016/j.jenvp.2023.102197

Objective: *Paper III* aimed to examine the preference for curves in images of indoor environments more implicitly, using a battery of RT paradigms that particularly focus on approach-avoidance behaviour.

Theoretical background: Prior studies proposed that contours and forms of the built environment can evoke emotional (e.g., preference) and behavioural (e.g., approach-avoidance) responses in human beings. Although there is no consensus yet regarding the source of the effect (i.e., an approach towards curvature or an avoidance of angularity), previous research has found that curved interior designs are not only aesthetically preferred (Dazkir & Read, 2012; Madani Nejad, 2007; van Oel & van den Berkhof, 2013; Vartanian et al., 2013, 2019) but also elicit a self-reported approach response (Dazkir & Read, 2012; Vartanian et al., 2019). However, results are inconclusive (Vartanian et al., 2013; Palumbo et al., 2020), and, to date, the evaluation of these approach-avoidance tendencies has primarily been conducted through explicit assessments such as self-reports. Using a battery of RT paradigms, *Paper III* aimed to investigate approach-avoidance tendencies in response to images presenting angular versus curved interior designs, specifically intending to capture attentional (dot probe task [DPT]), motoric (approach-avoidance task [AAT]), as well as associative-semantic (implicit association task [IAT]) and -motoric (stimulus-response compatibility task [SRCT]) biases.

Findings: The online study observed a significant influence of angularity versus curvature on approach-avoidance tendencies in two out of the four applied RT paradigms. The outcomes revealed associative biases in relation to approach-avoidance words (IAT) and movements (SRCT), but not in attentional (DPT) nor motoric biases (AAT). These findings were observed consistently across both RTs and error rates as outcome measures, as well as confirmed through sensitivity analysis. Specifically, the IAT highlighted semantic biases to associate curvature with approach and angularity with avoidance, demonstrating that these concepts were closely connected in participants' mental representations. Additionally, the SRCT confirmed biases in motoric representations. Although angularity was more readily avoided compared with curvature, the observed effects were attributable to within-curvature differences (faster approach and slower avoidance) rather than a specific response to angularity (similarly approached and avoided). These behavioural objective measures, which are less likely to be influenced by conscious evaluations in comparison with self-reports, support the notion that curved interior designs have a positive and pleasant effect rather than the fear responses evoked by angularity. The findings suggest the existence of (partially) automatic responses to curvature in interior design settings.

4. General discussion

Building on a well-documented general preference for curved over angular stimuli, this dissertation investigated the short-term effects of exposure to indoor environments with angular versus curved features on affective, cognitive, and behavioural responses. This question was approached through a series of three papers. *Paper I* compared the psychological responses to photo-realistic angular versus curved virtual interiors, surprisingly finding no positive effects of curvature on affective and spatial experience, momentary affect, cognitive performance, and perceived restorativeness. Using the typical presentation paradigm (i.e., images) in an online study, *Paper II* demonstrated that images of curved compared to angular interiors were positively evaluated in terms of explicit aesthetic preference and stress ratings. Testing this phenomenon using implicit measures, *Paper III* examined the effects on approach-avoidance behaviour finding evidence for links with semantic and motoric associations. Specifically, curvature was associated with approach and angularity with avoidance. Furthermore, participants approached curvature faster than they avoided it and avoided it slower than angularity, while they approached and avoided angularity equally.

In the subsequent sections, I will offer a detailed overview of the main findings of this dissertation. Initially, I will examine how the outcomes of this thesis respond to the research questions posed and consider their connection to different accounts regarding the source of the effect. Next, I will discuss the main limitations of the presented studies and propose potential directions for future research. Finally, I will delve into the possible implications of the findings detailed in this thesis for architecture and interior design.

4.1 Discussion of research questions

This dissertation aimed to examine the short-term effects of well-matched angular versus curved interior environments on affect, cognition, and behaviour, employing both virtual reality and images as presentation modes, with a specific focus on the research questions presented in Chapter 2.

4.1.1 Differences between angular and curved designs in VEs

Previous research suggests that interior environments and furniture with curved features are aesthetically preferred compared to those with angular ones and induce more positive emotions (Dazkir & Read, 2012; Madani Nejad, 2007; van Oel & van den Berkhof, 2013; Vartanian et al., 2013). However, most of the evidence stems from studies that used image stimuli and the effects in realistic, three-dimensional settings remain largely unexplored. In *Paper I*, we developed a novel VR paradigm to systematically explore the psychological effects of angular versus curved features in indoor environments using a variety of outcome measures. Beyond the previous focus on aesthetic preference, we additionally examined variables related to affective and spatial experience, momentary affect, cognitive performance, and perceived restorativeness. We adopted a free exploration paradigm, i.e., participants were unrestricted in moving in our VEs, with the purpose of simulating a close-to-reality spatial exploration. To further enhance ecological validity, we showcased immersive environments of high quality and detail, developed through the use of high-definition photo-realistic instant renderings and post-processing techniques.

Surprisingly, none of our 33 measured outcome variables showed significant positive effects of curvature, despite the study's relatively large sample size (N = 42). This was confirmed using both frequentist and Bayesian approaches. Indeed, the only differences observed between angular and curved conditions showed higher scores for angular conditions in terms of "novelty" and "order" evaluations. These results contrast with previous experimental studies that showed more positive reactions to curved as opposed to angular interiors in terms of pleasantness (Dazkir & Read, 2012), beauty (Vartanian et al., 2013, 2019), and stress reduction (Madani Nejad, 2007). In particular, the differences in "pleasantness" and "beauty" ratings were statistically insignificant, with rooms featuring curvature receiving descriptively higher ratings for pleasantness, albeit no evidence supporting this direction was found when taking a Bayesian approach. Similarly, no differences were observed in arousal dimensions or momentary affect, with low scores on negative affect and above-average scores on positive dimensions in both conditions. The study also found no differences in perceived restorativeness or cognitive performance, with poor evidence for the alternative hypothesis.

This absence of expected results in *Paper I* may be attributed to several factors stemming from methodological discrepancies with prior research. Firstly, the extended viewing time of 3 minutes in our study differs from some of the past ones that focused on immediate reactions through brief stimulus presentation (e.g., 84 ms in Bar & Neta, 2007; 3000 ms in Vartanian et al., 2013) or instructed participants to respond without thinking (Dazkir & Read, 2012). In fact, prior findings have indicated that while the preference for curved over angular stimuli seems to be robust under short viewing conditions, it diminishes with prolonged exposure. This trend was noted with both real objects (Corradi, Rosselló-Mir, et al., 2019; Maezawa et al., 2020) and abstract shapes (Palumbo & Bertamini, 2016), suggesting a potential influence of semantic content on shaping preferences. Furthermore, when comparing studies that used (subsets of) the same images of interiors, brief presentation durations resulted in curvilinear spaces being rated as more beautiful than rectilinear ones (Vartanian et al., 2013). However, when allowing participants to view the stimuli until they were ready to respond, a reversed pattern was observed, with images of rectilinear interiors being favoured by diverse participant groups, including those with ASD and quasi-experts in design, though no clear preference emerged among neurotypical adults (Palumbo et al., 2020). Secondly, our study employed a different evaluation method, using a psychometric 11-point scale that accommodates undecided responses, in contrast to the binary choice scales used in some of the previous studies (Bar & Neta, 2006; Vartanian et al., 2013, 2019), which may have skewed preference responses. Thirdly, the demographic composition of our sample was more diverse, recruited from a broader range of sources than the predominantly female psychology student cohorts of earlier studies (Palumbo et al., 2021), enhancing the generalizability of our findings.

To sum up, *Paper I* represents a significant advancement in the study of forms in indoor architectural settings by presenting, for the first time, photo-realistic virtual environments that differ only in the presence of angular or curved features. Despite the high level of control and the immediate collection of responses after participants freely explored these virtual spaces, no significant positive effects of curvature were found across a broad spectrum of psychological domains. This outcome challenges the established preference for curved over angular stimuli observed in abstract shapes and objects, suggesting a more complex relationship in realistic three-dimensional architectural contexts. In fact, a recent meta-analysis highlighted that the preference for curvature was more pronounced in real and imaginary objects than in spatial designs and symbols (Chuquichambi et al., 2022). The study attributed this discrepancy to potential mere exposure effect (Zajonc, 1968), where individuals, more accustomed to encountering and evaluating everyday curved and angular objects, exhibit a higher level of processing fluency for these objects compared to spatial settings. The findings of *Paper I* suggest that the psychological impact of indoor design in close-to-reality settings compared to images may not be reduced to simple effects of curvature and angularity alone. Instead, it may encompass more complex layers that influence space perception on a more personal and contextual basis. These insights provide a more accurate reflection of how people respond to angular versus curved interior designs in three-dimensional experimental settings and highlight the need for further research to unravel the intricate ways in which architectural design influences human responses.

4.1.2 Effects of images of angular versus curved interiors on explicit responses

Previous research has repeatedly demonstrated that when people are shown images depicting angular and curved stimuli, they exhibit a tendency to prefer curved ones. This applies to abstract shapes, everyday objects, and interior design and architectural settings. However, concerning the latter, research has mainly used images representing unmatched (Vartanian et al., 2013, 2019) or unrealistic stimuli (Dazkir & Read, 2012; Madani Nejad, 2007), limiting the generalizability of the observed effects. Given the unexpected null results from *Paper I*, observed in a close-to-reality virtual experience of space, *Paper II* generally sought to investigate whether the mode of presentation may influence the explicit affective responses to angular versus curved interiors. Therefore, we adopted the typical presentation paradigm and tested 20 images generated from the same virtual rooms used in *Paper I*, after ensuring insignificant differences in terms of low-level image features, such as edge density, hue, saturation, brightness, and entropy (Berman et al., 2014; Kardan et al., 2015).

Interestingly, consistent with our hypothesis, we observed a significant effect of contours on explicit affective responses when presenting images representing indoor environments with angular versus curved features. In terms of aesthetic preference, images depicting curved interiors received higher scores on the beauty and liking rating scales when compared with those showing angular ones, with small effect sizes. This finding aligns with prior research that has shown a preference for curvature in interior design (Banaei et al., 2017; Dazkir & Read, 2012; Madani Nejad, 2007; van Oel & van den Berkhof, 2013; Vartanian et al., 2013). In terms of stress responses, participants found images of curved interiors to be more restful and less stressful than those of angular ones, with moderate effect sizes. These effects are in agreement with the previously reported relaxing effect of curvature (Dazkir & Read, 2012; Madani Nejad, 2007). However, it is also possible to interpret these results as indicating an unpleasant or stress-inducing influence of angularity, given that the study's design does not allow us to determine the exact source of the effect (i.e., a positive effect of curves, negative effect of angles, or both).

As mentioned above, the study's findings reveal that the distinction between angular and curved interiors significantly influences aesthetic preference ratings. However, the factor "contour" only explained a small percentage of variance. This suggests that aesthetic responses are likely shaped by a broader array of factors. A recent meta-analysis explored the consistency of the preference for curves, identifying presentation time, stimulus type, expertise, and task as moderators (Chuquichambi et al., 2022). Notably, when spatial design stimuli are involved, the preference for curves manifests in small to non-significant effects, compared to meaningless shapes and objects. This discrepancy hints at the involvement of more complex processes, potentially swayed by factors such as familiarity, affordances, or individual differences. Indeed, the idiosyncrasies of preferences have been stressed in previous research, highlighting a stronger shared taste for natural aesthetic domains when compared to artifacts of human culture (Vessel et al., 2018). Generally, both objective and subjective factors were proposed to play a role in aesthetic evaluations (Chamberlain, 2022). In fact, our exploration of interior design style and participants' self-reported sex yielded a significant interaction with both factors. It seems that the preference for curves was only present in response to the modern and not the classic style. Moreover, ratings of the male subgroup were comparable with respect to angular and curved conditions, and the aesthetic preference for curves was only present in the female subgroup. This indicates that the aesthetic preference for curves was dependent on these two factors (i.e., style and participant sex). We discuss these interactions in more depth in section 4.1.5.

Unlike the findings from aesthetic preference, the impact of contours on stress ratings demonstrated more consistent and robust effects, unaffected by room interior design style or participant sex. Instead, the factor "contour" accounted for a larger share of variance (8% for restfulness and 12% for stressfulness as opposed to 1–2% in the case of aesthetic response). Despite a significant interaction between contour and style, images of curved interior designs consistently scored higher on restfulness and lower on stressfulness, regardless of whether the design style was modern or classic. These findings might relate to the biophilia hypothesis (Wilson, 1984), which posits that humans have an innate affinity to connect with nature, and the deriving design frameworks suggesting that curvature, being more prevalent in nature, is a key element of biophilic design (Kellert et al., 2011; Salingaros, 2015). The principle of biophilic design states that incorporating nature-like elements into the design of the built environment not only enhances aesthetic appeal, but also contributes to stress reduction in humans (Salingaros, 2019; Yin et al., 2020). At first glance, our findings seem to validate the biophilic benefits of incorporating curves into design. However, it is essential to approach these conclusions with caution. The observed effects may not solely be a direct positive response to curved shapes but could also reflect a negative reaction to angular ones, as suggested by the "threat hypothesis" (Bar & Neta, 2006). Additionally, the study did not explicitly examine the perceived naturalness of curves, indicating a potential avenue for further research in this domain.

In sum, using images, *Paper II* revealed an influence of angular versus curved designs in indoor built environments on aesthetic preference and stress ratings. Specifically, it found that individuals aesthetically preferred curvature, albeit this preference depended on style (specifically, modern style) and participant sex (noted only in women). Conversely, they consistently rated curvature as less stressful and more restful, regardless of style or sex, suggesting a possibly adaptive response to potentially "biophilic" curves. This research, conducted with fully-controlled photo-realistic images for the first time, suggests that the effects of angularity and curvature in indoor environments may be more generalizable with respect to psychological and physiological responses than aesthetic judgments, which might be informed by person-specific differences. Future research should focus on these aspects to inform designs aimed at mental health promotion. Finally, the significant outcomes seen when the same settings are presented using conventional methods (i.e., as images rather than through VR immersion) bring to light the need to explore how presentation techniques and immersion levels affect aesthetic evaluations, stress responses, and other reactions to spatial design. This is clearly an area that warrants deeper investigation.

4.1.3 Effects of images of angular versus curved interiors on implicit responses

It has been proposed that curved versus angular stimuli not only influence how environments are aesthetically evaluated, but also affect approach-avoidance decisions (Bertamini et al., 2016; Palumbo et al., 2015). This phenomenon has been attributed to either automatic appraisals or sensorimotor system responses (Corradi & Munar, 2019; Gómez-Puerto et al., 2016), with explanations ranging from an avoidance of angles (Bar & Neta, 2006, 2007) to an inherent appeal of curves (Bertamini et al., 2016; Palumbo et al., 2015). In the context of architecture and interior design, research has found that curved features may elicit a desire to approach rather than avoid indoor environments (Vartanian et al., 2019) and furniture (Dazkir & Read, 2012). However, such response tendencies have only been tested using explicit rating formats, with a noted heterogeneity in the reported effects (Palumbo et al., 2020; Vartanian et al., 2013), and the automatic behavioural responses to angular versus curved interiors remain largely understudied. We adopted an implicit testing strategy to investigate the preference for curves in well-matched, photo-realistic interior environments, with a particular focus on approach-avoidance tendencies. To that end, we utilised a battery of implicit tasks based on RT that can detect associations between mental representations and action/response tendencies. The test battery included the DPT (MacLeod et al., 2007), the AAT in stimulus-irrelevant format (Wiers et al., 2011), the IAT (Greenwald et al., 1998), and the SRCT (De Houwer et al., 2001). These tasks were meant to capture attentional (DPT), motoric (AAT), as well as associative-semantic (IAT) and -motoric (SRCT) biases. Similar tests were previously used in a study investigating environmental (built versus natural landscape) stimuli (DPT, AAT, IAT), identifying attentional and approach biases towards nature (Schiebel et al., 2022). Moreover, some of the tasks (IAT, SRCT) were also used in studies focusing on angular versus curved abstract shapes (Bertamini et al., 2016; Palumbo et al., 2015). To the best of our knowledge, implicit RT paradigms have not yet been used to assess responses to angular versus curved features in the built environments.

We used the DPT as a marker of potentially biased attention, building on the "threat hypothesis", which posits that humans have evolved to favour curvature due to a need to quickly detect and avoid edginess (Bar & Neta, 2006, 2007). We expected that if participants would find images depicting angular interior designs "threatening", they would respond faster to probes presented at the same location after them. However, the results showed no difference in RTs to probes presented on the side of images showing angular nor curved interiors, indicating that participants' attention was not biased by the different shapes shown in the stimuli. Despite previous research demonstrating the salience of angles (Bertamini et al., 2013; Cole et al., 2007), it might be argued that curves are processed more fluently and would lead to faster responses (Bertamini et al., 2019; Chuquichambi et al., 2020). Yet, our findings suggest similar RTs in response to both angular and curved conditions. Notably, several factors might explain the null results. Firstly, research has demonstrated faster processing of scene gist over individual objects (Hochstein & Ahissar, 2002; Oliva & Torralba, 2006). It is plausible that threat perception of angles in indoor environments has diminished due to learning and exposure effects (Vartanian et al., 2013). Secondly, it might be that differences between angular and curved conditions in our stimulus set were too subtle for detection considering the smaller size of the presented images in the DPT compared to the other administered tasks. Future research may want to explore the impact of more pronounced angularity or curvature on participant responses.

The study explored automatic behavioural biases toward angularity versus curvature using an AAT with implicit, stimulus-irrelevant instructions. Based on image orientation rather than contours, participants had to pull the stimulus towards themselves (approach) or push it away (avoid). Here, we also expected angular and curved features to be relevant even if participants were not instructed to explicitly attend to them. Contrary to expectations, no motoric biases towards either angular nor curved designs were observed. This finding aligns with existing literature that reports non-significant effects in AAT when instructions are implicit (Phaf et al., 2014). In fact, research on abstract shapes indicates that in a similar task such as the affective stimulus-response compatibility task (aSRC; Eder et al., 2013), participants' responses were only influenced when they were explicitly instructed to focus on certain features such as contour or symmetry (Chuquichambi, Corradi, et al., 2021). This suggests that making stimulus features task-relevant can enhance detection of compatibility effects by minimising the processing of irrelevant information (Fujita et al., 2007; Gollwitzer, 2012). Future research could investigate the impact of more pronounced shapes, or use explicit instructions to examine whether this would yield significant effects of angularity and/or curvature.

To explore how individuals semantically associate the concepts of approach and avoidance with curved and angular features in images of indoor environments, the study utilised an IAT. In this task, participants categorised images into hypothetical congruent (curved-approach, angular-avoid) and incongruent (angular-approach, curved-avoid) pairings. As hypothesised, participants were quicker in classifying images according to the congruent compared to incongruent pairings, suggesting a stronger semantic association between the concepts in their congruent forms. This finding aligns with previous research highlighting the positive effects of curved interior designs (Madani Nejad, 2007; van Oel & van den Berkhof, 2013; Vartanian et al., 2013). Specifically, it corroborates previous evidence supporting a self-reported tendency to approach curved furniture (Dazkir & Read, 2012) and spaces (Vartanian et al., 2019). Previous works on abstract shapes had used a similar task, demonstrating biases to associate contours with affective concepts such as valence and safety (Palumbo et al., 2015). To the best of our knowledge, this is the first study to identify (partially) automatic semantic associations with a behavioural outcome, namely, the concept of approach-avoidance. However, while the IAT established links with approach-avoidance behaviour, the task cannot determine the source of the effect, that is, whether it is resulting from an approach tendency towards curvature or an avoidance of angularity.

The origin of the effect could be detected with the last test of our study, the SRCT. This test assessed motoric representations related to approach-avoidance tendencies. Based on whether an image displayed interiors with angular or curved design features, participants moved a manikin towards or away from it, using keyboard buttons. As expected, the findings revealed a significant interaction between the images' contour and the movement direction. Specifically, images of curved interiors elicited faster approach and slower avoidance RT responses compared to those of angular ones, which were approached and avoided at comparable speeds. Additionally, images of angular interiors were more readily avoided compared to those of curved ones. These results align with earlier findings indicating an influence of contours on self-reported approach-avoidance decisions (Dazkir & Read, 2012; Vartanian et al., 2019). Moreover, they are also consistent with results from research on abstract shapes (Bertamini et al., 2016; Palumbo et al., 2015), showing faster approach and slower avoidance of curved abstract stimuli, with angular shapes showing no significant difference in response times, even in cases of polygons with sharply defined vertices (Palumbo et al., 2015). When comparing with the null results observed with the AAT, it needs to be noted that the SRCT might generally be more effective than the AAT in identifying approach-avoidance reactions due to its better criterion validity and the more intuitive task of moving a manikin rather than directly moving the stimulus (Krieglmeyer & Deutsch, 2010).

In summary, *Paper III* confirmed the impact of images of angular versus curved interior designs through two out of four RT paradigms. The study found biases associated with approach-avoidance words (using the IAT) and movements (using the SRCT), but did not find biases related to attentional (using the DPT) nor motoric responses (using the AAT). These results were consistent across both reaction times and error rates, and confirmed by the conducted sensitivity analysis. The IAT revealed that participants associated curvature with approach and angularity with avoidance, indicating that these concepts were closely linked in participant's mental representations. The SRCT showed significant biases in motoric representations, indicating slower avoidance responses towards curvature (compared to a faster approach), echoing findings from studies on abstract shapes. To the best of our knowledge, this is the first study to establish links between angularity and curvature and approach-avoidance tendencies using objective RT measures.

4.1.4 A positive effect of curves or a negative effect of angles?

While the preference for curves is well-documented across a spectrum of stimulus categories ranging from abstract shapes to everyday objects, the reasons for such effects are still a subject of debate (Corradi & Munar, 2019). One view, the threat hypothesis, argues that the effects result from appraisal mechanisms, possibly developed throughout evolution to quickly detect and avoid edges, which might be perceived by individuals as threatening (Bar & Neta, 2006, 2007). Other researchers challenged this perspective, and proposed a “curvature effect”, attributed to an inherent pleasant characteristic of curves (Bertamini et al., 2016; Palumbo et al., 2015), which are thought to activate sensorimotor mechanisms (Amir et al., 2011; Fantz & Miranda, 1975). Although it would not be possible to directly test the evolutionary perspective per se, one objective of this dissertation was to explore the potential reasons behind the effects of angularity and curvature in the built environment.

Using well-matched images depicting photo-realistic indoor environments with angular and curved features, we effectively demonstrated effects on both explicit and implicit psychological responses, in *Paper II* and *Paper III* respectively. *Paper II* indicated effects on aesthetic preference and stress ratings. In particular, images of curved contours scored higher on the beauty and liking scales, while images of angular contours received lower ratings on restfulness and higher ratings on stressfulness. However, it is not possible to determine whether these effects are attributable to a positive impact of curvature or a negative influence of angularity or both, as our measures were limited to subjective, explicit ratings, which do not allow detection of the source of the effect. In the same vein, *Paper III*, through the use of the IAT, identified semantic associations to link curvature with approach and angularity with avoidance. Yet, the task was not designed to detect whether these effects relate to an approach towards curves or an avoidance of angles.

In addition to the insights gained from explicit measures and the IAT, *Paper III* further employed the SRCT, revealing a significant interaction between contour and movement direction. A closer examination of the observed effects indicated that the influence seems to lay within the response to curvature, with images of curved interiors being approached faster than they were avoided by our participants. Although images showing angular interiors were avoided more quickly than those depicting curved ones, participants appeared to be indifferent towards approaching or avoiding them. Interestingly, participants approached both conditions in a similar manner, but exhibited more effort in avoiding images depicting curved conditions, which resulted in the slowest RTs. This implies a predisposition towards moving closer to and spending more time with curved features compared to angular ones within constructed indoor spaces. Our main interpretation of these findings endorses a positive/pleasant impact of curved interior designs (Vartanian et al., 2013), which may be considered as an aspect of biophilic design. It has been previously proposed that curvature, which is more prevalent in nature, is a key component of biophilic design (Kellert & Calabrese, 2015; Salingaros, 2015). Nonetheless, such claims need to be regarded with caution as we did not specifically test for the perception of naturalness. Future studies could explore whether curvature is indeed perceived as more natural than angularity in interior design settings.

4.1.5 Contextual and person-specific factors interacting with the observed effects

Beyond the sole effect of angular versus curved features of indoor environments, this dissertation also aimed to explore whether other contextual and person-specific factors interact with the observed effects. Therefore, we additionally examined the effects of style (modern versus classic) and participants' reported biological sex (female versus male).

The results from *Paper II* and *Paper III* revealed a significant interaction effect between style and contour in both explicit and implicit measures respectively. This aligns with an earlier study finding that two pairs of angular versus curved furniture, distinct in their styles, resulted in notably different self-reported pleasure and desire to approach (Dazkir & Read, 2012). Interestingly, *Paper II* found that the preference for curved designs was specific to images depicting modern interior design style, as exhibited in the beauty and liking ratings. This preference did not extend to images of classic interior design style, where no notable differences were observed in both rating scales. This implies that while the factor "contour" had a broad impact on aesthetic preferences, its influence was contingent on additional contextual elements, such as style, which accounted for slightly greater proportions of variance. Looking into the main effect of style, participants showed a preference for images of the modern rather than the classic style, reflected in the higher scores on beauty and liking. The relatively lower appreciation for the classic style could have influenced the overall scores, potentially obscuring the impact of contour. *Paper III* also found a notable interaction with style in the SRCT, akin to the outcomes observed with explicit evaluations of the same images in *Paper II*. In this context, the modern style additionally led to a greater neutrality towards angularity, while simultaneously prompting quicker RTs towards and slower RTs away from images depicting curved compared to angular conditions. However, aside from angularity and curvature, objects in the modern and classic settings differed in their geometric features, such as the distinct frames found in the classic style, which could have additionally impacted participants' responses. Generally, these outcomes seem to align with earlier research indicating that the preference for curved objects might not only stem from a biological predisposition but could also be influenced by fashion, trends, or a specific "Zeitgeist effect" denoting the spirit of the times (Carbon, 2010). A suggested confounding element, at least with respect to complex human-made artifacts, is the influence of time-specific preferences, as recent research showing a preference for curved designs was carried out during a time when curved aesthetics were commonly utilised. Indeed, technological advancements have enabled the incorporation of abstract curves and surfaces as fundamental components in contemporary design, notably within the realms of architecture and furniture, establishing their significance from the 20th century onwards (Lastra & De Miguel, 2020). In fact, a study focusing on car design revealed that curved conditions were only preferred when such designs were considered fashionable (Carbon, 2010). It was argued that when curved designs were favoured over angular ones, angular designs were seen as innovative. Thus, the mere exposure effect could explain the varying preferences for angularity or curvature in different scenarios. Our results, however, do not conclusively determine whether the observed impacts are solely due to time-specific styles, or if they stem from a broader disfavour towards the classic category, or a combination of both. This issue would necessitate further exploration of different variations.

Despite observing no significant outcomes in *Paper I* regarding the positive effects of curved interiors, we accounted for the influence of participant sex and conducted further exploratory analyses. These compared the responses of the male and female subgroups in each of the conditions separately. Interestingly, in six out of the 20 dimensions of the affective and spatial experience scale—specifically, calmness, cheerfulness, excitement, liveliness, familiarity, and experience—male participants rated rooms with angular features higher than the female subgroup. Additionally, they scored higher on the positive emotions of the momentary affective scale compared to female participants, showing significantly increased levels of interest, happiness, positivity, and activity after engaging with rooms with angular interiors. In the context of the mental arithmetic task, which involved serial subtraction as part of the Trier Stress Test (Kirschbaum et al., 1993) and has been previously utilised in environmental research (Mostajeran et al., 2021), male participants outperformed female participants following their exploration of rooms with angular interiors. These exploratory findings suggest potential sex-related differences in the perceptual, emotional, and cognitive responses to forms in the built environment. However, it is important to approach these results with caution as our sample was not balanced in terms of sex (25 women and 16 men responded to the questionnaires, while 27 women and 15 men took part in the cognitive task).

Similarly, exploratory analysis revealed sex-related differences in the findings of both *Paper II* and *Paper III*, where a balanced sample was ensured. Specifically, the outcomes of *Paper II* demonstrated that participants' self-reported sex influenced their aesthetic evaluation of the two presented conditions. Post-hoc analysis indicated that only female participants displayed an aesthetic preference for the curved conditions, whereas male participants rated images of both angular and curved interiors equally. Likewise, results of the IAT in *Paper III* showed a significant interaction with reported sex, suggesting stronger semantic associations in the female subgroup between curvature and approach, and angularity and avoidance. These results are consistent with prior research showing differences in the perception of abstract stimuli between men and women, albeit the study observed a combined influence of gender and academic degree (Palumbo et al., 2021). In fact, the last study to report such sex differences investigated wrapped candies, finding that girls significantly preferred spherical candies over cube-shaped ones in comparison to boys (Munroe et al., 1976), a choice related by the authors to "body conception", but which could be argued to rather relate to "projected body ideals".

One potential explanation for the differences we detected is provided by research associating curvature with femininity and angularity with masculinity (Madani Nejad, 2007; Palumbo et al., 2015). Such associations could lead to specific responses to angular and curved interior designs due to differences in identification with the respective contour. In spatial design, research has shown that both experts and laypeople perceived images of curved interior spaces as more feminine (Madani Nejad, 2007). Similar associations between curvature and female names as well as angularity and male names were also observed in a study using an IAT to test abstract shapes (Palumbo et al., 2015). Such differences may arise from societal norms and gender roles, as well as inherent sex differences (Lueptow et al., 1995). Indeed, previous studies have identified biological differences in beauty perception between both sexes, tracing them back to the distinct roles of male and female ancestors in hunter-gatherer societies (Cela-Conde et al., 2009). Another explanation for the identified sex-related differences in our studies could relate to specific responses to natural forms, which have been argued to resemble curves more than angles according to the literature on biophilic design (Kellert & Calabrese, 2015; Salingaros, 2015). Concretely, research has shown sex-related differences in semantic processing (Wirth et al., 2007), with evidence that women process natural categories more efficiently, while men more readily process human-made categories (Bermeitinger et al., 2008; Capitani et al., 1999; Laws, 1999). These differences also extend to object catagorisation, with systematic variations in how the two subgroups classify the same items (Pasterski et al., 2011). Moreover, recent research suggests that women might gain greater advantages from the salutogenic aspects of natural settings (Sudimac & Kühn, 2022). Yet, both angular and curved conditions in this thesis relate to man-made artifacts, and we have not directly tested whether curvature was indeed perceived as more natural. Therefore, such explanations require further investigation. Nonetheless, our findings provide initial confirmatory evidence of differences in the evaluation of curved versus angular interiors based on sex (since we instructed participants to report on their biological sex), although it remains unclear if these differences are attributed to sex or gender. Further investigation is required to determine if these effects are due to societal constructs or are inherent.

In sum, this dissertation provided evidence for the interaction of angular versus curved features in indoor environments with other factors such as style (modern versus classic) and participant biological sex (female versus male). The findings from *Papers II* and *III* reveal a significant interaction between style and contour. Specifically, *Paper II* observed that the preference for curved interiors was limited to modern style, as opposed to no preference in response to classic style. Moreover, *Paper III* revealed stronger SRCT effects in modern style, whereby shorter RTs towards and longer RTs away from images of curved compared to angular conditions were detected. These findings indicate that the affective and behavioural impacts of angularity and curvature might be influenced by context, such as style and time-specific preferences, suggesting a "Zeitgeist effect", to be further investigated. Moreover, exploratory analyses suggest sex-related differences in the responses to angular and curved interior environments. *Paper I* showed that male participants responded more favourably to angular interiors as evident in specific affective and cognitive measures. Conversely, *Papers II* revealed that female participants displayed a preference for curved conditions in terms of aesthetic preference evaluations. Moreover, *Paper III* showed that semantic associations between curvature and approach as well as angularity and avoidance were stronger in the female subgroup. These findings hint at underlying sex-related differences in the perception and evaluation of spatial forms, potentially influenced by societal norms, gender roles, or inherent biological differences. However, caution is required in interpreting these findings, as further research is needed to fully understand these interactions and their implications.

4.2 Limitations and directions for future research

Taken together, this dissertation examines the causal effects of short-term exposure to angular versus curved features in the built environment on affect, cognition, and behaviour. While it sheds light on important psychological aspects, the interpretation of its findings must consider certain challenges associated with the conducted studies.

We first discuss the common limitations across the three papers included in this dissertation. Generally, the first point relates to a potential sample bias resulting from the reliance on participants from WEIRD (Western, Educated, Industrialised, Rich, and Democratic) populations (Henrich et al., 2010). This focus may limit the generalisability of the findings, as psychological responses observed in these individuals may not represent global diversity. For example, while Western populations generally exhibit a strong preference for curved stimuli, this preference was found to be notably weaker among non-Western, Asian individuals (Dai et al., 2022; Maezawa et al., 2020). Additionally, the use of a research-dedicated platform for participant recruitment for the studies of *Papers II* and *III* might have introduced further bias, as these participants are likely more accustomed to experimental settings. The second point pertains to the stimuli's limited representativeness. The presented living room environments, while versatile and serving multiple functions (including those of waiting rooms in several architectural settings), do not capture the full range of functional spaces and styles. This limitation narrows the scope of the findings, making them less applicable to a broader range of settings. Future research should aim to include a broader array of styles and functional spaces to assess whether the observed effects are consistent across different indoor environments. Furthermore, the use of static image stimuli in *Papers II* and *III* limits the extent to which inferences about dynamic experiences can be made (Coburn et al., 2017; Gramann, 2013; Nasar, 1994). Considering the inconclusive results in *Paper I*, future studies may want to systematically explore various presentation modes (e.g., images, videos, VR) to better understand the impact of angular versus curved interiors on human responses. Third, the studies primarily focused on biological sex, overlooking the broad spectrum of gender identities. This oversight limits the understanding of how different gender identities might influence the perception of angular versus curved interiors. It is critical for future research to consider both gender identity and biological sex to capture a more comprehensive view of how these factors interact with the responses to the built environment. Fourth, the three studies did not consider interindividual differences beyond biological sex. Factors such as personality traits, cognitive abilities, expertise in arts and architecture, and neurological disorders could influence the responses to angular versus curved conditions (Banaei et al., 2020; Corradi, Belman, et al., 2019; Cotter et al., 2017; Palumbo et al., 2020; Vartanian et al., 2019). Additionally, it has been suggested that factors such as age, socioeconomic status, social class, health, and wealth can greatly affect how an individual perceives the beauty and impact of a work of art (Mastandrea et al., 2021). Similarly, research indicates that age-related differences could affect preferences for certain design attributes (Yildirim et al., 2015). Future research might want to investigate these interindividual differences in balanced samples to draw conclusions that may be applicable across specific groups of individuals. Finally, we note the lack of strong theoretical frameworks explaining the psychological mechanisms underlying the perception and evaluation of architectural stimuli. This gap is particularly prominent in the emerging fields exploring the psychological and physiological impacts of architecture and interior design (Higuera-Trujillo et al., 2021). Future research should focus on developing and applying robust theories to improve study relevance and applicability in design practices.

In *Paper I*, several limitations could have impacted the study's outcomes and interpretations. Although the lack of a predefined path in the VR environment enabled unrestricted exploration, fostering a more naturalistic spatial experience, it also introduced variability in exposure and engagement levels among participants, potentially compromising the consistency of the findings. Future research might want to test predefined paths to understand whether more homogeneity in exposure leads to significant effects of angular versus curved interiors. Moreover, the evaluation process was extensive, involving 31 outcome variables in VR, which could have led to the so-called museum fatigue phenomenon (Gilman, 1916)—a phenomenon initially attributed to physical fatigue but later associated with cognitive factors such as satisfaction levels, information overload, and attention maintenance challenges (Morii et al., 2017). Future research could streamline the number of outcome variables. Additionally, the assessment of the VEs perceived restorativeness, conducted post-VR session using images, may not have fully captured the dynamic nature of restorative experiences as they unfolded. Furthermore, the assessment of momentary affect included a broad range of negative emotions, which might not fully encapsulate the nuanced emotional responses participants have to the VEs. Interestingly, participants showed minimal negative emotions and used a wider range of the provided scale when responding to items that included both positive and negative options. We refined the assessment tool in *Paper II*, and were actually able to capture significant affective responses, but to images. Finally, the cognitive task utilised to evaluate cognitive performance might have been perceived by participants as a source of stress. While its efficacy has been demonstrated in environmental settings (Mostajeran et al., 2021), the stress potentially induced by the task could have obscured any effects of angularity or curvature. These limitations highlight the complexity of designing VR studies and underscore the importance of methodological considerations in interpreting the resulting findings. Addressing these issues in future research could deepen our understanding of how angular versus curved virtual interiors influence affective, cognitive, and behavioural responses.

When examining the findings presented in *Paper II*, it is crucial to address the study's reliance on subjective, self-reported data. This methodological choice lacks the objectivity necessary for decisive conclusions, particularly concerning the source of curvature and/or angularity effects observed in the study. While the study successfully identified significant effects on affective responses, and the reliability of our measures was supported by Cronbach's coefficients, the high degree of cross-correlation among rating dimensions necessitates further scrutiny. This step is essential not only for identifying the key factors that shape affective responses to interior design but also for the development of reliable psychometric scales. Moreover, the fact that the manipulated factors accounted for a mere fraction of the variance highlights the presence of additional, potentially impactful factors on aesthetic and emotional responses to angularity and curvature. Given the role of initial affect and interindividual differences in influencing the response to physical environments, future research could aim for more balanced designs by considering factors such as mood, psychopathology, and expertise in architecture, among other variables. Despite our effort to assess expertise, only 2.5% of our participants qualified as experts (with a relevant training or professional background in architecture), rendering us unable to conduct any moderation analyses.

Acknowledging the limitations of subjective methodologies, *Paper III* sought to address this gap and explore the psychological impact of angularity versus curvature in interior design using a more objective implicit testing strategy. However, this approach raises important questions regarding the terminology used in research, specifically the use of terms like "implicit" or "automatic". These terms, used interchangeably in research, imply a lack of explicit goals and awareness among participants (De Houwer et al., 2009), which we cannot definitively claim in some of the tasks we used. Specifically, our employment of the IAT and SRCT, which required participants to be aware of and directly respond to the study variables (i.e., angularity versus curvature), demonstrated significant effects. This might question the "implicitness" or "automaticity" of responses, and arguably, it makes the distinction from explicit methods (i.e., self-reports) less clear. Another challenge in *Paper III* were technical issues that resulted in a reduction of 75 participants in the AAT sample. Additionally, with a 67% error rate, it was unclear whether all participants followed the instruction to use a mouse, as compliance was not verified. Other than that, it could be thought that the angularity versus curvature manipulation might have been too subtle to be detected by participants, explaining the lack of effects in certain paradigms (i.e., DPT, AAT). Yet, the manipulation checks and explicit ratings in *Paper II*, as well as the responses in the IAT and SRCT in *Paper III*, suggest the manipulation was sufficiently noticeable.

Moving forward, it is imperative to delve deeper into the intricate ways in which angularity and curvature within indoor environments impact human psychology and physiology. Having identified significant influences on (explicit and implicit) affective and behavioural responses, the next critical step involves exploring the neural mechanisms that underlie these effects. To this end, we have already started planning a study that integrates fMRI and VR. This innovative approach aims to unravel the neural foundations that contribute to the appeal of curvature and/or the potential stress-inducing properties of angularity. By focusing on regions of the brain associated with pleasure (e.g., ventral striatum) and stress (e.g., amygdala), we aim to provide a nuanced understanding of how architectural forms affect individuals at a neural level. The use of VR paradigms in this regard offers a more immersive experience compared to traditional methodologies that often rely on static image presentations (Vartanian et al., 2013), thereby enhancing the ecological validity of our potential findings. Aside from spatial representations, it is of course also crucial to investigate real-life environments, to understand whether the observed effects persist in naturalistic settings. This entails conducting field studies in various architectural settings to observe and measure the psychological and physiological responses of individuals to different forms of angularity and curvature. Such studies are essential for validating the findings from laboratory-based research and ensuring that they are applicable to real-world scenarios. Furthermore, the exploration of long-term impacts posed by angularity and curvature represents another vital research avenue. Longitudinal studies are indispensable for understanding the sustained effects that arise from ongoing interactions with these environmental features. This aspect holds particular significance in the realm of mental health-promoting environments, such as psychiatric facilities and therapeutic spaces. In these settings, individuals are in continuous engagement with their surroundings, making it crucial to understand how architectural features can influence mental well-being over time. By investigating these prolonged effects, we can begin to inform the design of spaces that not only cater to immediate psychological and physiological needs but also contribute to long-term mental health and resilience.

4.3 Potential applications to architecture and interior design

The findings presented in this dissertation shed light on the intricate mechanisms that govern the perception and evaluation of angular versus curved stimuli within the realms of interior design and architecture. These insights have profound implications for the creation of spaces that are attuned to human affective and behavioural responses. The findings from this dissertation uncovered a favourable influence of curvature. This influence not only potentially enhances aesthetic appeal of spaces but may also mitigate (self-reported) stress and shape how individuals tend to approach or avoid these spaces. Consequently, curvature, which has been previously claimed as "biophilic" (Kellert & Calabrese, 2015; Salingaros, 2015), emerges as an important architectural factor in fostering human well-being.

These revelations pave the way for the formulation of evidence-based design strategies that aim to prioritise mental and physical health considerations. While our investigation focused on (images or spatial representations of) residential environments, it is important to emphasise that the principles uncovered extend beyond the confines of the home. Living areas are ubiquitous across various functional spaces. For instance, in healthcare settings, the design of therapeutic environments can significantly enhance patient recovery and overall well-being (Mascherek et al., 2022; Stichler, 2001). Similarly, in workplace environments, where individuals spend a significant portion of their daily time, interior design can play a significant role in enhancing cognitive performance and promoting better mental well-being (Alyan et al., 2021; Shen et al., 2020). The strategic integration of curved elements and furniture can resonate with the innate expectations of humans, thereby reinforcing mental health and well-being. Nevertheless, while these insights are primarily drawn from image-based evidence, they necessitate a cautious interpretation and underscore the need for further investigation, especially given the null results observed when delivering a close-to-reality experience. To fully harness the potential of angularity and curvature in indoor design, additional research is imperative to decode the various processing systems and pathways in the human brain that are responsible for these partially automatic responses. Moreover, understanding how these responses may differ across diverse populations, cultural contexts, and functional spaces is crucial.

The connection between built environments and mental health unveils immense opportunities for integrating scientific findings into architectural practice (Robinson & Pallasmaa, 2015). This knowledge holds the potential to transform residential areas, healthcare settings, educational spaces, workplaces, and even urban planning initiatives, creating environments that promote recovery, learning, creativity, and emotional well-being. It emphasises the significance of thoughtful, evidence-based design in elevating the quality of urban life, advocating for designs that nurture cognitive development, foster positive emotions, and encourage positive behavioural outcomes. However, the preliminary nature of the current findings accentuates the necessity for additional research to corroborate and expand upon the observed effects in real-world scenarios.

4.4 Conclusion

This cumulative dissertation has conducted a comprehensive exploration of the psychological impacts of interior environments with angular versus curved features, employing both VR and images as presentation mediums. Across three publications, this body of work has sought to unravel the short-term effects of these environmental features on individuals' affect, behaviour, and cognition. *Paper I* developed a novel VR paradigm, investigating, for the first time, well-matched photo-realistic virtual rooms with angular versus curved features. Surprisingly, the study revealed no significant positive effects of curvature across a range of psychological domains, including affective and spatial experience, momentary affect, cognitive performance, and perceived restorativeness. These results were confirmed using both frequentist and Bayesian analytical frameworks. Interestingly, when presenting images of the same stimuli in *Paper II*, after controlling for insignificant differences in terms of low-level features, we observed effects on explicit responses. Specifically, participants self-reported higher aesthetic preference and reduced stress when exposed to images of curved as opposed to angular interiors. Furthermore, *Paper III* employed an implicit testing strategy identifying effects of angular and curved interiors on approach-avoidance behaviour using objective measures. Although we observed no effects on attentional and motoric biases per se, this approach revealed effects on semantic and motoric representations. Specifically, curvature was semantically associated with approach, and angularity with avoidance. Moreover, curvature was approached faster than avoided, and avoided slower than angularity, indicating effects on motoric representations that are likely linked to a certain positive response to intrinsic properties of potentially "biophilic" curves rather than a threat elicited by angularity.

In synthesising these findings, this dissertation contributes valuable empirical insights into the causal effects of short-term exposure to indoor environments with angular versus curved features, with a particular emphasis on image-based evidence. The research underscores the potential of curvature to elicit positive psychological responses, offering significant implications for architectural and interior design strategies aimed at promoting mental health and well-being through evidence-based approaches. However, the absence of significant findings in the VR-based experiment introduces a note of caution, suggesting that the impact of presentation modes on the perception of angularity and curvature warrants further investigation. Therefore, this dissertation not only advances our understanding of the psychological effects of interior design but also highlights the need for continued exploration into how environmental features influence our experience of the built environment. In doing so, it lays the groundwork for future research that can further refine our approach to creating spaces that promote human well-being.

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Appendices

A: Paper I

Tawil, N., Sztuka, I. M., Pohlmann, K., Sudimac, S., & Kühn, S. (2021). The living space: Psychological well-being and mental health in response to interiors presented in virtual reality. *International Journal of Environmental Research and Public Health*, *18*(23), Article 12510. https://doi.org/10.3390/ijerph182312510

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Article

The Living Space: Psychological Well-Being and Mental Health in Response to Interiors Presented in Virtual Reality

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Abstract: There has been a recent interest in how architecture affects mental health and psychological well-being, motivated by the fact that we spend the majority of our waking time inside and interacting with built environments. Some studies have investigated the psychological responses to indoor design parameters; for instance, contours, and proposed that curved interiors, when compared to angular ones, were aesthetically preferred and induced higher positive emotions. The present study aimed to systematically examine this hypothesis and further explore the impact of contrasting contours on affect, behavior, and cognition. We exposed 42 participants to four well-matched indoor living rooms under a free-exploration photorealistic virtual reality paradigm. We included style as an explorative second-level variable. Out of the 33 outcome variables measured, and after correcting for false discoveries, only two eventually confirmed differences in the contours analysis, in favor of angular rooms. Analysis of style primarily validated the contrast of our stimulus set, and showed significance in one other dependent variable. Results of additional analysis using the Bayesian framework were in line with those of the frequentist approach. The present results provide evidence against the hypothesis that curvature is preferred, suggesting that the psychological response to contours in a close-to-reality architectural setting could be more complex. This study, therefore, helps to communicate a more complete scientific view on the experience of interior spaces and proposes directions for necessary future research.

Keywords: indoor architecture; interiors; contours; affect; behavior; cognition; spatial experience; virtual reality; well-being; mental health

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1. Introduction

Built (man-made) environments have become fundamental components of human existence. For the majority of our waking time, we navigate and interact with architectural environments while we live, connect, learn, work, and recreate. The spaces encountered in daily life vary in their physical and aesthetic properties, and may have an influence on affect, behavior, and cognition, and eventually impact mental health and psychological well-being [1,2]. These effects are likely the outcome of an interaction between the physical properties of the perceived space on the one hand, and the perceiver's characteristics and the meaning they create on the other [3–5].

When accounting for the considerable time spent inside buildings, two-thirds of which is in dwellings [6], the glaring gap in linking variations in physical features of architecture to psychological states is surprising [7,8]. It has been previously suggested that this can be attributed to methodological and disciplinary incongruences between architecture and psychology [7–9]. Architectural research connecting the human response to design relies on philosophical constructs, whereas traditional psychological research investigating the human–environment relationship relies on observation and subjective measures [9,10]. A better understanding of the human–environment interaction could contribute to informing design strategies in ways to optimize psychological well-being and mental health [11]. Although the discussion has been initiated, a commonly accepted methodology across disciplines is still lacking [12].

A domain in which first successful attempts have been made to link architectural features to psychological responses in human beings concerns contours. We refer to contours here to describe the "edge or line that defines or bounds a shape or an object" [13]. The interest in the response to contours derived from empirical studies in various disciplines such as arts, aesthetics, visual cognition, and (social) psychology among others, which have reported differences in perception. Early studies from the first quarter of the 20th century have found that straight lines were associated with unpleasant "feeling tones" that denote strong motor expression (e.g., agitating, hard, furious, and serious), whereas curved ones were associated with adjectives indicating relatively more pleasantness and less movement (e.g., gentle, quiet, and lazy) [14,15]. Subsequent studies have investigated the hypothesis that curved/rounded/curvilinear conditions are more appealing to humans than angular/edgy/rectilinear ones. This hypothesis has been shown to be correct using different types of visual stimuli including lines [14–18], font types [19,20], geometric shapes and simple forms [21–24], irregular shapes and meaningless patterns [3,4,16,22–30], images of familiar objects [3,26,31–36], sketches of familiar objects [33,37], in addition to sketches and images of designed products [38,39]. Different studies have found the effect to be present across species humans and apes [35], cultures—Western vs. non-Western [14,16,19,24,29,35,38–40], and ages—toddlers [27] and infants [18,23]. However, the source of this preference is still under debate. Some researchers proposed that angularity conveys threat, suggesting that the preference reflects adaptive behavior [31,32]. Other research has attributed the observed effect to higher cognitive processes and susceptibility to the influence of semantic meaning and perceptual qualities that are not strictly limited to contour [35]. Conversely, additional studies proposed a "curvature effect" that was not linked to a negative response to angularity for what it affords but rather caused by intrinsic characteristics of the curved stimuli [29], with preference modulated by positive valence [34]. Moreover, other studies have investigated additional variables beyond simple curves and angles. Those included both properties of the stimuli—e.g., complexity [22,24,28–30,38], symmetry [24,36], balance [22,24], novelty/innovativeness [38], meaningfulness [26,29], typicality [38,39], familiarity [4,33], as well as individual differences of the perceivers—e.g., sex [3,27,30], expertise in art/design [3,4,24,33,38], academic degree [33], personality traits [3,22,33], cognitive styles [26], and neurological disorders such as autism [4,21,30], in an attempt to understand whether they affect or modulate contour perception. Different outcome measures have been used in previous studies, including forced-choice response [29,31,32], rating/visual analogue scales [4,16,19–22,24,29,30,33,37,39], and selection procedures [26], in addition to more implicit measures, such as association [14,17,20,25,28] and approach-avoidance tasks [3,16,28,36], reaction and/or viewing time [18,22,26,27], and observed postural behavior [21]. With regard to contours in the indoor environment, similar effects were proposed by the scarce set of studies available until now. Spaces with curvilinear/curved features, in comparison with those with angular/rectilinear ones, were preferred among different ages [41], and induced higher positive emotions such as pleasure [42–45], relaxation, safety, privacy [46], and a desire to approach [44]. The majority of these studies relied largely on subjective semantic scales, where stimuli were rated according to a limited list of paired opposite adjectives to depict emotional responses (i.e., valence, arousal, approach-avoidance, and some spatial properties). It is worth noting that the stimuli used, for the most part, did not reflect realistic environments. More recent research used different approaches and new experimental tools to investigate the architectural experience. The effect of contour on aesthetic judgment and approach-avoidance decisions was examined in one of the very first functional magnetic resonance imaging (fMRI) studies to examine architectural perception [8]. Images of existing real-life indoor environments were presented for three seconds in the scanner, and participants rated each image and used a joystick to indicate whether they would like to enter or exit the environment. Results showed that curvilinear interiors were more likely judged as beautiful, compared to rectilinear ones. Moreover, they were found to activate the medial orbitofrontal cortex—titled as anterior cingulate cortex (ACC) in the publication exclusively, which has previously been related to positive valence and pleasantness [47]. In contrast with previous fMRI evidence from studies investigating familiar objects [31], no amygdala activation for rectilinear spaces was found. Consequently, given the amygdala's role in processing information related to fear and arousal [48], the results did not confirm the hypothesis of the threat effect evoked by angularity. Additionally, unlike what was hypothesized, contour did not affect approach-avoidance decisions. The stimulus set was partially tested in more recent studies that examined individual differences. Eight images were presented to experts and laypersons [49], and 80 to quasi-experts, individuals with autism spectrum condition (ASC), and a matched neurotypical group [4]. Results were not consistent across the different studies, with the latest one finding a preference for rectilinear spaces within all three groups. Two major setbacks may have caused the inconsistencies between the reported results. The first concerns the use of 2D images (static stimuli) to represent realistic environments and investigate a real-life experience [50], and the second relates to the fact that the stimuli were not well-matched. Creating controlled testing environments in which separate architectural design features can be altered and tested each at a time represents, in fact, one of the main challenges in quantifying the impact of design on human experience [7]. With the recent technological advancements in virtual reality (VR) and computer-aided design (CAD) software, it is now possible to develop experimental settings that can replicate the experience of a real environment under controlled conditions [51,52], while evoking similar user responses [53,54]. Combining human monitoring techniques with advanced VR environments can enable the acquisition of objective evidence for evaluating the human response to indoor design [9,52,55]. For example, one study investigated different interior form features using VR combined with electroencephalogram (EEG), during active exploration of empty white-colored virtual environments [10]. Results showed higher pleasure and arousal ratings and increased theta activity in the ACC when exploring curved geometries, as opposed to more linear ones. However, source localization of the EEG signal in the brain is a complex task with forward and inverse problems, calling the exact location of the source ACC into question. Another example study examined neurophysiological and behavioral responses during the appreciation of virtual environments, using EEG and explicit ratings of novelty, familiarity, comfort, pleasantness, and arousal [56,57]. Despite the fact that the two virtual rooms used in the studies represented contrasting contours (i.e., the "modern design" room had angular furniture, and the "cutting edge design" room displayed furniture with rounded edges), the researchers rather focused on style in their categorization of the stimuli. Whereas the interest of the study was not in finding a preferred environment, but rather to explore the relationship among each of the perceptual dimensions and correlate them with brain activity, modern and cutting edge environments were perceived, respectively, as more familiar and more novel, but no differences in ratings of pleasantness, arousal and comfort were reported. Taken as a whole, the evidence for curvature preference, although seemingly robust with abstract shapes and lines, is yet far from being confirmed in the context of indoor architecture, and requires further thorough investigations.

Another line of research exploring the response to built environments has investigated the restorative properties of indoor spaces. The attention restoration theory (ART) proposes that natural environments, filled with "soft fascinations", could restore cognitive capacity, reduce mental fatigue, and increase focus and attention [58]. Being in restorative environments could, therefore, change negative states to positive ones. Building on the biophilia hypothesis, which suggests that humans have an innate connection with nature [59], a framework for biophilic design has emerged [60]. By bringing elements of nature into living spaces (directly or indirectly), positive effects might be initiated. Studies investigating biophilic interventions in virtual indoor environments have found a stress reduction and restorative effect [61,62].

Within the scope of the present study, we aimed to systematically examine the influence of contours (angular versus curved) in virtual indoor architectural settings on affect, behavior, and cognition. Given the significant time urban dwellers spend in the home environment, which has considerably increased since the COVID-19 outbreak in March 2020, we selected the residential space as the context of our present investigation. Interiors are considered a major part of architecture, more than ever in the revolutionary works of modernist architects who regarded interior spaces as the essence (e.g., Bruno Zevi, Hans Scharoun), highlighted the importance of furniture, and influenced modern furniture design (e.g., Alvar Aalto, Marcel Breuer). Furthermore, we wanted to account for the evidence that architectural style and layout influence the response to form [44], and to architecture per se, knowing that results of studies on the perception and evaluation of style are inconsistent [63,64]. Hence, we included style as an explorative second-level variable. Previous studies investigating aesthetic styles have used classifications such as modern/contemporary vs. classical [65–67] vs. traditional [68], among others. We opted for "modern vs. classic" for the interdisciplinary potential of the dichotomy. We refer to "classic" to denote the variant styles of the traditional abacus of architecture, up to the beginning of the 20th century [69]. "Modern", on the other hand, refers to the architecture of both 20th and 21st centuries, starting from modernism and the stream of styles it inspired by completely breaking with the past [70].

As we aimed to delve deeper beyond the mere investigation of pleasantness, beauty, and arousal, our behavioral measures covered a larger set of affective and psychological dimensions, for a better overview of spatial perception. To inspect the impact of contour on cognition and restorativeness, we included a measure of perceived restored attention, building on the attention restoration theory (ART) [58], and a mental arithmetic task from the Trier social stress test [71], previously used in environmental VR studies [72]. We present here a new paradigm that allows the collection of both explicit and implicit measures of the human response to indoor environments while allowing for a close-to-reality experience. To the best of our knowledge, none of the previous studies have explored high-quality photorealistic, yet well-matched virtual stimuli representing contour contrasting conditions within a free-exploration setting, while controlling for style. Extending on the findings of the scarce studies inspecting contours in the architectural context [8,10,44,46,49,73] and the seemingly robust scientific and empirical evidence supporting curvature preference in other domains (references above), we expected curved conditions to positively impact the self-reported emotional and spatial experience, and to improve cognitive performance as well as the self-reported feeling of restorativeness.

2. Materials and Methods

2.1. Participants

A sample size estimation using G*Power—version 3.1.9.7 (Dusseldorf University, Dusseldorf, Germany), resulted in the need for 36 participants to enable medium effect size. Due to the high potentiality of technical errors, and the increasing rate of cancelled sessions as a result of the COVID-19 pandemic, the recruitment process was kept open until reaching *N* = 36 individuals who provided usable complete sets of behavioral VR data. Eventually, 48 healthy adults were enrolled, aged between 18 and 40 years, with no severe visual impairments. Further inclusion criteria included fluency in German language and absence of diagnosed mental or neurodegenerative disorder or cognitive impairment. Subjects were recruited through the Castellum Database of the Max Planck Institute for Human Development in Berlin (MPIB) and an online platform (https://www.ebay-kleinanzeigen.de/) and were compensated with 10 euros/h. All participants signed the consent form before the experiment.

2.2. Stimulus

Two pairs of living rooms were created for the purpose of the study (Figure 1). Rooms of each pair were identical in their design, except that one had angular window openings, furniture, fixtures, accessories, patterns, and other specific details, while the other had curved counterparts. The main contrast between the pairs was style (classified under: modern vs. classic), with some differences in layout, furniture components, and materials, which were seen necessary to reflect the style. "Classic rooms" included features from the neo-classicism period (e.g., "ornamental" furniture of Louis XV and VI style; wallcovering; detailed door and windows; more objects in the room), while "modern rooms" followed the "less is more" principle (e.g., Ludwig Mies van der Rohe) in a minimal style (e.g., less detailed furniture, door and windows; less objects in the room). Moreover, the classic pair included elements of biophilic design (e.g., wood furniture, plants, images of plants, more surfaces with green color). The main challenge was to design objects/elements that reflect well-proportioned, yet matching counterparts in both contour versions, without causing a change to style or familiarity. Hence, furniture design was inspired from common pieces that exist in both contour versions, although changing contours or proportions of famous designer pieces was completely avoided. In order to control for additional confounding factors, rooms' boundaries, ceiling, floor, door and windows locations, main seating positions, main light, and primary color (green) were kept identical between the pairs, in addition to the outdoor window view portraying a natural environment.

Figure 1. Virtual 3D environments, created for the study. Upper images display the modern style, and the bottom ones the classic style. **Top left:** angular modern (AM). **Top right:** curved modern (CM). **Bottom left:** angular classic (CA). **Bottom right:** curved classic (CC). Images were taken from the Unity project with a perspective that does not represent a human eye view, to show maximum coverage of the room.

The size of the virtual room was similar to the MPIB VR lab space dimensions and fixed accordingly to (L × W × H = 4.9 × 3.9 × 3 m) so that free movement was possible during participants' exploration. Three-dimensional models of all the objects and details of the rooms were created using 3Ds Max—version Theseus, 2020 (Autodesk Inc., Mill Valley, CA, USA), and the paradigm with all the tasks was implemented using the gaming software Unity—version 2019.2.1f1, 64-bit (Unity Technologies, San Francisco, CA, USA). The rooms were rendered in real-time during the experiment, using Unity High Definition Render Pipeline (HDRP, version 6.9.1) and were displayed with Steam VR (Valve Corporation, Bellevue, WA, USA)—multiple updates during experiment, no standing version to report, through an HTC Vive Pro headset (HTC corporation, New Taipei, Taiwan), connected to a wireless adapter to allow for unobstructed movement. In order to increase immersion, a real physical large couch was included in the set-up, positioned at the same location as in the virtual rooms. Participants could use it within their exploration time, and were asked to sit on it to perform the cognitive tasks (Figure 2).

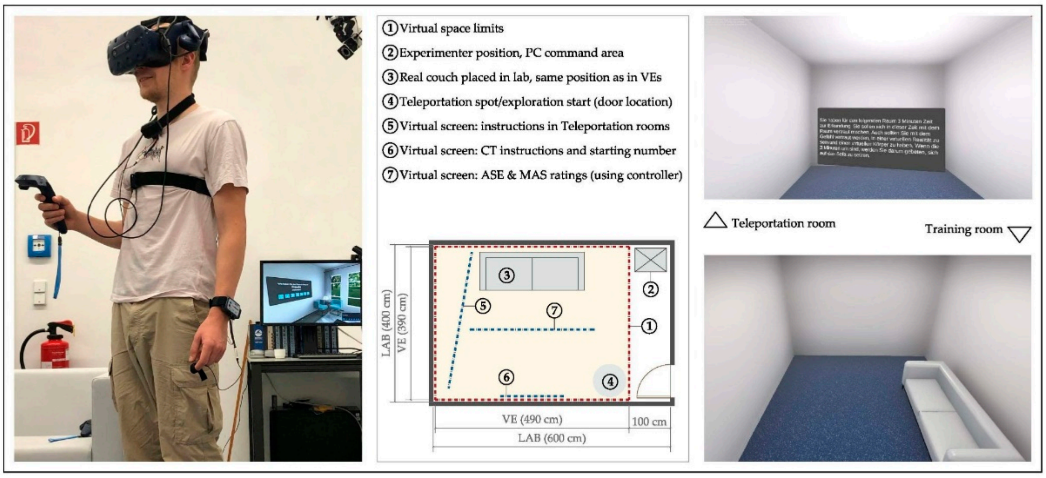


Figure 2. Virtual reality (VR) laboratory set up. **Left side:** VR setup in pilot session, participant about to start responding to rating scales. The physical couch is shown on the right side of the participant. **Middle:** general layout showing the virtual space in relation to the actual laboratory conditions, experimenter position, physical couch position, starting point of each exploration task, and virtual screens that appear successively during the paradigm. **Top right:** teleportation room, presented at the start of the VR session, and in between each of the rooms. **Bottom right:** training room, simulating the laboratory appearance.

Additionally, a virtual training room was created, simulating the lab appearance (Figure 2) including the physical couch, with one version having angular edges (for the couch, lighting fixture, and door accessories), while the other had curved counterparts.

As the study comprised a within-subject design, all participants were tested under all conditions in randomized order, always starting with the training room. Participants with odd ID numbers were first exposed to the training room with curved features, while those with even IDs were assigned to the one with angular ones. Using counterbalancing through a Latin square design, and after eliminating sequences where rooms of the same pair would have been shown successively, four groups were identified, to which participants were randomly assigned: Group A (AM, AC, CM, CC); Group B (AC, CM, CC, AM); Group C (CM, CC, AM, AC); and Group D (CC, AM, AC, CM), where AM is "angular modern", CM is "curved modern", AC is "angular classic", and CC is "curved classic".

2.3. Measures

The main part of the experimental paradigm consisted of the VR session. In each room, participants started exploring the virtual space for 3 min, followed by a 2-min cognitive task in a sitting position, and responded to a set of questions. Multiple questionnaires were administered before and after the VR session (we mention below only those included within the present analyses).

2.3.1. Questionnaires

The in-VR questionnaires included two sections assessing respectively the affective and spatial experience (ASE), and momentary affective state (MAS). ASE consisted of 20 items related to the subjective perception of emotional and spatial dimensions. Participants provided self-reports on 20 bipolar (−5 = "describes strongly", 0 = "neutral", 5 = "describes strongly") dimensions using 11-point numeric scales, tagged by two opposite descriptive adjectives on each of the sides. Dimensions encompassed valence, arousal, and dominance, but also covered other spatial aspects (e.g., organization, spatiality, naturalness), and were retrieved from previous studies [7,8,56,74], with some additions that were found to be relevant to the study (Table S1). All anchor adjectives were translated to German, for the purpose of this experiment. MAS was assessed using 11-point intensity rating scales for 11 dimensions (original German version used in previous studies [75]). The dimensions assess different domains: emotional feelings, bodily sensation, valence and arousal, and cognitive and motivational states (Table S2). The first 6 scales were unipolar (0 = "little", 5 = "neutral", 10 = "very"), followed by 5 bipolar scales tagged by one to four descriptive adjectives as anchors (−5 = "describes strongly", 0 = "neutral", 5 = "describes strongly"). A pre-measure was also collected before the VR session to control for the baseline affective state. In sum, participants responded to 31 dimensions, in-VR, after exposure to each of the rooms, with a total of 155 questions (including the training room).

As part of the post-VR PC-based questionnaire, subjects reported on more aspects of the virtual, spatial, and cognitive experience. Perceived restorativeness (PR) was measured using an adapted 12-item German version of the Perceived Restorativeness Scale (PRS) [76], under four categories: fascination, being away, coherence, and scope (Table S3). Each item was rated on a five-point Likert scale from 0 (not at all) to 4 (completely).

2.3.2. Cognitive Task (CT)

Cognitive performance was evaluated using the results of an in-VR two-minute skip counting task [72]. After exploring each of the simulated conditions, participants were asked to keep subtracting 13 from a starting 4-digit number that was shown on a virtual screen and to pronounce the intermediate results out loud. When participants made mistakes they were prompted to start anew from the same starting number. The sequence of numbers was the same for all participants, and answers were collected manually by experimenters. Individual scores were calculated by dividing the total number of correct answers (in all attempts) by the number of attempts.

2.3.3. Additional Measures

To evaluate the overall VR experience, and control for specific undesired effects, cyber-sickness was measured using an adapted German version of the Simulation Sickness Questionnaire (SSQ) [77], administered both pre and post-VR sessions. SSQ consists of 16 items based on a four-point Likert scale ranging from 0 (symptom not existent) to 3 (very severe symptom), which can be computed into three representative subscores: Nausea-related (N), Oculomotor-related (O), Disorientation-related (D), in addition to a Total Score (TS) representing the overall severity of cybersickness experienced by participants. Moreover, presence was assessed using the iGroup Presence Questionnaire (IPQ) [78]—adapted from the German version available online (www.igroup.org, Accessed on 15 September 2020) administered post-VR. IPQ contains 14 items rated on a five-point Likert scale (1–5) tagged with different anchors, according to the four sub-scales that measure different components of presence: General Presence (GP), Spatial Presence (SP), Involvement (INV), and Experienced Realism (REAL). Both SSQ and IPQ were administered right after the VR session, as part of the post-VR questionnaire. Additionally, we collected information related to demographics and other individual differences that are beyond the scope of the present analyses.

2.4. Procedure

All experimental sessions were conducted in the VR lab at the MPIB (November to December 2020), in compliance with the institute's COVID-19 regulations for lab hygiene. The experiment was composed of three parts: (1) pre-VR questionnaires and preparation; (2) immersive session; and, (3) post-VR questionnaires and tasks. Participants received the consent form via email before the day of the experiment. They were encouraged to read and sign the form, and to fill in the pre-VR questionnaire before coming to the lab, otherwise, those were completed on the day of the experiment. Upon arrival, participants were presented with an introduction to the study, filled a PC-based questionnaire to collect baseline measures for the affective state and simulation sickness symptoms, and performed a short training session on the cognitive task. Next, they were prepared for the VR session. Details were described thoroughly, the head-mounted display (HMD) was put on with the help of the research assistance staff, and subjects were guided to stand in the teleportation areas next to the room door. The VR session started with an empty teleportation room showing instructions for 20 s, followed by the training room, for familiarization with all in-VR tasks. Each room was simulated for 3 min of free exploration, and participants were encouraged to explore as they needed to, until they felt they could later recognize the room from a photo. At the end of the exploration time, a message was shown at eye level with a message to sit on the couch. Instructions for the cognitive task were displayed on a screen at the wall facing the couch, and when participants confirmed readiness, the starting number was shown. Answers were manually written down by the experimenter, who prompted the participant to "restart" after a wrong number was named, until a "stop" sign was shown at the end of the 2 min. Later, a screen appeared in the middle of the room with instructions on how to answer the questionnaire using the controller. Once all questions were answered, participants were asked to leave the controller on the couch and go to the teleportation spot at the door. The sequence of events and tasks is displayed in Figure 3 (upper side). The process was repeated for all rooms, with the teleportation instruction room presented for 20 s in between. At the end of the immersive session, a sign was shown at eye level indicating "the end", HMD was dismantled, and participants took a break. The third part of the experiment included the PC-based questionnaire in addition to further tasks that were not used for the present data analysis. Details of the experimental paradigm are displayed in Figure 3.

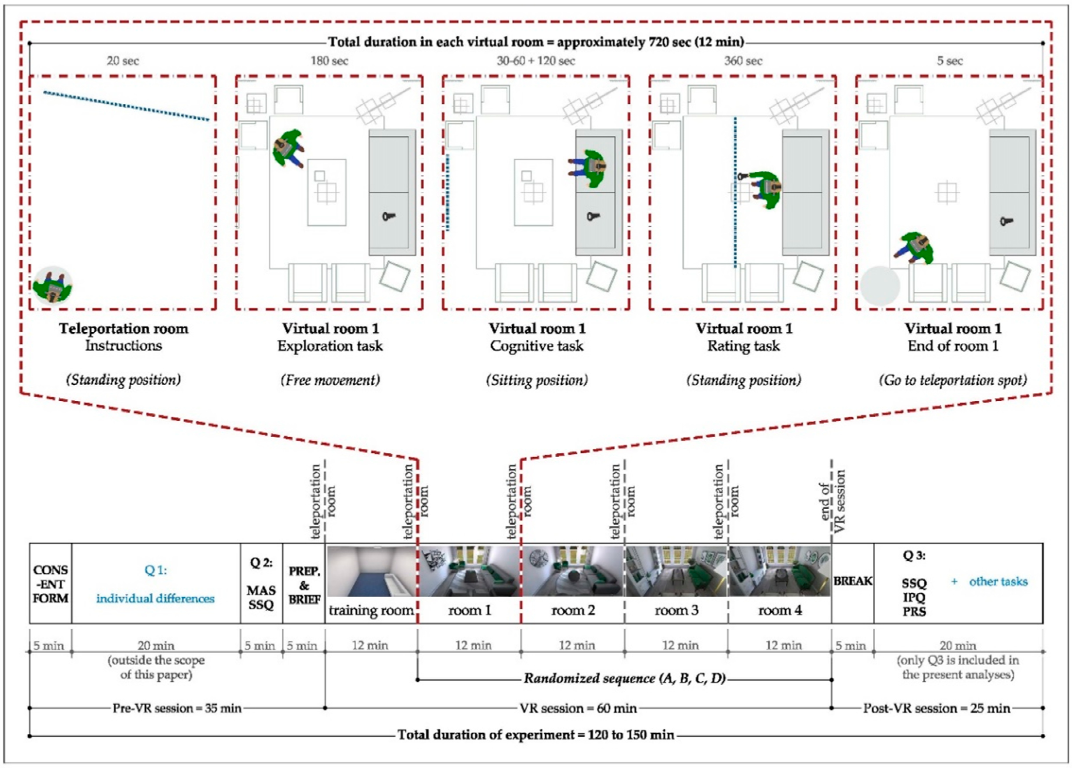


Figure 3. Details of the experimental paradigm. **Bottom:** The bar shows all phases of the experiment (pre-VR, immersive, and post-VR sessions) along with the respective approximate duration. The mentioned durations are based on the average of the time spent by different participants. **Up:** The upper layouts display the sequence of events denoting tasks and instructions in each of the virtual environments. Room AM (angular modern) is displayed in a top view layout as an example. The average duration in each virtual room was 12 min (with an approximate total of 60 min). Some events were fixed and had a predefined time (e.g., teleportation room, exploration tasks, cognitive task), while others depended on the participant's speed (e.g., reading cognitive task instructions and readiness to start, rating tasks, moving back to teleportation spot). Q1 and tasks in the last section mentioned as "other tasks" are excluded from the present analyses. Note: SSQ = simulation sickness questionnaire, IPQ = IGroup presence questionnaire and PRS = perceived restorativeness scale.

2.5. Data Analysis

We preregistered our research plan, which can be retrieved from (https://aspredicted.org/vp93z.pdf, Accessed on 23 February 2021). During data preprocessing, sessions with technical software/hardware errors, and those where participants requested breaks or showed severe symptoms of simulation sickness were excluded. Out of the 48 participants enrolled, a range of 36–40 (85.36% born in Germany; ASE and MAS: F = 25, M = 16; CT: F = 27, M = 15; PRS: F = 23, M= 13) were included in the analyses (Table S4).

Self-reports assessed with questionnaires (MAS, ASE, PRS) in addition to the cognitive task scores were analyzed using paired samples two-tailed *t*-tests to examine differences in contour (angular vs. curved) and style (modern vs. classic). When the normality assumption was not met, instead of paired sample *t*-tests, the Wilcoxon signed-rank test was used. Statistical tests were performed separately for each of the dimensions of the ASE and MAS. For ease of reference, we will be referring to rooms according to their condition in the following parts of the paper (e.g., angular rooms, classic rooms, etc.).

Considering that we collected 33 separate outcome variables, and conducted two different tests with each (angular vs. curved, modern vs. classic), eventually we had to conduct 66 frequentist statistical tests. When performing multiple statistical tests, one should take into account that setting the alpha value to 0.05 will result in 5/100 significant results purely by chance, in our case 3.3 significant tests. According to the Bonferroni correction method, which strongly controls for family-wise error rate, the critical value for each comparison is the type I error rate divided by the number of comparisons: $\alpha/k = 0.05/66 = 0.00076$. However, we also checked for the false discovery rate (FDR) correction, as the Bonferroni correction has been considered overly conservative [79]. FDR correction controls for the proportion of "discoveries" (significant results) that are false positives.

To examine if the observed non-significant results in the frequentist approach represent an absence of the predicted relation between room contour and dependent variables measuring mood and cognition, we examined the amount of evidence in favor of the null hypothesis using the Bayesian framework [80]. The BF_{01} in the Bayesian framework indicates how much more likely it is that the data occur given the null hypothesis.

The analyses within the frequentist approach were conducted using R Studio—v1.4 Tiger Daylily (RStudio, Boston, MA, USA), and Bayesian analyses using JASP—version 0.14.1.0 (University of Amsterdam, Amsterdam, The Netherlands).

3. Results

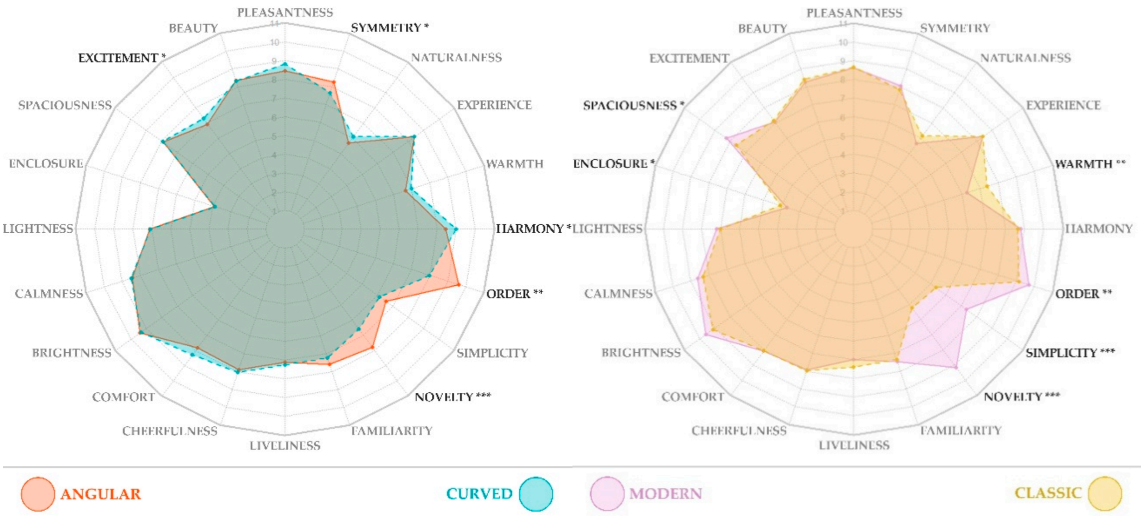
3.1. Behavioral Measures

3.1.1. Affective and Spatial Experience (ASE)

The paired-samples *t*-test revealed that participants rated angular rooms higher compared to curved rooms on dimensions novelty ($t(40) = 3.95$, $p < 0.001$), order ($t(40) = 6.20$, $p < 0.001$) and symmetry ($t(40) = 2.13$, $p = 0.039$), whereas curved rooms were rated as more exciting ($Z = 2.01$, $p = 0.044$) and harmonious than angular rooms ($t(40) = -2.39$, $p = 0.022$).

Regarding the room style, modern rooms were perceived as more novel ($Z = 5.31$, $p < 0.001$), more simple ($t(40) = 6.26$, $p < 0.001$), more ordered ($t(40) = 2.78$, $p = 0.008$) and more spacious ($Z = 2.49$, $p = 0.013$) compared to classic rooms, while the latter were rated as warmer ($t(40) = -3.23$, $p = 0.002$) and more enclosed ($Z = -1.45$, $p = 0.014$) than modern rooms.

We found no statistically significant difference in any of the dimensions: pleasantness, beauty, lightness, calmness, brightness, comfort, cheerfulness, liveliness, familiarity, experience, and naturalness neither for contour nor style comparisons. Participants' responses on the affective and spatial dimensions are illustrated in Figure 4.



(**a**) (**b**)

Figure 4. Display of participants' responses to the bipolar dimensions of the affective and spatial experience questionnaire. The scales were converted from (−5, 0, 5) to (1–11) for analysis and display purposes. Individual scores were calculated based on averaging responses to every two rooms presenting the same condition, and the charts' scores represent means on each of the dimensions. Plot (**a**) displays results for contour conditions (angular vs. curved), and plot (**b**) shows results of style conditions (modern vs. curved). Significant dimensions are marked with asterisks (*** for $p < 0.001$, ** for $p < 0.01$, and * for $p < 0.05$) and are written in black color for ease of reference. These graphics were created in R Studio, using package fmsb (Minato Nakazawa, 2021, Available on https://cran.r-project.org/web/packages/fmsb/index.html).

3.1.2. Momentary Affective State (MAS)

Contrary to our hypothesis, we did not find any effects of contour on momentary affective states. Moreover, Bayesian factors show that the evidence for no effect ranges from anecdotal evidence for a null result for contour effect on the self-report of being active (BF_{01} = 1.16), to moderate evidence for a null result in the case of self-reported fear (BF_{01} = 8.41). Similarly, there was no effect of style on momentary affective state, and Bayes factors span from anecdotal evidence for the absence of the style effect—on the heartbeat (BF_{01} = 2.00) up to moderate evidence—in the case of alertness (BF_{01} = 5.37). Participants' responses are shown in Figure 5.

3.1.3. Perceived Restorativeness (PR)

There was no difference in self-reported restored attention after having been immersed in angular compared to curved rooms—$t(35) = -0.79$, $p = 0.436$, nor in modern compared to classic rooms—$t(35) = -0.94$, $p = 0.352$. Bayesian factor indicates that there was anecdotal evidence in favor of an absence of effect of contour (BF_{01} = 2.7) and moderate evidence of absence of style effect on perceived restorativeness (BF_{01} = 3.7).

3.2. Cognitive Task (CT)

In line with the behavioral data, we found no effect of contour ($Z = -0.43$, $p = 0.667$) or room style ($Z = 0.59$, $p = 0.552$) on cognitive performance. The evidence in favour of null results is moderate for both contour (BF_{01} = 5.12) and style (BF_{01} = 4.79) effects on cognitive performance.

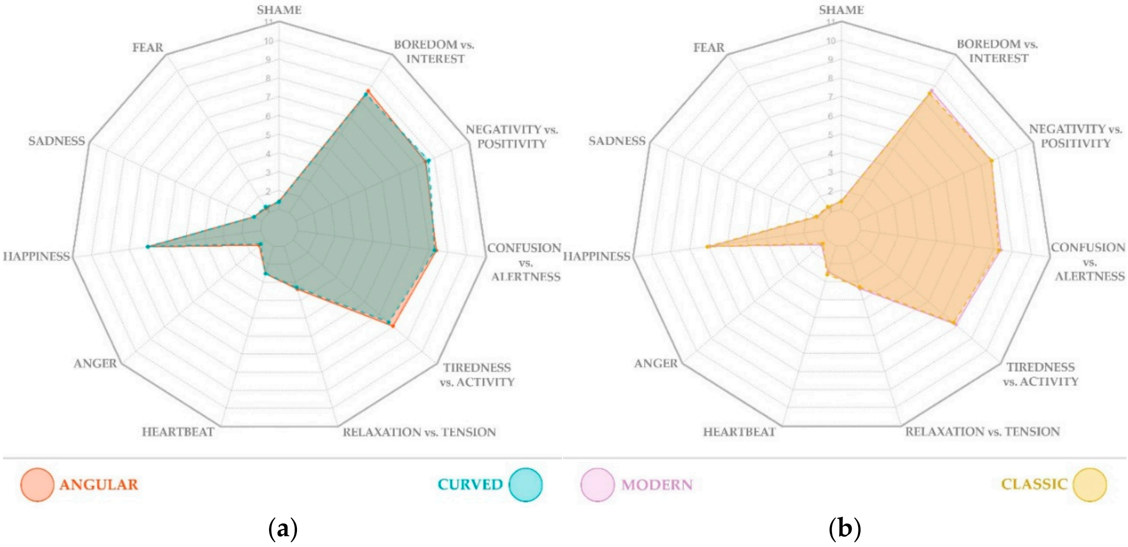


Figure 5. Display of participants' responses to the momentary affect questionnaire. Emotional feelings and bodily sensation were rated on unipolar scales (0–10), while arousal and valence (tension, activity, positivity) and cognitive (alertness) and motivational (interest) states ratings were presented on bipolar scales (−5, 0, 5). Both scales were converted to (1–11) for analysis and display purposes. Individual scores were calculated based on averaging responses to every two rooms presenting the same condition, and the charts' scores represent means on each of the dimensions. Plot (**a**) displays results for contour conditions (angular vs. curved), and plot (**b**) shows results of style conditions (modern vs. classic). These graphics were created in R Studio, using package fmsb (Minato Nakazawa, 2021, Available on: https://cran.r-project.org/web/packages/fmsb/index.html).

3.3. Virtual Reality (VR) Experience

A paired sample Wilcoxon signed-rank test indicated a significant increase of the overall cybersickness symptoms experienced by participants ($Z = 4.5423$, $p < 0.001$) from pre- ($Mdn = 7.48$, $IQR = 22.44$) to post- measurements ($Mdn = 26.18$, $IQR = 29.92$) (Table S5). This suggests that the total stay in VR increased the simulation sickness symptoms. We calculated a (post-pre) total score and performed additional analyses to control for the effect of simulation sickness on participants' responses. However, no main effects were found.

IPQ scores were computed for each of the subscales. On a 1–5 scale, mean scores were respectively GP ($M = 3.93$, $SD = 0.91$), SP ($M = 3.44$, $SD = 0.63$), INV ($M = 3.27$, $SD = 0.98$), and REAL ($M = 2.68$, $SD = 0.47$), indicating above medium values for all the subscales, and an acceptable feeling of presence.

3.4. Additional Analyses

Out of the 66 frequentist tests we conducted, we expected 3.3 to be significant by pure chance. However, five returned significance in contour comparison, and six in style (marked with asterisks in Tables 1 and 2). When applying the Bonferroni method, with the corrected threshold of $p < 0.00076$, four tests survived the correction: novelty and order in contour comparison in favor of angular rooms, in addition to novelty and simplicity in favor of modern rooms when comparing style. However, when applying a less stringent correction method, the FDR correction, warmth remains significant in style comparison with classic rooms perceived as warmer than modern ones.

In line with the frequentist approach findings and the FDR correction, the harmonic mean of the Bayesian factors BF_{01} only indicated strong evidence for the alternative hypothesis (<0.1) in the case of the five aforementioned dimensions in the respective comparisons. All statistical tests and Bayes factors are reported in Tables 1 and 2.

Table 1. Results of the statistical analyses performed on contour conditions using a classical frequentist approach and a Bayesian approach, in addition to the central tendency. Where data is normally distributed, means with standard deviation, and Student *t*-test results are reported. In the case of unmet normality assumption, we report median and IQR, and Wilcoxon signed-rank test results. Effect sizes and alternative hypotheses are also shown for each of the outcome measures.

Dependent Variables	Contour (Angular × Curved) Central Tendency				Classical Frequentist Approach	Bayesian Approach	
	Angular		*Curved*		*Paired sample* t*-test*	*Hypothesis*	BF_{01}
Questionnaire assessing momentary affective state; $N = 41$; Age = 18–40 ($M = 27.71$); F = 25, M = 16							
Shame	1	(0.5)	1	(0.5)	$Z = -0.227, p = 0.821, r = -0.035$	angular ≠ curved	$BF_{01} = 5.38$
Fear	1	(0.5)	1	(0.5)	$Z = -0.804, p = 0.422, r = -0.126$	angular > curved	$BF_{01} = 8.408$
Sadness	1	(1)	1	(0.5)	$Z = 0.267, p = 0.789, r = 0.042$	angular > curved	$BF_{01} = 4.75$
Happiness	6.99	(±2.38)	7.01	(±2.27)	$t(40) = -0.128, p = 0.899, d = 0.02$	angular < curved	$BF_{01} = 5.356$
Anger	1	(0)	1	(0)	$Z = 1.469, p = 0.142, r = 0.229$	angular > curved	$BF_{01} = 1.635$
Heartbeat	2	(2)	2	(2)	$Z = -0.696, p = 0.486, r = -0.109$	angular ≠ curved	$BF_{01} = 4.801$
Tension	2.5	(2.5)	2.5	(2)	$Z = 0.193, p = 0.847, r = 0.03$	angular > curved	$BF_{01} = 4.855$
Activity	8	(3)	8	(3)	$Z = 1.590, p = 0.112, r = 0.248$	angular ≠ curved	$BF_{01} = 1.16$
Alertness	8.5	(2)	8.5	(1.5)	$Z = 0.336, p = 0.737, r = 0.052$	angular ≠ curved	$BF_{01} = 5.352$
Positivity	9	(2.5)	9	(2)	$Z = -0.893, p = 0.372, r = -0.139$	angular < curved	$BF_{01} = 2.36$
Interest	8.5	(2.5)	8.5	(2.5)	$Z = 1.336, p = 0.182, r = 0.209$	angular ≠ curved	$BF_{01} = 2.53$
Questionnaire assessing affective and spatial experience; $N = 41$; Age = 18–40 ($M = 27.71$); F = 25, M = 16							
Peasantness	8.46	(±1.54)	8.82	(±1.39)	$t(40) = -1.615, p = 0.114, d = 0.252$	angular < curved	$BF_{01} = 0.959$
Beauty	9	(2.5)	8.5	(1.5)	$Z = -0.197, p = 0.844, r = -0.031$	angular < curved	$BF_{01} = 5.607$
Excitement [1]	**7**	**(2.5)**	**7.5**	**(2.5)**	$\mathbf{Z = -2.009, p = 0.046\ *, r = -0.314}$	**angular < curved**	$\mathbf{BF_{01} = 0.742}$
Spaciousness	7.93	(±1.69)	7.95	(±1.71)	$t(40) = -0.112, p = 0.911, d = 0.018$	angular ≠ curved	$BF_{01} = 5.89$
Enclosure	3.91	(±1.59)	3.87	(±1.81)	$t(40) = 0.168, p = 0.867, d = 0.026$	angular ≠ curved	$BF_{01} = 5.85$
Lightness	7	(3)	7	(3)	$Z = 0.548, p = 0.584, r = 0.086$	angular < curved	$BF_{01} = 7.414$
Calmness	8.43	(±1.18)	8.50	(±1.41)	$t(40) = -0.335, p = 0.740, d = 0.052$	angular < curved	$BF_{01} = 4.487$
Brightness	9.43	(±1.32)	9.35	(±1.6)	$t(40) = 0.414, p = 0.681, d = 0.065$	angular ≠ curved	$BF_{01} = 5.47$
Comfort	8	(2)	8.5	(2)	$Z = -1.617, p = 0.106, r = -0.252$	angular < curved	$BF_{01} = 0.774$
Cheerfulness	8	(2.5)	8	(1.5)	$Z = -1.173, p = 0.241, r = -0.183$	angular < curved	$BF_{01} = 2.244$
Liveliness	7.5	(2.5)	7	(3)	$Z = -0.026, p = 0.980, r = -0.004$	angular ≠ curved	$BF_{01} = 5.641$
Familiarity	7.57	(±2.07)	7.23	(±1.98)	$t(40) = 1.123, p = 0.268, d = 0.175$	angular ≠ curved	$BF_{01} = 3.301$
Novelty [1]	**7.79**	**(±1.64)**	**6.60**	**(±1.88)**	$\mathbf{t(40) = 3.946, p < 0.001\ ***, d = 0.616}$	**angular ≠ curved**	$\mathbf{BF_{01} = 0.0116}$
Simplicity	6.56	(±1.76)	6.13	(±1.86)	$t(40) = 1.478, p = 0.147, d = 0.231$	angular > curved	$BF_{01} = 1.18$
Order [1]	**9.60**	**(±1.05)**	**7.98**	**(±1.76)**	$\mathbf{t(40) = 6.196, p < 0.001\ ***, d = 0.968}$	**angular ≠ curved**	$\mathbf{BF_{01} = 0.0000162}$
Harmony [1]	**8.45**	**(±1.57)**	**8.98**	**(±1.26)**	$\mathbf{t(40) = -2.390, p = 0.022\ *, d = 0.373}$	**angular < curved**	$\mathbf{BF_{01} = 0.241}$
Warmth	6.5	(2.5)	7	(3.5)	$Z = -0.939, p = 0.348, r = -0.147$	angular ≠ curved	$BF_{01} = 3.435$
Experience	8.40	(±1.51)	8.39	(±1.58)	$t(40) = 0.053, p = 0.958, d = 0.008$	angular < curved	$BF_{01} = 6.172$
Naturalness	5.67	(±2.22)	6.12	(±2.26)	$t(40) = -1.523, p = 0.136, d = 0.238$	angular < curved	$BF_{01} = 1.103$
Symmetry [1]	**8.26**	**(±1.81)**	**7.66**	**(±1.82)**	$\mathbf{t(40) = 2.130, p = 0.039\ *, d = 0.333}$	**angular ≠ curved**	$\mathbf{BF_{01} = 0.779}$
Questionnaire on perceived restorativeness; $N = 36$; Age = 18–40 ($M = 27.31$); F = 23, M = 13							
Total score	3.10	(±0.54)	3.16	(±0.52)	$t(35) = -0.789, p = 0.436, d = 0.131$	angular < curved	$BF_{01} = 2.7$
Cognitive task scores; $N = 42$; Age = 18–40 ($M = 27.55$); F = 27, M = 15							
CT scores	9.86	(8.56)	9.56	(9.25)	$Z = -0.431, p = 0.666, r = -0.067$	angular < curved	$BF_{01} = 5.123$

[1] Rows in bold indicate statistically significant outcome measures (bolded for ease of reference). Significance is also marked with asterisks next to *p*-values.

Table 2. Results of the statistical analyses performed on style conditions using a classical frequentist approach and a Bayesian approach, in addition to the central tendency. Where data are normally distributed, means with standard deviation, and Student *t*-test results are reported. In the case of unmet normality assumption, we report median and IQR, and Wilcoxon signed-rank test results. Effect sizes and alternative hypotheses are also shown for each of the outcome measures.

Dependent Variables	Style (Modern × Classic)						
	Central Tendency				Classical Frequentist Approach	Bayesian Approach	
	Modern		*Classic*		*Paired sample t-test*	*Hypothesis*	*BF_{01}*
Questionnaire assessing momentary affective state; $N = 41$; Age = 18–40 ($M = 27.71$); F = 25, M = 16							
Shame	1	(0.5)	1	(0.5)	$Z = -0.261$, $p = 0.794$ $r = -0.041$	modern ≠ classic	$BF_{01} = 5.171$
Fear	1	(0.5)	1	(0.5)	$Z = -1.103$, $p = 0.27$, $r = -0.172$	modern ≠ classic	$BF_{01} = 4.069$
Sadness	1	(1)	1	(0.5)	$Z = 0.118$, $p = 0.906$, $r = 0.018$	modern ≠ classic	$BF_{01} = 5.08$
Happiness	7.5	(3)	7.5	(3.5)	$Z = -0.823$, $p = 0.411$ $r = -0.128$	modern ≠ classic	$BF_{01} = 4.265$
Anger	1	(0.5)	1	(0)	$Z = 1.718$, $p = 0.086$, $r = 0.268$	modern ≠ classic	$BF_{01} = 2.15$
Heartbeat	2	(2)	2	(2)	$Z = -1.464$, $p = 0.143$, $r = -0.229$	modern ≠ classic	$BF_{01} = 2.003$
Tension	3.39	(±2.01)	3.29	(±1.97)	$t(40) = 0.555$, $p = 0.582$, $d = 0.087$	modern ≠ classic	$BF_{01} = 5.129$
Activity	8	(2)	8.5	(2.5)	$Z = 0.508$, $p = 0.612$, $r = 0.079$	modern ≠ classic	$BF_{01} = 4.701$
Alertness	8.38	(±1.61)	8.30	(±1.86)	$t(40) = 0.458$, $p = 0.650$, $d = 0.072$	modern ≠ classic	$BF_{01} = 5.37$
Positivity	9	(2)	9	(2.5)	$Z = -1.151$, $p = 0.250$, $r = -0.180$	modern ≠ classic	$BF_{01} = 4.462$
Interest	8.5	(1.5)	8.5	(2)	$Z = 0.690$, $p = 0.49$, $r = 0.109$	modern ≠ classic	$BF_{01} = 4.35$
Questionnaire assessing affective and spatial experience; $N = 41$; Age = 18–40 ($M = 27.71$); F = 25, M = 16							
Pleasantness	9	(1.5)	9	(1)	$Z = -0.210$, $p = 0.834$, $r = -0.033$	modern ≠ classic	$BF_{01} = 5.608$
Beauty	8.5	(1.5)	9	(2)	$Z = -0.937$, $p = 0.349$ $r = -0.146$	modern ≠ classic	$BF_{01} = 4.36$
Excitement	7.07	(±1.84)	7.17	(±1.96)	$t(40) = -0.315$, $p = 0.754$, $d = 0.049$	modern ≠ classic	$BF_{01} = 5.657$
Spaciousness[1]	**8.5**	**(2)**	**7.5**	**(3)**	$\mathbf{Z = 2.487}$, $\mathbf{p = 0.0129}$ *****, $\mathbf{r = 0.388}$	**modern ≠ classic**	$\mathbf{BF_{01} = 0.139}$
Enclosure[1]	**3.5**	**(1.5)**	**4**	**(2)**	$\mathbf{Z = -2.452}$, $\mathbf{p = 0.014}$ *****, $\mathbf{r = -0.383}$	**modern ≠ classic**	$\mathbf{BF_{01} = 0.275}$
Lightness	7.21	(±1.92)	7.01	(±1.86)	$t(40) = 0.750$, $p = 0.458$, $d = 0.117$	modern ≠ classic	$BF_{01} = 4.55$
Calmness	8.61	(±1.23)	8.32	(±1.62)	$t(40) = 0.998$ $p = 0.324$, $d = 0.156$	modern ≠ classic	$BF_{01} = 3.726$
Brightness	9.5	(1.5)	10	(2.5)	$Z = 1.617$, $p = 0.106$, $r = 0.253$	modern ≠ classic	$BF_{01} = 1.068$
Comfort	8.07	(±1.78)	8.05	(±2.06)	$t(40) = 0.060$, $p = 0.952$, $d = 0.009$	modern ≠ classic	$BF_{01} = 5.918$
Cheerfulness	7.93	(±1.51)	7.99	(±1.69)	$t(40) = -0.213$, $p = 0.832$, $d = 0.033$	modern ≠ classic	$BF_{01} = 5.803$
Liveliness	6.98	(±2.16)	7.39	(±2.02)	$t(40) = -1.121$, $p = 0.269$, $d = 0.175$	modern ≠ classic	$BF_{01} = 3.307$
Familiarity	7.5	(3)	7.5	(3.5)	$Z = 1.113$, $p = 0.266$, $r = 0.174$	modern ≠ classic	$BF_{01} = 4.528$
Novelty[1]	**9**	**(1.5)**	**4.5**	**(3)**	$\mathbf{Z = 5.308}$, $\mathbf{p < 0.001}$ *******, $\mathbf{r = 0.829}$	**modern > classic**	$\mathbf{BF_{01} = 0.0000576}$
Simplicity[1]	**7.34**	**(±1.79)**	**5.35**	**(±1.93)**	$\mathbf{t(40) = 6.262}$, $\mathbf{p < 0.001}$ *******, $\mathbf{d = 0.978}$	**modern ≠ classic**	$\mathbf{BF_{01} = 0.00001322}$
Order[1]	**9.70**	**(±1.09)**	**9.15**	**(±1.42)**	$\mathbf{t(40) = 2.780}$, $\mathbf{p = 0.008}$ ******, $\mathbf{d = 0.434}$	**modern ≠ classic**	$\mathbf{BF_{01} = 0.21}$
Harmony	8.78	(±1.46)	8.65	(±1.64)	$t(40) = 0.458$, $p = 0.649$, $d = 0.072$	modern ≠ classic	$BF_{01} = 5.371$
Warmth[1]	**6.26**	**(±2.27)**	**7.39**	**(±1.98)**	$\mathbf{t(40) = -3.236}$, $\mathbf{p = 0.002}$ ******, $\mathbf{d = 0.505}$	**modern ≠ classic**	$\mathbf{BF_{01} = 0.0727}$
Experience	8.39	(±1.56)	8.40	(±1.73)	$t(40) = -0.042$, $p = 0.967$, $d = 0.007$	modern ≠ classic	$BF_{01} = 5.924$
Naturalness	5.65	(±2.28)	6.15	(±2.37)	$t(40) = -1.411$, $p = 0.166$, $d = 0.220$	modern ≠ classic	$BF_{01} = 2.37$
Symmetry	8.06	(±1.83)	7.85	(±1.74)	$t(40) = 0.793$, $p = 0.432$, $d = 0.124$	modern ≠ classic	$BF_{01} = 4.416$
Questionnaire on perceived restorativeness; $N = 36$; Age = 18–40 ($M = 27.31$); F = 23, M = 13							
Total score	3.07	(±0.6)	3.20	(±0.67)	$t(35) = -0.942$, $p = 0.352$, $d = 0.157$	modern ≠ classic	$BF_{01} = 3.7$
Cognitive task scores; $N = 42$; Age = 18–40 ($M = 27.55$); F = 27, M = 15							
CT scores	10.58	(10.14)	9.50	(7.61)	$Z = 0.594$, $p = 0.553$, $r = 0.092$	modern ≠ classic	$BF_{01} = 4.791$

[1] Rows in bold indicate statistically significant outcome measures (bolded for ease of reference). Significance is also marked with asterisks next to *p*-values.

4. Discussion

Within the scope of the present study, we primarily examined the potential psychological response to indoor virtual living rooms with contrasting contour conditions (angular and curved) on affect, behavior, and cognition. Such findings would contribute to understanding the relationship between humans and the built environments they occupy, and would inform the design of therapeutic settings in ways to optimize cognitive functioning, physical and mental health, and well-being. The very few studies that have investigated these conditions in indoor architectural settings have used for that purpose either photos of existing spaces [4,8,49], computer-generated three-dimensional images in color [45] and greyscale [44], sketches and line drawings [46], or schematic virtual environments where the overall form of the room was manipulated [10,73]. Most of these studies reported a preference for, and higher positive emotion in curved/curvilinear conditions as opposed to angular/rectilinear/linear ones (references above), with more recent studies reporting an opposite effect [4]. This may be the result of problems that are prominent to this new field of study [12], among which is a lack of systematic development of a coherent theoretical and experimental framework [57]. We took several measures in an attempt to address some of the methodological shortcomings of previous studies. The first one concerns the nature of the stimuli. For that, we ensured that the virtual environments presented are fully matched in terms of contour contrast, and avoided the possible effects of other confounding variables (e.g., lighting conditions, outside view, room size, floor finish, ceiling height and finish, door location and size, and so on). All these variables were kept identical in all four simulated rooms. Moreover, we included a second level-variable, architectural style, so that we presented to participants a variety that could cover different aesthetic preferences, noting that findings of previous studies were inconsistent with regard to preference. The second shortcoming is related to the lack of real-life architectural experience in previous studies and the predominant use of static stimuli. Therefore, we opted for a VR set-up that stimulates 3D rather than 2D perception, with a free-exploration paradigm and no restrictions on the path; subjects were able to explore the space from different viewing angles, whether standing, sitting, or crouching to see a specific detail. Moreover, we presented high-quality and detailed immersive environments, which were created via high-definition photorealistic instant renderings and post-processing methods (videos of the room can be found on https://drive.google.com/drive/folders/1rIPx0GBHubAsQaWxBWnkY7odOPXn_yiL, Accessed on 19 September 2021). However, we respected the recommended guidelines to reduce VR-induced symptoms and effects by providing high-quality graphics and ensuring that the immersive session did not exceed the recommended maximum duration [81]. Moreover, we familiarized all our participants with the VR system by means of a training session. Third, with regard to outcome measures, we aimed to extend beyond the limited conventional ratings of valence and arousal, criticized by some as not representative of the spatial aesthetic experience [53]. Hence, we included a relatively large set of affective, behavioral, and cognitive measures. Extending from previous evidence on the curvature preference and positive affective effects in both non-architectural and architectural settings, we expected the curved conditions to positively influence momentary affect, emotional and spatial experience, cognitive performance, and perceived restorativeness.

To our surprise, we did not find relevant positive effects of contour in most of the outcome measures, although the study had a comparably large sample size (e.g., N = 18 [8], 17 [10], 71 × two groups [49]). In fact, the only differences observed between the two contrasting conditions, after correcting for false discoveries, favored angular versions on "novelty" and "order" ratings. This finding stands in contrast to some experimental studies where ratings of pleasantness, attractiveness/beauty, and arousal indicated more positive responses to curved rather angular conditions (e.g., [8,44,46,49]). In particular, we were surprised that in our analysis, differences in self-reports on both "pleasantness" and "beauty" were statistically insignificant. While results indicated a non-significant trend in the predicted direction indicating higher pleasantness ratings for rooms with curvature, the Bayes factor indicated no evidence in this direction. As for beauty, ratings' means were very similar in both conditions. This is in line with a previous study, where contour had no effect on beauty judgments in laypeople [49]. We also did not find any differences in ratings of arousal dimensions neither in ASE nor in MAS (e.g., excitement, liveliness, calmness, interest, tension, heartbeat, alertness, activity). In terms of momentary affect in general, our results mainly indicated no evidence for the threat hypothesis, as ratings on "fear" were at the lower extreme in both conditions. As a matter of fact, all scores on negative affect were considerably low (e.g., shame, anger, sadness), while all items related to positive dimensions in both MAS and ASE were above average (considering 6 is the midpoint of the 1–11 scale) for both conditions. This effect is consistent with a previous study [56,57], where no differences were reported on valence (pleasantness, comfort) and arousal dimensions between simulated furnished rooms (cutting edge with rounded furniture and modern with angular edges), albeit those were highly rated when compared to an empty room. One could think that participants reported a pleasant experience in all of the furnished rooms because they were impressed by the degree of realism in those, or by the virtual experience per se. But then the effect would drop after "affective habituation" [82]. As response bias was proposed as a function of presentation order in lengthy sequential preference judgments [83], we controlled for the stimulus presentation sequence and found no main effects. We also did not find any differences in perceived restorativeness, nor in cognitive performance, while Bayes' factors showed poor evidence of the alternative hypothesis.

In our exploratory analyses of style, results primarily validated our stimuli's second-level contrast with modern rooms being rated significantly higher than classic ones on the "traditional/novel" scale. This effect was reconfirmed within the Bayesian analysis which indicated strong evidence for the alternative hypothesis. No main difference in the general assessment of style on positive or negative affect or aesthetic value measures was observed, consistent with some previous studies [63,65–67], except for complexity and warmth, in favor of classic rooms. While the results of complexity ratings confirmed some previous findings [67], and could be argued as a natural result of the classical style being inclusive of more details (e.g., ornaments) in its principles, the slight difference in the color palette between the two styles could be a confounding factor in the case of warmth. On the other hand, the inclusion of more "green" or "biophilic" features did not impact ratings on naturalness or perceived restorativeness. We also find this surprising as these elements are considered within the biophilic design framework. No other effect of style was found in any of the other outcome variables. Future studies primarily investigating architectural style should aim at maximizing the control for confounding variables by providing well-matched high and low-level properties.

Comparing our almost null results in terms of contour comparison to previous findings of studies that investigated indoor environments and familiar objects, it could be explained by several points. The first concerns the relatively extended viewing time in our study (3 min of exploration time), when compared with previous ones, which mostly relied on gut reactions, by either presenting the stimuli very shortly (84 to 3000 ms) (e.g., [8,31]), or by instructing participants to immediately respond without thinking (e.g., [44]). Previous investigations have found that preference for curved stimuli, which was pronounced under limited times (84 to 150 ms), faded when the stimulus was displayed until response. This finding was replicated with images of real objects [26,35] and abstract shapes [29]. An influence of meaning and semantic content on preference was suggested. In fact, when presenting the same images of indoor environments until response, effects were not consistent with previous studies [4,10,46], and a preference for rectilinear interiors was actually found across the three groups of participants in the most recent study: individuals with autism spectrum condition, neurotypical adults, and design and art students. Another point to consider concerns the use of forced-choice dichotomous scales in some of the previous studies reporting the preference of curved conditions (e.g., beautiful/not beautiful, or like/dislike). The lack of a response options in the middle might have boosted the preference response, as proposed by some researchers, when interpreting the different effects found in their study investigating abstract shapes [29]. We opted for a psychometric

11-point scale to allow for undecided responses. The third point relates to the fact that most of the previous research investigating contour, in general, has targeted similar populations, particularly female participants and psychology students [30], causing limitations in terms of generalizing results. However, we included a rather heterogeneous sample, recruited via more diversified databases. Last but not least, additional potential reasons concern the cultural and individual differences between the populations of the different studies. Culture was proposed to effect aesthetic preference and sensitivity, with the latter suggested change over time, exposure, and perspective [3]. From an architecture point of view, interiors, with the potential affordances (see James Gibson) they create, host the complex interaction between specific atmospheres shaped by different spatial compositions, the perceiver's characteristics, and their interpretation [5]. A probabilistic model of aesthetic response was proposed to explain the ongoing interaction between humans and their physical environments [50], and identified, in addition to design attributes, a series of factors including biology, personality, social and cultural experience, goals, expectations, associations, and internal constructs. These factors are suggested to contribute to the aesthetic response, impacting affect, physiological response, and behavior. The model acknowledged the complexity of the architectural experience, and further highlighted the major limitation caused by the neglect of the human movement's influence on the spatial experience in studies that use static stimuli. More than two decades after its publication, most of the known effects still relate to static stimuli rather than real-life experiences.

Even though recent research is targeting inter-individual differences in shape preferences in spaces and objects' contexts, the role of individual measures on preference is as yet uncertain, requiring further investigations [33,84]. However, when looking closely at previous studies, an interesting sex effect appears. While a curvature preference was observed when the sample predominantly consisted of female psychology, art, and design students [44,49], environments with rectilinear properties were preferred when the sample had a prevalence of male (design students, neurotypical or autistic participants) [49]. The same set of images showed a preference for curved interiors when the sample size consisted of more females than males [8,49]. The authors interpreted the preference for rectilinear spaces in their study as the result of familiarity, which was previously found to be relevant for preference formation [34,38], although other studies investigating drawings of familiar objects have found it to modulate preference for curvature [33]. The sex effect was also found when presenting sketches of familiar objects, where females judged curvilinear objects as more peaceful than males [37]. Additionally, another recent study presenting abstract shapes as stimuli has found that curvature preference was stronger for female students in psychology [30]. This effect was potentially attributed to gender rather than biological determinants. In this present study, post hoc analyses showed a sex effect, however, beyond the preference of one of the conditions over the other (Post-hoc)). Namely, when looking solely at angular rooms, males performed better than females in the cognitive task. Additionally, they rated those rooms higher than females on six out of the 20 affective and spatial dimensions, and reported higher scores on positive affect after exploring them. Although such results could possibly hint at a higher appreciation of angularity in males, this finding is to be interpreted cautiously for many reasons. First, our sample was not balanced in terms of sex and consisted of females more than males. Second, higher scores related to angular conditions do not necessarily indicate the preference of a shape over the other. This suggests that future works could benefit from including equally sized sex groups.

However, there are some limitations to the present study. Although the stimuli were still presented during rating tasks, the evaluation time was relatively long (3 min of exploration vs. an average of 9 min for CT and self-reports). Participants had to provide ratings in each room for 31 questions. This might have caused an effect known as the "museum-fatigue effect" [85], which has been found in many experimental observations and laboratory experiments. Causes were originally attributed to fatigue, but later to other cognitive factors such as satisfaction, information overload, and limitations in attentional capacity [83]. In terms of momentary affect, we had selected a scale that includes a broad range of negative emotions, to evaluate the threat hypothesis previously proposed [31]. However, participants scored very low on negative emotions and used more of the given scale for questions that offered both positive and negative anchors. In future studies, more focus should be directed to positive emotions. Concerning cognitive performance, the selected task was stress-inducing, which is why it is part of the Trier stress test. Although it had proven efficacy in previous studies investigating physical environments [72], it could be that the stress induced by the task might have overlapped the possible effects of contours.

Future studies may want to focus more strongly on implicit measures of emotions, less stress-inducing cognitive tasks, a lower number of outcome variables, and a more positive set of emotions. Sex could be further explored through the selection of a well-balanced sample. One route is to examine inter-individual differences, which include personality traits and expertise in arts and design. However, more differences should be taken into account, such as cultural background, previous experience with VR, information on familiar and lived architectural environments, among others.

5. Conclusions

In summary, while the evidence for curved contour preference in the context of abstract shapes and lines seems robust, it does not appear to be as strong in architectural settings, as multiple studies fail to demonstrate or replicate findings. The present study addressed previous limitations and found that exposure to contrasting contours in virtual interiors within a heterogeneous sample did not elicit significant differences in response to a broad set of psychological dimensions, with tasks and questionnaires administered directly after free exploration, yet within the virtual space, to record an immediate response. The fact that we assessed multiple domains during a close-to-reality architectural experience of fully controlled stimuli, not finding major effects in any of them, makes the study the most comprehensive in the field until now. This suggests that the psychological response to indoor design is much more complex and cannot be reduced into a generalized effect of contour or style, and could involve further multifaceted layers that affect the judgment of spaces on a more individual and contextual level. These results will help to convey a more real-life perspective of the response to the architectural experience in experimental settings and highlight the necessity of further investigations by providing directions for future research.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/ijerph182312510/s1, Table S1: Affective and spatial experience (ASE) dimensions with their respective domains, along with the tagged descriptive adjectives and numeric scales, Table S2: Momentary affective state (MAS) dimensions with their respective domains, along with the tagged descriptive adjectives and numeric scales, Table S3: Perceived Restorativeness Scale (PRS) items, along with the respective original subscales they represent, Table S4: Included/excluded participants for each set of measures, along with reasons for exclusion, Table S5: Scores on the SSQ, including the three subscales (Nausea, Oculomotor disturbance, and Disorientation), in addition to the total score, Post-hoc: Exploratory analysis of sex, Videos: Short videos inside the rooms

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Supplementary Materials

1. Tables and Figures

Table S1. Affective and spatial experience (ASE) dimensions with their respective domains, along with the tagged descriptive adjectives and numeric scales.

Dimension	Anchors	Left	Right
Pleasantness	unpleasant vs. pleasant	5 = describes strongly	5 = describes strongly
Beauty	ugly vs. beautiful	5 = describes strongly	5 = describes strongly
Excitement	not exciting vs. exciting	5 = describes strongly	5 = describes strongly
Spaciousness	narrow vs. spacious	5 = describes strongly	5 = describes strongly
Enclosure	open vs. closed	5 = describes strongly	5 = describes strongly
Lightness	overwhelming vs. light	5 = describes strongly	5 = describes strongly
Calmness	stressful vs. calming	5 = describes strongly	5 = describes strongly
Brightness	dark vs. bright	5 = describes strongly	5 = describes strongly
Comfort	uncomfortable vs. comfortable	5 = describes strongly	5 = describes strongly
Cheerfulness	depressing vs. cheerful	5 = describes strongly	5 = describes strongly
Liveliness	lifeless vs. lively	5 = describes strongly	5 = describes strongly
Familiarity	unfamiliar vs. familiar	5 = describes strongly	5 = describes strongly
Novelty	traditional vs. novel	5 = describes strongly	5 = describes strongly
Simplicity	complex vs. simple	5 = describes strongly	5 = describes strongly
Order	chaotic vs. ordered	5 = describes strongly	5 = describes strongly
Harmony	not harmonious vs. harmonious	5 = describes strongly	5 = describes strongly
Warmth	cold vs. warm	5 = describes strongly	5 = describes strongly
Experience	bad vs. good	5 = describes strongly	5 = describes strongly
Naturalness	artificial vs. natural	5 = describes strongly	5 = describes strongly
Symmetry	asymmetrical vs. symmetrical	5 = describes strongly	5 = describes strongly

Table S2. Momentary affective state (MAS) dimensions with their respective domains, along with the tagged descriptive adjectives and numeric scales.

Domain	Dimension	Anchors	Left	Right
Emotional feeling	Shame	embarrassed / ridiculed / ashamed / foolish	0 = little	10 = too much
	Fear	frightened / timid / afraid / scared	0 = little	10 = too much
	Sadness	sad / depressed / miserable / dejected	0 = little	10 = too much
	Happiness	happy / gay / cheerful / delighted	0 = little	10 = too much
	Anger	angry / annoyed / mad / sore	0 = little	10 = too much
Bodily sensation	Heartbeat	sensation of a pounding heart	0 = little	10 = too much
Arousal & valence	Relaxation vs. tension	(calm / relaxed / placid / at ease) vs. (nervous / restless / tense / wound up)	5 = applies very much	5 = applies very much
	Tiredness vs. activity	(tired / fatigued / sluggish / exhausted) vs. (energetic / active / animated / lively)	5 = applies very much	5 = applies very much
	Negativity vs. positivity	(negative / unpleasant) vs. (positive / pleasant)	5 = applies very much	5 = applies very much
Cognitive states	Confusion vs. alertness	(confused /baffled / perplexed) vs. (alert / attentive / receptive / lucid)	5 = applies very much	5 = applies very much
Motivational states	Boredom vs. interest	(bored / indifferent / dull) vs. (curious / interested / motivated)	5 = applies very much	5 = applies very much

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Table S3. Perceived Restorativeness Scale (PRS) items, along with the respective original subscales they represent: BA=Being away, COM=Compatibility, COH=Coherence, FA=Fascination, SCO=Scope.

Statement	Original subscale	Top	Bottom
This place piques my curiosity.	FA	0 = not true at all	4 = absolutely true
There are a lot to explore and discover here.	FA	0 = not true at all	4 = absolutely true
A lot of interesting things get my attention here.	FA	0 = not true at all	4 = absolutely true
The things and processes that I observed here are in natural harmony.	COH	0 = not true at all	4 = absolutely true
This place is fascinating.	FA	0 = not true at all	4 = absolutely true
To be here corresponds to my personal inclinations.	COM	0 = not true at all	4 = absolutely true
It is easy to do what I want here.	COM	0 = not true at all	4 = absolutely true
This place is a world of its own.	SCO	0 = not true at all	4 = absolutely true
Everything seems to have its place here.	COH	0 = not true at all	4 = absolutely true
When I stay here, nothing unwanted disturbs my concentration.	BA	0 = not true at all	4 = absolutely true
Spending time here creates a welcome change from my daily routine.	BA	0 = not true at all	4 = absolutely true
In this place the order of things is easy to see.	COH	0 = not true at all	4 = absolutely true

Table S4. Included/excluded participants for each set of measures, along with reasons for exclusion.

Measure	Excluded	Reason	N
General	3	dropped out (simulation sickness symptoms or headache)	45
ASE & MAS	4	technical errors[1]	41
CP	3	technical errors [1]	42
PRS	9	missing values[2]	36

[1] Technical errors include software/hardware errors, which resulted in either drop out before the end of the experiment, or multiple restarts leading to missing values in the datasets. [2] Missing values could have been due to a question not answered, or errors in data extraction.

Table S5. Scores on the SSQ, including the three subscales (Nausea, Oculomotor disturbance, and Disorientation), in addition to the total score.

Measure	Mdn	IQR	Range	Mdn	IQR	Range
		pre			post	
Nausea (N)	9.54	19.08	(0-19.08)	9.54	28.62	(0-28.62)
Oculomotor Disturbance (O)	7.58	15.16	(0-15.16)	22.74	22.27	(15.16-37.90)
Disorientation (D)	0.00	13.92	(0-13.92)	13.92	41.76	(0-41.76)
Total SS score (TS)	**7.48**	**22.44**	**(0-22.44)**	**26.18**	**29.92**	**(11.22-41.14)**

2. Exploratory Analysis of Sex (Post-Hoc)

As we attempted to control for sex, post-hoc analyses revealed a specific effect of both angular and modern rooms when comparing males and females' responses in each of the conditions separately. This effect was present in 3 out of 4 sets of outcome measures in the contour comparison, and 2 sets when comparing style.

Within the contour analysis, males rated angular rooms higher than females on 6 dimensions of the ASE out of the 20 tested: calmness ($t(36.423) = 2.905$, $p = 0.006$), cheerfulness ($t(38.356) = 2.803$, $p = 0.008$), excitement ($t(35.862) = 2.149$, $p = 0.034$), liveliness ($t(36.562) = 2.588$, $p = 0.0138$), familiarity ($t(38.606) = 2.525$, $p = 0.0158$), and experience ($t(38.195) = 2.118$, $p = 0.047$). Consistently, they reported higher on the positive emotions of the MAS, where they felt significantly more interested ($t(38.971) = 2.156$, $p = 0.034$), happy ($t(39) = 2.52$, $p = 0.016$), positive ($t(36.692) = 2.081$, $p = 0.044$), and active ($t(38.813) = 2.286$, $p = 0.028$) than women after angular rooms. They also performed better than females on the cognitive task after exploring angular rooms ($t(20.601) = 2.197$, $p = 0.039$).

The sex effect extended to room style, within the same 4 above mentioned positive dimensions of the MAS, where males reported on their momentary affective state with significantly higher values than females, after being exposed to modern rooms. Males reported more interest (t(38.58) = 2.97, p = 0.005), alertness (t(37.53) = 2.75, p = 0.009), happiness (t(38.99) = 2.47, p = 0.018), positivity (t(31.27) = 2.127, p = 0.04), and activity (t(38.89) = 3.03, p = 0.004). Moreover, they rated modern rooms higher than women on 7 out of the ASE's 20 dimensions: calmness (t(37.87) = 2.072, p = 0.045), cheerfulness (t(37.01) = 2.944, p = 0.005), excitement (t(36.774) = 2.472, p = 0.018), liveliness (t(31.428) = 2.072, p = 0.009), familiarity (t(37.235) = 3.455, p = 0.001), pleasantness (t(38.722) = 2.06, p = 0.045), and comfort (t(38.424) = 2.99, p = 0.005).

B: Paper II

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The contour effect: Differences in the aesthetic preference and stress response to photo-realistic living environments

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The interest in the response to contours has recently re-emerged, with various studies suggesting a universal preference for curved over angular stimuli. Although no consensus has yet been reached on the reasons for this preference, similar effects have been proposed in interior environments. However, the scarcely available research primarily depends on schematic or unmatched stimuli and faces heterogeneity in the reported results. In a within-subject design, we investigated the claimed contour effect in photo-realistic indoor environments using stimulus material previously tested in virtual reality (VR). A total of 198 online participants rated 20 living room images, exclusively manipulated on the contours (angular vs. curved) and style (modern vs. classic) levels. The scales represented aesthetic (beauty and liking) and stress (rest and stress) responses. Beyond our main focus on contours, we additionally examined style and sex effects to account for potential interactions. Results revealed a significant main effect of contours on both aesthetic (η^2_g=1–2%) and stress (η^2_g=8–12%) ratings. As expected, images of curved (vs. angular) contours scored higher on beauty, liking, and rest scales, and lower on stress. Regarding interactions with style, curvature was aesthetically preferred over angularity only within images depicting modern interiors, however, its positive effect on stress responses remained significant irrespective of style. Furthermore, we observed sex differences in aesthetic but not in stress evaluations, with curvature preference only found in participants who indicated female as their sex. In sum, our study primarily confirms positive effects of curvature, however, with multiple layers. First, the impact on aesthetic preference seems to be influenced by individual and contextual factors. Second, in terms of stress responses, which might be especially relevant for designs intended to promote mental-health, the consistent effects suggest a more generalizable, potentially biophilic characteristic of curves. To the best of our knowledge, this is the first study to demonstrate these effects in fully-matched, photo-realistic, and multi-perspective interior design stimuli. From the background of a previous VR trial from our research group, whereby the same rooms did not elicit any differences, our findings propose that static vs. immersive presentations might yield different results in the response to contours.

KEYWORDS

interior design, contours, style, aesthetic preference, stress response, sex-related differences, biophilia

Introduction

The human-environment interaction has recently been in the focus of many fields of research from humanities to natural sciences, with bourgeoning interdisciplinary efforts attempting to link characteristics of sensory stimuli to psychological responses and mental states. It is now widely accepted that the aesthetics of our physical surroundings, whether natural or man-made, can play a meaningful role in shaping our mood and overall well-being (Wohlwill, 1976; Gibson, 1979; Evans and McCoy, 1998; Gifford, 2002; Evans, 2003; Staats et al., 2003; Elliot and Maier, 2014; Coburn et al., 2020). Yet, little is known about this relationship within built settings, particularly with regards to the identification of features that drive the observed effects and the underlying psychological mechanisms (Eberhard, 2009; Graham et al., 2015; Coburn et al., 2017; Bower et al., 2019).

Affect: Aesthetic preference vs. stress response

During an aesthetic experience, visual properties and higher-order content are segregated along multiple brain regions involved in the regulation of reward and judgment (Chatterjee and Vartanian, 2014). An active simultaneous involvement of emotional, cognitive, and contextual factors is suggested to mediate such aesthetic encounters (Chatterjee and Vartanian, 2014; Coburn et al., 2017). Among the various proposed theoretical models addressing the alternating roles of affect and cognition, it has been commonly agreed that evaluations/judgments are the result of bottom-up stimulus properties and top-down appraisals (Leder et al., 2004; Mastandrea and Bartoli, 2011; Chatterjee and Vartanian, 2016; Chamberlain, 2022). Experiencing a positive and pleasant aesthetic encounter will therefore increase positive affect (Leder et al., 2004), potentially benefiting health and well-being (Coburn et al., 2017). Despite the remaining open questions of which subjective (top-down) and objective (bottom-up) features exactly drive (interindividual) differences in empirical aesthetics, consistent response patterns were found and attributed to certain aesthetic primitives. Stimulus properties such as contour shape (Bar and Neta, 2007; Vartanian et al., 2013), color (Palmer et al., 2013; Strauss et al., 2013; Elliot and Maier, 2014), as well as symmetry (Tyler, 2003; Bertamini et al., 2018, 2019), order, complexity (Nadal et al., 2010; Van Geert and Wagemans, 2021), and global image properties (e.g., fractality) were proposed as objective predictors of aesthetic preference (Chamberlain, 2022). However, other approaches stress the idiosyncrasies of preferences, demonstrating a stronger shared taste for natural or naturally inspired aesthetic domains as opposed to artifacts of human culture (Vessel et al., 2018).

Although aesthetic preference has been long argued as part of the affective domain (within the broad pleasantness dimension), a differentiation between conscious responses (i.e., preference as cognitive accompaniments of an emotion) and innate ones (i.e., affects) has been made (Ulrich, 1983). Beyond preference, physical environments can affect the stress response inducing changes on the psychological, physiological (bodily), hormonal (cortisol), and behavioral levels (Ulrich et al., 2008). For instance, it has become increasingly clear that the exposure to natural environments can reduce psychological and physiological stress (Ulrich et al., 1991; Berto, 2014), with new evidence of a causal effect on stress-related brain regions (Sudimac et al., 2022). Such mechanisms are linked to the biophilia hypothesis which suggests an innate evolutionary-based tendency for humans to connect with nature (Wilson, 1984). This hypothesis has been extended onto man-made environments, and frameworks of biophilic design have emerged (Browning et al., 2014; Kellert and Calabrese, 2015; Salingaros, 2015, 2019; Coburn et al., 2019), proposing that elements such as light, colors, fractals, representation of nature, and also curves, not only increase perceived aesthetic value, but can also reduce stress in humans (Salingaros, 2019; Yin et al., 2020).

The contour effect, learnt or innate?

Among the many environmental features, contour shapes have been proposed to play a fundamental role in how we perceive our surroundings (Loffler, 2008; Chuquichambi et al., 2022). Over the last two decades, the investigation of contours has recently regained momentum with seemingly robust evidence supporting a universal positive effect of curvature (Bar and Neta, 2007; Gómez-Puerto et al., 2016; Palumbo and Bertamini, 2016; Cotter et al., 2017). When presented with images showing lines, abstract/geometric shapes, drawings/images of real objects, or sketches/images of products (e.g., packages, car interiors), it appears that people prefer curved over angular or edgy stimuli (Gordon, 1909; Leder and Carbon, 2005; Bar and Neta, 2006; Silvia and Barona, 2009; Westerman et al., 2012; Palumbo et al., 2015; Chuquichambi et al., 2021). Findings were replicated under different experimental paradigms, further exploring other possible stimulus-related mediators, but also interindividual differences (moderators) of this phenomenal effect (refer to Tawil et al., 2021 and Corradi and Munar, 2019 for a more detailed review).

However, the origin of this phenomenon is still under debate, with no consensus reached as to the psychological mechanisms that drive it. On the one hand, the cumulative evidence from humans of different ages (including newborns and infants) (Fantz and Miranda, 1975; Jadva et al., 2010) and cultures (Gómez-Puerto et al., 2018), as well as non-human animals (Munar et al., 2015), facilitated a conceivable notion of an evolutionary adaptive behavior, possibly developed through the avoidance of the potentially harmful edges (Bar and Neta, 2006). This "threat hypothesis" was backed up by neuroimaging data showing the activation of cerebral areas involved in processing of threat and fear (i.e., amygdala) when viewing greyscale images of edgy everyday objects, as opposed to their curved counterparts (Bar and Neta, 2007). Besides the evolutionary-based approach, other research found that the preference for curvature can also be modulated by trends or Zeitgeist effects (Carbon, 2010). Zeitgeist effects -translated literally as "spirit of the times"– designate time-related fluctuations in values (for instance, aesthetic ones) influenced by societal phenomena. This perspective noted the omnipresence of curvature in current contemporary times, enabled by technological advancements that allow the production of curves in time and cost-efficient ways, highlighting a confounding factor of time-specific preferences. Conversely, a different approach considered that the preference might stem from the shape of the curvature by itself, which provides good stimulus continuity (Wagemans et al., 2012), and thereby answers to one of the main Gestalt principles (Bertamini et al., 2016). A review developed a unifying framework for research on the psychological and neural mechanisms of curvature preference, distinguishing between sensorimotor-based explanations and those originating from appraisals (Gómez-Puerto et al., 2016). The review proposed that the learnt versus evolved/innate origins of the preference are not mutually exclusive, however, they require further research to uncover cultural and evolutionary foundations.

Contours in interior environments

Extending on the empirical evidence for this suggested contour effect, an encouraging body of experimental literature proposed similar patterns in the context of architecture and interior design. A positive response to curved/curvilinear as opposed to angular/rectilinear spaces was observed when reacting to images representing matched sketches/line drawings (Madani Nejad, 2007), colored (van Oel and van den Berkhof, 2013) or greyscale (Dazkir and Read, 2012) computer-generated scenes, and images of real environments (Vartanian et al., 2013, 2019), in addition to drawings of building facades (Ruta et al., 2019). Studies have shown that curvature was preferred over angularity and resulted in higher self-reported positive emotions such as pleasure (Küller, 1980; Hesselgren, 1987; Dazkir and Read, 2012; van Oel and van den Berkhof, 2013), relaxation, safety, privacy (Madani Nejad, 2007), in addition to a self-reported decision to approach (Dazkir and Read, 2012).

Most of previous studies used subjective semantic scales to depict affective and behavioral responses (e.g., valence, arousal, and approach-avoidance), with recent approaches including neuroscientific measures such as neuroimaging (Vartanian et al., 2013; Banaei et al., 2017). Although earlier research has attempted to cover a wider range of emotional responses, more recent studies have been focused on aesthetic preference measures, such as liking, pleasantness, attractiveness, and beauty. We note however that the main portion of the evidence on the contour effect originates from empirical aesthetics, a discipline highly concerned with the question of hedonic tones. This has been noted as a general limitation of the emerging lines of research investigating the effects of architectural spaces, which are mostly restricted to aesthetics and disregard other components of the cognitive-emotional dimension of architecture (Higuera-Trujillo et al., 2021). Beyond aesthetic preference and hedonic tones, environmental psychologists explore affective responses from additional domains, and highlight a particular role of the environment in regulating emotions and affecting mood (e.g., stress reduction Ulrich et al., 1991), thereby influencing human psychology and physiology.

In terms of stimulus material, previous research mainly adopted traditional presentation methods and used either matched but unrealistic stimuli with a limited number of images [e.g., $N=8$ in Madani Nejad (2007); $N=4$ in Dazkir and Read (2012)], or a higher number of images of real environments at the (substantial) cost of accepting a considerable number of confounding factors (Vartanian et al., 2013, 2019), adding in both cases further limitations to the generalizability of results. Research investigating objects, on the other hand, ensured matched stimuli, and presented greyscale photographs of real objects (Bar and Neta, 2007; Cotter et al., 2017) or line drawings (Chuquichambi et al., 2021; Sinico et al., 2021). However, to the best of our knowledge, all previous studies were typically restricted to one image per environment/object, thereby showing stimuli exclusively from one side. It is worth noting that the subject has received little experimental scrutiny beyond traditional stimulus presentation methods (i.e., static images), with very limited endeavors adopting real life objects/environments or virtual reality (VR) to reflect the three-dimensional experience. When comparing with traditional presentation modes, evidence on the curvature effect in virtual environments seems inconsistent. Empty virtual rooms with curved boundaries were found to elicit more pleasantness and arousal than those with linear boundaries (Banaei et al., 2017), while no effects were observed in another study where participants were immersed in photo-realistic virtual interiors (Tawil et al., 2021).

Additional (heterogeneous) evidence is emerging with extended research efforts and attempts to uncover the underlying psychological and neuronal mechanisms of this positive effect of curvature in interior contexts. While neuroimaging data resulting from an investigation of everyday objects demonstrated an activation of the amygdala when individuals perceive edgy stimuli (Bar and Neta, 2007), this was not observed with interior design stimuli (Vartanian et al., 2013), Conversely, curvilinear environments activated the medial orbitofrontal cortex. Subsets of the same image set were used in following studies yielding inconsistent effects, with the latest one finding a preference for rectilinear over curvilinear interiors (Palumbo et al., 2020). Interestingly, in the same study, curved abstract shapes were still preferred over angular ones. Of note, unlike the majority of previous research, in this study participants were mostly men.

Indeed, recent evidence suggested that the positive curvature effects might be moderated by individual factors such as gender and academic degree, highlighting that most of the findings from previous studies relied largely on female psychology students (Palumbo et al., 2021). Earlier research, however, has identified sex differences, linking contour preference and sketch production to symbolic representations of the human body morphology (Munroe et al., 1976). Similar tendencies were also observed in a previous study from our lab, where a significant positive effect of angular rooms (on cognitive performance and subjective ratings of affect and spatial experience) was found in male when compared to female participants (Tawil et al., 2021). However, to date, no study has yet attempted to examine these differences in contours evaluation with interior design stimuli.

The present study

Within the scope of the present study, we aimed to investigate the response to contours in interior environments, while addressing some of the limitations of previous research. Given that our earlier investigation of these effects in VR returned null results, we opted to test our stimulus material under the traditional presentation paradigm (i.e., presenting 2D static images), similarly to the biggest portion of previous studies. However, we provided more than one perspective of the same environment. Eventually, we presented 20 well-matched photo-realistic images representing a contrast in contours (angular vs. curved). We included style (modern vs. classic) as a second-level factor to take into consideration the evidence on a Zeitgeist effect potentially moderating curvature preference (Carbon, 2010). For the purpose of exploring internal processes possibly responsible for the assumed positive effects of curved contours beyond mere preference, we distinguished between aesthetic and stress responses. Aesthetic preference was represented by self-reports on beauty and liking, two measures that were mostly used in previous research. Stress response, on the other hand, was explored through the lens of the basic physiological antagonism parasympathetic – sympathetic activation, therefore, we included subjective evaluations of rest and stress. Moreover, we took the decision (after pre-registering) to control for a balanced sample in terms of reported biological sex in order to identify any potential differences. We expected a positive impact of curved contours on the explicit responses collected *via* subjective ratings of aesthetic preference (i.e., higher beauty and liking scores) and stress response (i.e., lower stress and higher rest scores). Conversely, considering the scarcity of evidence in the literature, we did not have a strong *a priori* prediction regarding any of the interactions of contour with style and/or biological sex.

Materials and methods

Participants

Based on unpublished results from a previous study piloting an implicit task using similar stimuli as in the present study (i.e., static images), a sample size estimation using G*Power—version 3.1 (Dusseldorf University, Dusseldorf, Germany) resulted in the need for 138 participants to enable a small effect size ($f=0.10$) with an alpha of 0.05 and a power of 0.80 for a within-subjects repeated measures ANOVA. Due to the potentiality of technical errors (or abortion mid-experiment), we aimed for a sample of up to 200 participants, to obtain at least 150 full datasets. The additional sample buffer was considered because the *apriori* effect size was based on one experimental task only. Recruitment was carried out *via* the online platform Prolific (www.prolific.co), and was stratified by sex (50:50). Eventually, 198 healthy adults were included in the study (aged between 18 and 69 years, $Mdn = 27.0 \pm 10.9$; 50% female participants), with no severe/uncorrected visual impairments. Further in−/exclusion criteria included fluency in German and self-reported absence of diagnosed mental or neurological disorder. Subjects were compensated with 8£ for participating in all parts of the experiment, which lasted for approximately 1 h in total. For further sample characteristics, see Table 1.

Stimulus material

The stimulus material was derived from a previous study where stimuli were presented in VR (Tawil et al., 2021). Minor adjustments were implemented to achieve further control over possible confounding variables. Two pairs of virtual living rooms were created using Autodesk's 3ds Max (L × W × H = 4.9 × 3.9 × 3 meters) and implemented in the gaming software Unity (version 2019.2.1f1, 64-bit). Rooms of each pair were identical in their design, except that one had angular objects, while the other had curved counterparts (factor 1 contour: angular vs. curved). The second contrast was the interior design style (factor 2 style: modern vs. classic). Each room included 18 objects that were matched in terms of bounding sizes, materials, and colors, and contrasted according to the study design factors (a comparative list of all objects from all rooms along with their images and dimensions is included in section 1.3 of the Supplementary material). The pairs were designed (by an expert in architecture) with the main objective of providing balanced and proportional objects that still reflect the same design spirit/style, without appearing unrealistic or unfamiliar. Therefore, they were inspired by common furniture that exist in both contour versions. In terms of style, we intended a periodic contrast rather than one relating to specific aesthetics, in order to investigate the previously proposed Zeitgeist effect (Carbon, 2010). However, to discriminate between the styles, the "classic" pair had items that originate from more traditional design periods (e.g., "Rococo" Louis XV furniture, "neoclassical" Louis XVI furniture, and "Georgian" sliding slash windows), while the "modern" one included items inspired by "minimalism," a much more recent style characterized by simplicity and clean lines. To provide diversity in the stimulus set, different cameras were placed inside the virtual rooms to capture different viewpoints from a first-person perspective. Images were rendered using Unity High Definition Render Pipeline (HDRP, version 6.9.1), and captured within Unity using

TABLE 1 Sample characteristics (*N*=198).

	Range[a]	*M*	*SD*	Freq.	%
Biol. variables					
Median age	18–69	27.0	10.9	–	–
Self-reported biological Sex (male/ female)[b]		–	–	99/99	50/50
Net income					
<1.250	–	–	–	84	42.4
1.250–1749	–	–	–	30	15.2
1.750–2.249	–	–	–	16	8.1
2.250–2.999	–	–	–	28	14.1
3.000–3.999	–	–	–	13	6.6
4.000–4.999	–	–	–	6	3.0
>5.000	–	–	–	8	4.0
do not want to answer	–	–	–	13	6.6
Education					
Median years of education[c]	5–13	12	1.33	–	–
Nominal level of education[d]					
No school degree	–	–	–	1	0.5
Low school degree	–	–	–	2	1.0
Middle school or lower	–	–	–	18	9.1
Highschool (A-levels)	–	–	–	177	89.4
Architectural/aesthetics knowledge					
Profession architecture/ interior design – yes	–	–	–	5	2.5
Median VAIAK – interest[e]	11–74	37.0	14.5	–	–
Median interior design interest VAS[f]	0–100	61.0	27.5	–	–
Median interior design – knowledge VAS[f]	0–100	23.0	23.8	–	–
Psychopathology					
Median DASS21- stress[g]	0–36	10.0	7.24	24	12.1
Median DASS21 – anxiety[g]	0–28	2.0	5.32	41	20.7
Median DASS21 – depression[g]	0–42	4.0	7.95	50	25.3

[a]Observed value range.
[b]The terms "male" and "female" are used as grouping adjectives, as this was how participants were asked to (dichotomously) classify themselves.
[c]School and professional education.
[d]Based on German education system.
[e]VAIAK, Vienna Art Interest and Knowledge Questionnaire, interest subscale, total scores can range from 1 to 77, in the original validation study, the mean for lay people was *M* = 37.9, SD = 12.9 (Specker et al., 2020).
[f]Visual analogue scale (0–100) to rate interest or knowledge concerning architecture and interior design.
[g]Values under frequency column are the number of subjects reaching a clinically meaningful cut-off (i.e., moderate severity) on the DASS21, depression, Anxiety and Stress Scale 21. The terms "male" and "female" are used as grouping adjectives, as this was how participants were asked to (dichotomously) classify themselves.

the tool "Screenshot Utility",[1] downloaded *via* the Unity Asset Store. Image size was set to 5,075 × 2,160 pixels, 4K resolution with ratio 21:9. Since we aimed to control for low-level image features [using ImageDecomposer[2] provided by Berman and colleagues (Berman et al., 2014; Kardan et al., 2015)], eventually, five out of the 15 generated images were selected per room, capturing all angles (for details on the low-level feature values and t-tests to compare curved vs. angular and modern vs. classic stimuli, please refer to section 1.1 of the Supplementary material) and a total of 20 images were included in the final stimulus set (the virtual cameras' positions are shown in Figure 1 for each of the perspective views). Each image belonged to one of the four categories: angular modern (AM), curved modern (CM), angular classic (AC), and curved classic (CC). Examples of the stimuli used are shown in Figure 1 (refer to section 1.2 of the Supplementary material for the complete stimulus set).

Experimental design and procedure

The experiment was implemented online using Inquisit 6 (millisecond, 2021), and a link to the study was provided for the participants on the online-recruitment-platform Prolific,[3] with a

1 https://assetstore.unity.com/packages/tools/utilities/screenshot-utility-177723

2 https://www.dropbox.com/sh/wykarfxm4jnhda0/AAAx8p3tIFBEqTdLSNIInGOla?dl=0

3 www.prolific.co

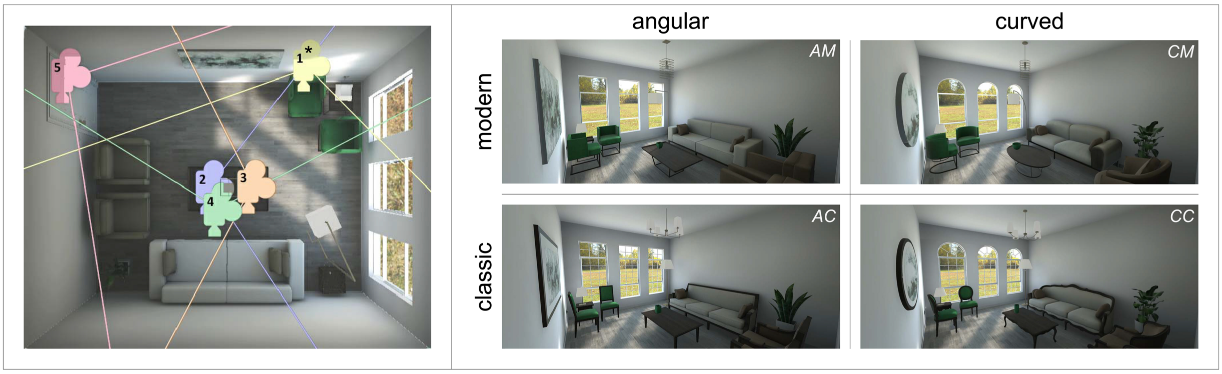

FIGURE 1
Stimulus material. Left: Plan of the room illustrating the five viewpoints/perspectives, numbered according to the order of presentation (angular modern condition is displayed as a room example). All cameras were positioned to simulate eye view from standing position (approximately 1,500 mm), except for camera 1 (marked with a star (*)) which was placed to replicate a view from a sitting position. Right: Example stimuli representing the 2×2 design and depicting "perspective 5" in all four conditions: angular modern (AM), curved modern (CM), angular classic (AC), and curved classic (CC).

completion code shown at the end for collection of the monetary compensation. Subjects were first presented with the study information, asked for their informed consent, and answered questions concerning the eligibility criteria. The experiment included three main sections. First, participants responded to a set of four different reaction time paradigms (1) *approach-avoidance task* (AAT; Wiers et al., 2011), (2) *implicit association task* (IAT; Greenwald et al., 1998), (3) *dot-probe* (DP; Bradley et al., 1992), and (4) *manikin task* (MT), (De Houwer et al., 2001)] that were intended to capture implicit responses, but which are not part of the current paper. Second, participants filled out questionnaires (only those reported in demographics later on in this paper are fully cited here) assessing socio-demographic details, general interest/knowledge in arts and architecture (adapted from The Vienna Art Interest and Art Knowledge Questionnaire, VAIAK; Specker et al., 2020), preferred interior design styles, tendencies to depression, anxiety, and stress to check psychopathology levels (DASS-21; Lovibond and Lovibond, 1995), and personality traits, in addition to information about growing up, current housing conditions and exposure to nature. Within the socio-demographic questionnaire, participants were also asked to indicate their biological sex (male or female), thus, for reasons of simplicity, we will be using the term "sex" when referring to related potential differences, and the adjectives "male" and "female" for the subgroups of participants who indicated either category. In the third part, which constitutes the main focus of the present analysis, participants responded to two sets of rating tasks, created for the purpose of this experiment. Each set was composed of four blocks, randomized across participants. Responses were collected on visual analogue scales (VAS, 0–100, numbers were invisible to participants to avoid direct comparisons) anchored with statements on both endpoints and shown below the to-be-rated image (for details on the questions in German language, see Supplementary Table 1). Images were set to 50, 50% (height, width) of their original size and placed at the center of X (50%) and slightly upwards (30%), relative to the screen size of participants (example slides are shown in Figure 2 below).

Rating task 1 – General appraisal scale (GAS)

In each of the GAS blocks, participants rated the four images displayed in Figure 1 (AM, CM, AC, CC; depicting a general perspective view from the door) on six dimensions representing a general spatial evaluation (VAS scales 0–100). Thus, a total of 4 (images) × 6 (rating dimensions) = 24 ratings were completed by each participant. The order of the rating dimensions was kept identical across blocks (i.e., edginess, roundness, curiosity, novelty, order/structure, and complexity), but images were presented in random order (refer to Figure 2 below). We will only report ratings on edginess and roundness, as these scales were intended as a stimulus manipulation check. The items (translated from German) were for *edginess* "How edgy do you perceive this room to be?" (left anchor: [0] "not edgy at all," right anchor: [100] "very edgy"), and for *roundness* "How round do you perceive this room to be?" (left anchor: [0] "not round at all," right anchor: [100] "very round").

Rating task 2 – Aesthetic and stress response (ASR)

Rating scales of the ASR represented "aesthetic preference", namely, *beauty* and *liking,* that were mostly used in previous studies on contours [e.g., (Vartanian et al., 2013; Palumbo et al., 2020)], in addition to "stress responses", operationalized to resemble basic psycho-physiological states in the form of self-reports on *rest* and *stress* (adapted from Madani Nejad, 2007). Blocks of the ASR scale were each related to one different dimension (beauty, liking, stress, rest), and presented in randomized order. Within every randomized block, participants rated each of the 20 stimuli, always presented in the same order, hence a total of 80 responses were collected from each participant (20 trials × 4 blocks) (refer to Figure 2). The items (translated from

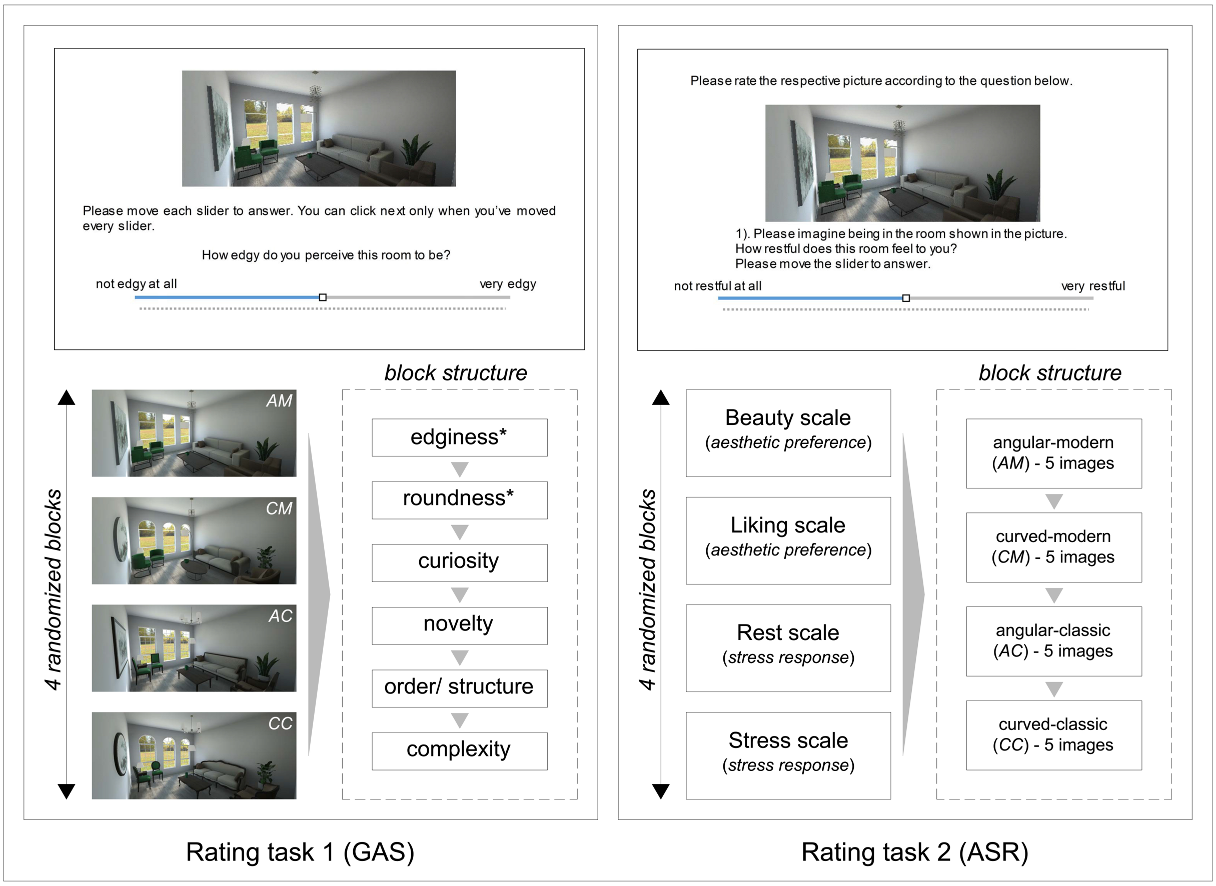

FIGURE 2
Illustration of the rating tasks structure. Left: Rating task 1 – General appraisal scale (GAS), consisting of four randomized blocks, each including six ratings (DV) of the same image (IV). Dimensions marked with a star (*) were meant for manipulation check and were reported within the present analyses. An example slide is illustrated on top of the structure, depicting "edginess" rating. Right: Rating task 2 – Aesthetic and stress response (ASR), consisting of four randomized blocks, each including ratings for 20 images (IV) on one single dimension (DV). The example slide shows "rest" rating scale. Both example trials are reconstructed and translated from German for illustration purposes.

German) were for *liking* "How much do you like the room shown in this picture" (left anchor [0] "not at all," right anchor [100] "very much"), for *beauty* "Please rate the beauty of the room shown in this picture" (left anchor [0] "not beautiful at all," [100] "very beautiful"), *rest* "Please imagine being in the room shown in the picture. How restful does this room feel to you?" (left anchor [0] "not restful at all"; right anchor [100] "very restful"), and for *stress* "Please imagine being in the room shown in the picture. How would you describe your emotional reaction?" (left anchor [0] "relaxed"; right anchor [100] "stressed").

Data analysis

We preregistered our research plan (which can be retrieved from https://aspredicted.org/B65_HP6) before the start of the study, as part of a larger experiment that adopted a novel approach using a battery of implicit tasks. However, due to the complexity of the experiment, we find it a crucial initial step to first explore, discuss, and report explicit responses to be able to relate the present study to previous ones with explicit assessments and to interpret any potential effects found through the reaction time paradigms. Although the explicit measures were not detailed in the preregistration, a general preference for curved over angular shapes was assumed, which would also be reflected in explicit rating differences of the stimulus material; i.e. higher aesthetic ratings, and lower stress as well as higher rest ratings for curved vs. angular stimuli.

All data analysis was conducted using R Studio—v1.4 Tiger Daylily (RStudio, Boston, MA, United States).

We split the analysis into three parts, matching the logic of our research questions, and following both a theory- and data-driven stepwise approach. The dependent variables (DVs) were participants' responses on the 0–100 VAS scales. Mean scores were assessed for each dependent variable (i.e., rating dimension) *via* repeated-measures analysis of variance (RM ANOVA). All analyses were controlled for repetitions within participants by means of the factor "subject."

We first conducted a manipulation check to test the contrast validity of our stimulus set (level 0). Thereby, to confirm the contour contrast was well discriminated within both styles, participants' ratings on "edginess" and "roundness" were analyzed separately following two 2 (contour: angular vs. curved) × 2 (style: classic vs. modern) repeated-measures ANOVAs. One dataset was excluded from the analysis due to missing values ($N = 197$ subjects included), and a total of 788 observations (197 participants × 4 images) were included in the analysis of each of the two rating scales (total = 1,576 data points).

For the main analyses, we conducted four two-way repeated measures ANOVA for each of the rating dimensions of the ASR scale to compare the main effects of contours (angular vs. curved) and style (classic vs. modern) as within-subject factors [IVs], as well as their interaction effects on the aesthetic (beauty, liking) and stress (rest, stress) response rating scores [DV] (level 1). Although we were interested in the overall response to the rooms rather than to each individual frame, we did not aggregate scores across perspectives prior to conducting the tests, and total of 3,960 data points were included in each of the four models (198 participants × 20 images). Since the effect of style exclusively was not part of the research questions addressed in this paper, related main effect analyses are briefly described within the manuscript (but are included in detail in Supplementary Table 9).

In the following step, and as we intended to examine potential sex differences (see introduction section for details), we conducted separate mixed ANOVAS for each of the dimensions of the ASR, with contours (angular vs. curved) as a within-subjects factor and sex as a between-subjects factor and as moderator variable [i.e., interaction effects]) (level 2).

For all models, we first report the main omnibus effects then interactions (with the respective descriptive statistics and effect sizes), each followed by the related pairwise comparisons on the different stimulus factors corrected using the False Discovery Rate method (FDR; Benjamini and Hochberg, 1995), along with effect sizes estimated by means of Cohen's d (Cohen, 1988). According to the commonly used interpretation, effect sizes are referred to as small ($d = 0.2$), medium ($d = 0.5$), or large ($d = 0.8$). We used the package "afex" (Singmann et al., 2022) to fit the models and produce inferential statistics, package "emmeans" (Lenth et al., 2022) for the pairwise comparisons, and package "effectsize" to compute Cohen's d values (Ben-Shachar et al., 2020).

Furthermore, we performed reliability analyses to check whether the ratings employed served as reliable measurement techniques for the aesthetic and stress responses to contours. For each of the rating scales, the different stimuli were regarded as "items" which were used to calculate Cronbach's α. As each image was repeated only once within each rating scale, every rating value was considered as one "item." Using function "cronbach.alpha" from the package "ltm" (Rizopoulos, 2022), Cronbach's α was calculated separately for each group of stimuli that we expected to produce similar explicit response (separately for each of the four combinations resulting from the 2×2 design).

Results

Manipulation check – Level 0

Results of the manipulation check (level 0) confirmed a highly significant main effect of contours on both *edginess* [$F(1, 196) = 2567.11$, $p < 0.001$, $\eta^2_g = 0.83$) and *roundness* [$F(1,196) = 2173.42$, $p < 0.001$, $\eta^2_g = 0.82$] ratings. Pairwise comparisons showed that images of angular contours were rated as more *edgy* [$t(196) = 50.67$, $p < 0.001$, $d = 3.62$; $M = 88.96 \pm 11.22$] and less *round* [$t(196) = -46.62$, $p < 0.001$, $d = 3.33$; $M = 7.87 \pm 10.29$] than those of curved ones (*edginess*: $M = 18.81 \pm 14.68$; *roundness*: $M = 77.11 \pm 16$) with exceptionally large effect sizes.

Significant interactions of contours with style were observed within both *edginess* [$F(1,196) = 10.85$, $p = 0.001$, $\eta^2_g = 0.01$] and *roundness* [$F(1,196) = 10.15$, $p = 0.002$, $\eta^2_g = 0.01$] scales. Post-hoc comparisons revealed that while our sample rated the angular versions of the images equally among the two styles concerning both edginess and roundness, significant differences were observed between ratings of the curved versions when they were depicting a classic as opposed to modern style [*edginess:* $t(196) = -4.85$, $p < 0.001$, $d = 0.35$; *roundness:* $t(196) = 4.19$, $p < 0.001$, $d = 0.30$], whereby images of classic style were perceived as edgier and less round than their modern counterparts. However, effect sizes were small (*edginess*: $d = 0.35$; *roundness*: $d = 0.3$), and this did not substantially influence the effects of contour, which remained particularly significant for the two rating dimensions within both styles ($d > 2.78$ for all four comparisons) (see Supplementary Figure 1 for a graphical depiction of main effects of contour and the interaction with style, and Supplementary Tables 2–6 for further descriptives).

Aesthetic and stress response ratings (level 1)

Main effect of contours

The 2 (contour: angular vs. curved) × 2 (style: modern vs. classic) RM ANOVA confirmed a general main effect of contours on all four dimensions of the ASR: *beauty* [$F(1,197) = 10.09$, $p = 0.002$, $\eta^2_g = 0.01$], *liking* [$F(1,197) = 6.32$, $p = 0.013$, $\eta^2_g = 0.01$], *rest* [$F(1,197) = 99.18$, $p < 0.001$, $\eta^2_g = 0.12$], and *stress* [$F(1,197) = 63.80$, $p < 0.001$, $\eta^2_g = 0.08$].

Pairwise comparisons revealed that images of curved contours were rated significantly higher than those of angular ones on aesthetic preference scales with small effect sizes: *beauty* [$t(197) = -3.18$, $p = 0.002$, $d = 0.23$; curved: $M = 51.72 \pm 14.87$, angular: $M = 47.75 \pm 15.07$] and *liking* [$t(197) = -2.51$, $p = 0.01$, $d = 0.18$; curved: $M = 51.22 \pm 15.57$, angular: 47.68 ± 16.13]. Furthermore, in terms of stress response, images of curved contours scored higher on *rest* [$t(197) = -9.96$, $p < 0.001$, $d = 0.71$; curved: $M = 55.1 \pm 13.30$, angular: $M = 43.34 \pm 15.30$] and lower on *stress* [$t(197) = 7.99$, $p < 0.001$, $d = 0.57$;

curved: $M = 37.39 \pm 11.83$, angular: $M = 46.22 \pm 13.62$] when compared with images showing angular interiors, with medium effect sizes. Figure 3 depicts the results of the contour main effect (refer Supplementary Tables 7, 8 for further descriptives).

Main effect of style

The main effect of style was also significant for all the scales of the ASR (see Supplementary Figure 2 for a graphical depiction of main effects of style, and Supplementary Tables 7, 9 for complete inferential statistics and descriptives).

Interaction of contours × style

There was a statistically significant interaction of contours with style in all the ASR scales *beauty* [$F(1,197) = 24.78$, $p < 0.001$, $\eta^2_g = 0.01$], *liking* [$F(1,197) = 45.75$, $p < 0.001$, $\eta^2_g = 0.01$], *rest* [$F(1,197) = 85.25$, $p < 0.001$, $\eta^2_g = 0.02$], and *stress* [$F(1,197) = 24.89$, $p < 0.001$, $\eta^2_g = 0.01$]. Effects of contours as a function of style are shown in Figure 4 (refer to Supplementary Tables 7, 10, 11 for further descriptives).

Interestingly, in terms of "aesthetic preference", post-hoc pairwise comparisons revealed statistically significant differences with small effect size only within the *modern style*, whereby *beauty* [$t(197) = -5.21$, $p < 0.001$, $d = 0.37$] and *liking* [$t(197) = -5.07$, $p < 0.001$, $d = 0.36$] scores were significantly higher for curved conditions (*beauty*: $M = 55.82 \pm 16.06$; *liking*: $M = 56.66 \pm 16.87$) as opposed to angular ones (*beauty*: $M = 46.87 \pm 17.01$, *liking*: $M = 49.00 \pm 19.32$). No significant differences were observed between images of angular and curved contours within the *classic style* in any of the two scales ($p > 0.05$). Interestingly, although insignificant, the direction of the effect was reversed in *liking* ratings, with curved conditions scoring lower than angular ones within the classic style category (refer to Supplementary Tables 7, 10, 11 for further descriptives).

Conversely, concerning "stress response", significant differences were observed in *rest* and *stress* scores within both *modern* (medium to large effects) (*rest*: $t(197) = -12.95$, $p < 0.001$, $d = 0.92$; *stress*: $t(197) = 9.43$, $p < 0.001$, $d = 0.67$) and *classic* (small effects) (*rest*: $t(197) = -5.45$, $p < 0.001$, $d = 0.39$; *stress*: $t(197) = 4.90$, $p < 0.001$, $d = 0.35$) conditions. Within the *modern style*, images of curved contours were rated as more restful ($M = 59.33 \pm 14.07$) and less stressful ($M = 33.45 \pm 12.77$) when compared with those of angular ones (*rest*: $M = 42.90 \pm 16.79$; *stress*: $M = 45.03 \pm 15.13$). The same applied to the *classic style*, however, the magnitude of the effect was less pronounced (refer to Supplementary Tables 10, 11 for further descriptives).

Sex-related differences (level 2)

Aesthetic preference ratings

ANOVA results showed a statistically significant two-way interaction of sex and contours for the *beauty* [$F(1,196) = 10.27$, $p = 0.002$, $\eta^2_g = 0.02$] and *liking* [$F(1,196) = 8.7$, $p = 0.004$,

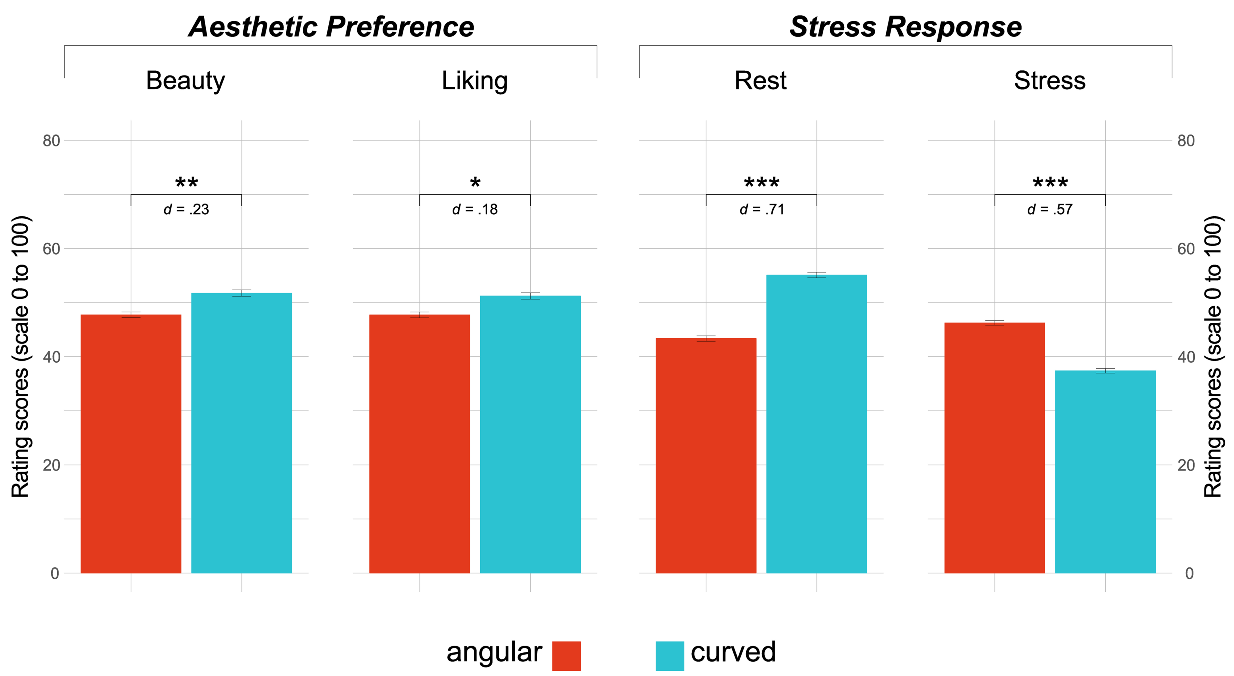

FIGURE 3
Contour main effect. Left to Right: Results of the analyses comparing mean scores of images of angular vs. curved interiors on the four rating scales representing "aesthetic preference" (*beauty* and *liking)* and "stress response" (*rest* and *stress*) evaluations. Scoring is on a range of 0–100. Bar graphs represent mean scores; error bars indicate standard errors. Asterisks represent significance, *$p<0.05$, **$p<0.01$, and *** $p<0.001$.

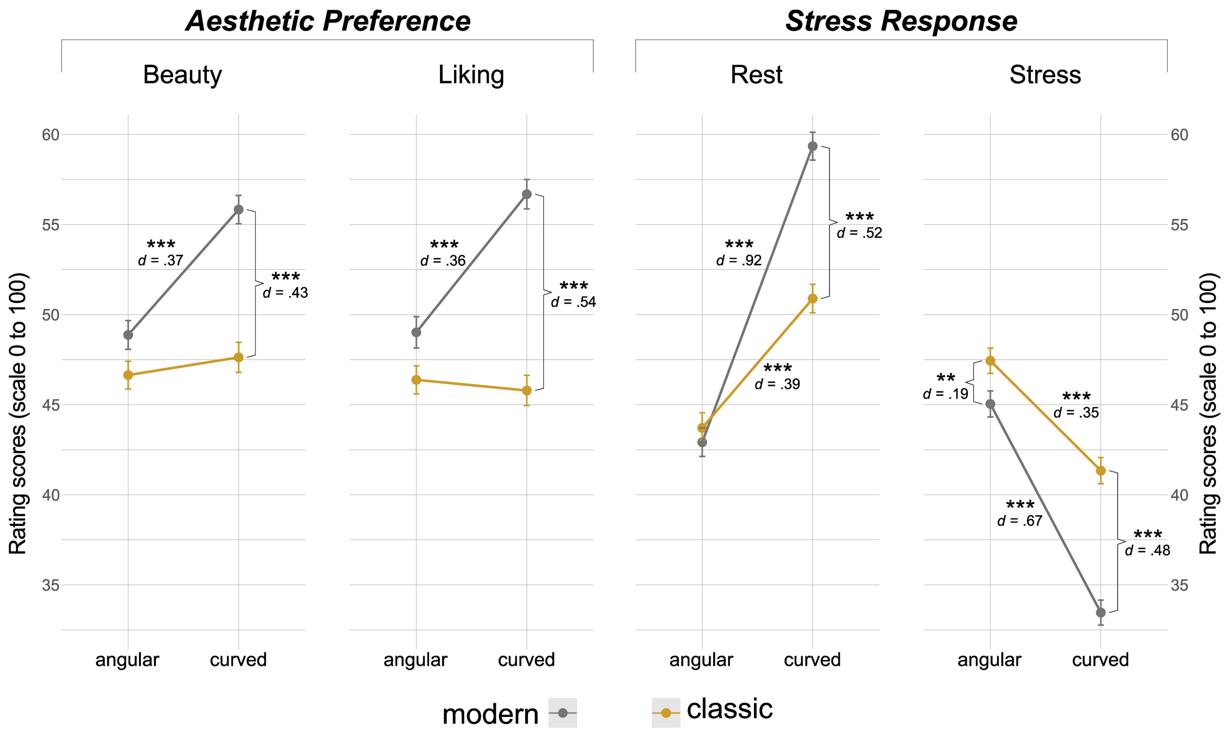

FIGURE 4
Contours and Style interaction. Left to right: Interaction plots depicting effects of contours, as a function of style, on each of the four rating scales representing "aesthetic preference" (*beauty* and *liking)* and "stress response" (*rest* and *emotion*) evaluations. Scoring is on a range of 0–100. Error bars represent means and standard errors. Lines do not indicate any temporal component between data points. Asterisks represent significance, *$p<0.05$, **$p<0.01$, and *** $p<0.001$.

$\eta^2_g = 0.02$] ratings (refer to Supplementary Table 12). Interestingly, post-hoc pairwise t-tests indicated that the positive effect of curved conditions was only significant and therewith mostly driven by participants who indicated their biological sex as female (referred to as female participants hereafter), who had rated images significantly higher on *beauty* [$t(196) = -4.56$, $p < 0.001$, $d = 0.33$] and *liking* [$t(196) = -3.90$, $p < 0.001$, $d = 0.28$] when they were showing curved (*beauty*: $M = 53.85 \pm 13.11$; *liking*: $M = 53.21 \pm 14.09$) as opposed to angular interiors (*beauty*: $M = 45.97 \pm 14.23$; *liking*: $M = 45.61 \pm 14.45$). There were no observed significant effects of contours on the preference ratings of participants who indicated male as their biological sex (referred to as male participants hereafter) ($p > 0.05$) (refer to Supplementary Tables 13, 14 for further descriptives).

Stress response ratings

Similar to preference measures, significant interactions of sex and contours were observed in both stress response ratings, namely *rest* [$F(1,196) = 11.2$, $p = 0.001$, $\eta^2_g = 0.02$] and *stress* [$F(1,196) = 6.06$, $p = 0.015$, $\eta^2_g = 0.01$]. However, in contrast with aesthetic preference, the positive effect of curved conditions was found to be significant in both sex groups, although with descriptively lower magnitude in male participants (refer to Supplementary Tables 13, 14 for complete inferential statistics and descriptives). Effects of contours as a function of sex (for both aesthetic preference and stress response) are shown in Figure 5.

Reliability analysis

The reliability analysis indicated acceptable to good internal consistencies among the different rating scales across all 20 respective stimuli within each of the four stimulus categories (i.e., Cronbach's α range for *beauty:* $0.80 < \alpha < 0.85$, *liking:* $0.8 < \alpha < 0.87$, *rest:* $0.74 < \alpha < 0.81$, and *stress:* $0.71 < \alpha < 0.81$). The results of the reliability calculations are presented in Table 2, along with the respective confidence intervals.

Discussion

In the previous literature, a positive effect of curved as opposed to angular stimuli has been empirically demonstrated, mostly in studies testing images of abstract shapes and (greyscale) everyday objects in different experimental paradigms. However, no consensus has yet been reached as to the source of this preference, with some scholars attributing the preference to attractive intrinsic properties of curves (Palumbo and Bertamini, 2016), while others proposed that it is caused by a possible sense of "threat" elicited by angularity/edginess (Bar and Neta, 2006). A growing body of experimental literature has suggested similar effects in the context of interior spaces and architecture (Dazkir and Read, 2012; Vartanian et al., 2013; van Oel and van den Berkhof, 2013). To investigate this phenomenon in different psychological domains and further examine whether other stimulus- or person-related characteristics can interact with the effect (i.e., interior design style and reported biological sex), we measured the explicit responses to matching photo-realistic images exclusively contrasted in terms of contours (angular vs. curved) and interior design style (modern vs. classic), in a balanced sample in terms of sex ($N = 198$). Building on the evidence in the literature, we hypothesized a positive impact of curved contours on both explicit aesthetic and stress responses collected *via* ratings of beauty, liking, rest, and stress (higher beauty, liking, and rest, and lower stress).

The effects of contours on aesthetic preference ratings

In line with our hypothesis, our results revealed that contour was a significant predictor for the variability in aesthetic response ratings. The post-hoc results showed that participants, in general, preferred images of curved contours, as indicated by the higher ratings on the liking scale, and found them more beautiful than those showing angular ones. These results support previous findings (Bar and Neta, 2006; Dazkir and Read, 2012; Vartanian et al., 2013, 2019; van Oel and van den Berkhof, 2013) and provide additional evidence on the effects of contours on aesthetic evaluations.

Despite the statistically significant main effects of contours in explaining the variability of aesthetic preference ratings, the percentage of explained variance was considerably low (i.e., 1% for *beauty* and *liking*) suggesting that factors other than contours may play a stronger role in the aesthetic response. In fact, both objective (characteristics of stimuli) and subjective (characteristics of context) factors are proposed to be important in shaping aesthetic experiences (Chamberlain, 2022). In a recent meta-analysis, the first to inspect the consistency of the curvature preference hypothesis, factors other than perceptual contour properties were identified as moderators of the effect, namely, presentation time, stimulus type, expertise, and task (Chuquichambi et al., 2022, pre-print). The study found small to non-significant effects with spatial design stimuli as opposed to larger effects with meaningless or real object stimuli. It might be that the sensitivity to curves in architectural settings involves more complex processes influenced by familiarity, meaning/affordances, or other observer-related differences. Although

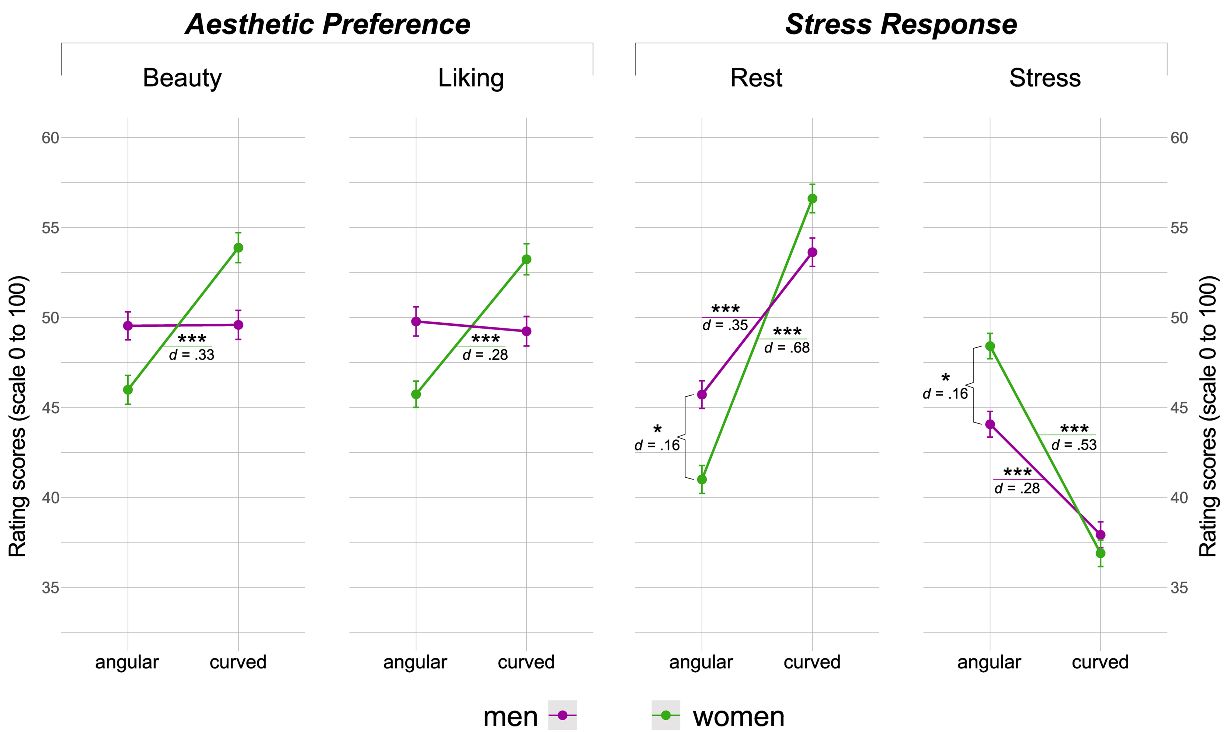

FIGURE 5
Contours and sex interaction. Left to right: Interaction plots depicting effects of contours, as a function of sex, on each of the four rating scales representing "aesthetic preference" (*beauty* and *liking)* and "stress response" (*rest* and *emotion)* evaluations. The terms "male" and "female" are used as grouping adjectives, as this was how participants were asked to (dichotomously) classify themselves. Scoring is on a range of 0–100. Error bars represent means and standard errors. Lines do not indicate any temporal component between data points. Asterisks represent significance, *$p<0.05$, **$p<0.01$, and *** $p<0.001$.

TABLE 2 Reliability of the rating scales (*N*=198), 5 items (5 picture per category AM, AC, CM, and CC).

	Beauty		Liking		Rest		Stress	
	Cronbach's α	CI	Cronbach's α	CI	Cronbach's α	CI	Cronbach's α	CI
Angular-modern (AM)	0.82	0.76–0.86	0.85	0.80–0.88	0.80	0.73–0.84	0.75	0.68–0.81
Angular-classic (AC)	0.83	0.78–0.86	0.84	0.79–0.88	0.80	0.74–0.84	0.78	0.72–0.83
Curved-modern (CM)	0.80	0.73–0.85	0.80	0.74–0.80	0.74	0.66–0.80	0.71	0.64–0.77
Curved classic (CC)	0.85	0.80–0.88	0.87	0.83–0.90	0.81	0.75–0.86	0.81	0.74–0.85

Bootstrap 95% confidence intervals (CI) based on 1,000 samples (2.5–97.5%).

we collected information on expertise, only 2.5% of our sample were identified as experts (had a training/profession in architecture/interior design), thereby not qualifying to run any moderation analyses.

Moreover, our results revealed a significant interaction effect between style and contours, confirming the idea of contextual factors other than contour shape *per se* influencing the evaluation. This is consistent with a previous study in which two pairs differing in their styles yielded significantly different self-reported pleasure and approach responses (Dazkir and Read, 2012). Interestingly, when looking at contours within each of the styles separately, results showed that the positive evaluation of curved versions on beauty and liking scales was conditional to the interiors belonging to the modern style, with no significant differences observed within the classic style category. This suggests that, although contours played a general role in aesthetic preference, the effect was dependent on other contextual factors, i.e., in this case style, which explained marginally larger proportions of variance (1 to 2%). Indeed, our sample preferred images of modern over classic style, and rated them significantly higher on the beauty and liking scales. The generally less favorable ratings of classic style might have affected scores and masked the contour-effects. At first glance, these results could be interpreted as being in accordance with previous findings which suggested that in addition to the proposed biological inclination towards curved objects, this preference could also be partly modulated by fashion, trends or Zeitgeist effects (Carbon, 2010). A confounding factor of time-specific preferences was suggested, since recent studies demonstrating a favoring of curved designs have been conducted in a period where curvature has been frequently used. Although we have not instructed our participants to evaluate the images as if they perceived them from a historical perspective, a similar Zeitgeist effect is to be expected when considering the style contrast of our stimulus set. However, the findings cannot confirm whether the observed effects strictly relate to time-specific aesthetics, or are rather the result of the generally negative appreciation of the classic category, or both, a question which would require investigating additional variations.

The effects of contours on stress response ratings

Generally, contour was a significant predictor of the variability in stress response ratings. Effects were robust and consistent. Pairwise comparisons showed that participants rated images of curved contours as more restful and less stressful than their angular counterparts. In line with previous findings (Madani Nejad, 2007; Dazkir and Read, 2012), our results provide evidence for the relaxing effect of curved contours in interior environments.

Contrary to the findings for aesthetic preference, the curvature positive effect was not dependent upon style, and the factor contour explained larger proportions of variance (8% for *rest* and 12% for *stress* as opposed to 1–2% in the case of aesthetic response). Although there was a significant interaction effect of contours with style, when examining the explicit stress response in rest and stress scales, curvature had a significant, similar positive effect on ratings in both interior design styles (i.e., higher rest and lower stress). The style comparisons showed that images depicting classic style were generally more negatively rated on both scales when compared to those belonging to the modern category, however, the contour effect remained significant. This suggests an overall stronger and more consistent effect of contours on stress response as compared to aesthetics, since stress-related findings "survived" the generally less favorable ratings of the classic style. With reference to the biophilia hypothesis and the deriving frameworks suggesting curvature as a biophilic asset in architecture and design (Kellert and Calabrese, 2015; Salingaros, 2015), it has been argued that nature commonly includes more curves than angles, therefore individuals are expected to be naturally drawn to curves (Salingaros, 2015; Coburn et al., 2019). Beyond exclusive preference, researchers have highlighted a role of curvature (and biophilic design *per* *se*) in reducing physical (bodily) and psychological stress (Salingaros, 2015, 2019). Our results present first evidence for the relaxing effects of curvature within fully controlled, yet ecologically valid settings.

Sex-related differences

Aesthetic preference ratings

When looking into scores of both sex groups separately, we found a significant effect of the factor "sex" for explaining the variability of aesthetic preferences. Specifically, female participants generally liked images of curved contours more than those of angular ones and rated them higher on beauty, while no differences were observed in male participants' ratings on both scales. This finding is in line with re-emerging implicit evidence suggesting potential differences in the appreciation of contours observed with abstract stimuli (Palumbo et al., 2021) and virtual indoor environments (Tawil et al., 2021). In fact, earlier research had examined sex differences in preference and production of shapes, and had associated those with "sex-linked symbolic properties" of the stimuli (Munroe et al., 1976). The last study to report sex differences investigated wrapped candies in children (Munroe et al., 1976). Although generally children from both sex groups ($N = 175$) chose the spherical candy over the cube shaped one more frequently, girls chose it even significantly more than boys (83% vs. 57%). The authors linked the effect to one's conception of their own body, at least regarding objects to be ingested. However, considering the age range of the study population (4 to 12 years old), it could be argued that the results rather speak for "projected body ideals," as body curves of both male and female sexes are thought to be similar until teenage years. Associations between curvature and femininity were previously proposed in spatial design, whereas sketches of interior spaces were found to be rated higher on the "masculine-feminine" scale as levels of curvature increased (Madani Nejad, 2007). More recent works noted that the main portion of the evidence on the effects of contour in most domains generally stems from homogeneous samples (i.e., female psychology students) (Palumbo et al., 2020), and indeed, a subsequent study observed a stronger preference for meaningless curves within this specific population (Palumbo et al., 2021). The findings were interpreted as evidence that the preference for curves has both social and biological roots. Generally, it has been suggested that men and women vary in how they respond to aesthetics (Djamasbi et al., 2007). Such differences could be related to social norms and gender stereotypes, but also to more biological sex differences (Lueptow et al., 1995). Biologically, sex-related differences in the neural correlate of beauty have been previously demonstrated, with the observed different strategies used for assessing aesthetics attributed to a division of labor between male and female hunter-gatherer hominin ancestors (Cela-Conde et al., 2009). Although our results present the first confirmatory evidence on sex-related differences in the aesthetic preference of curved interiors, the findings do not allow to discriminate whether these effects are sex- or gender-related. Since our sample reported on biological sex, we are using the term "sex," however, further research is needed to clarify whether these effects result from social constructs related to gender, or are rather intrinsic.

Stress response ratings

Conversely, in terms of stress response, our results showed that the factor "sex" did not have a substantial effect on the significance of any of the ratings scores on rest and stress dimensions. Both sex groups rated images of curved contours higher on rest and lower on stress when compared with those showing angular ones. However, the magnitude of the effect was descriptively higher in the female as opposed to male subgroup. Overall however, we observed more consistent effects than in aesthetic preference ratings, with larger effect sizes. The results imply that contours could have a more global effect on the explicit stress response. When comparing the ratings of the two subgroups within each contour category, descriptively, female participants rated images of angular contours more negatively, and those of curved contours more positively when compared with male participants. However, the differences only reached significance in the case of angularity, specifically in both stress response ratings.

In sum, whereas curvature was found to be aesthetically preferred over angularity, this explicit preference was conditioned by the factors "style" and "sex." In contrast, curvature's positive effects on explicit stress responses were not dependent on other stimulus- (i.e., style) or individual (i.e., sex-related) factors. The amount of explained variance by contour was considerably higher for stress as opposed to only small amounts explained for aesthetics. Moreover, post-hoc results showed small effect sizes in aesthetic preference ratings compared to those found in the stress response evaluations (medium to large effects). We interpret the independence of the curvature positive effect on the stress responses from context (style) and reported biological sex as hinting towards a generalized, hence perhaps adaptive, phenomenon. Future efforts could examine more implicit mechanisms that present objective indicators of a stress-reduction effect.

Before concluding our discussion, it is worth mentioning that although we observed an effect of curvature when presenting two-dimensional static images of the rooms, the same environments experienced in 3D and in real human scale *via* immersion in VR did not elicit any differences on a large set of affective and cognitive measures, including similar ratings as in the present study. VR has been proposed as an alternative to the costly real life setups, as it allows the manipulation and control of relevant experimental parameters (Franz et al., 2005), while providing the opportunity to enable a feeling of presence in a space, evoking responses that are similar to those elicited by real environments (Bishop and Rohrmann, 2003; Villa and Labayrade, 2012). This is particularly important within the increasing acknowledgement of the role of the body in the architectural experience (Spence, 2020). The present findings reiterate previous concerns as to whether environments affect us in the same way, or ultimately differently, when being inside them as opposed to looking at their image (Nasar, 1994). Although we are not able to directly compare the present results with the ones from our previous study, it is necessary to further explore and compare the curvature effect on the psychological and physiological responses within different presentation modes.

Limitations and directions for future research

Overall, this paper is far from providing decisive directions, as our current results are limited to explicit responses collected through self-reports, thereby lacking the objectivity required to draw affirmative conclusions. Although our measures lacked a common operationalization of such assessments, we were able to draw initial differentiation on the effects of contour on two different psychological domains that hypothetically operate through different mechanisms. Here, it is worth noting that Cronbach's coefficients confirmed the reliability of our measures, as they revealed good levels of internal consistencies, especially when considering the low number of "items" (5 items by category). However, given the high cross-correlations between all four rating dimensions (refer to Supplementary Table 15), further research is needed to define the most relevant factors when it comes to rating subjective responses to interior design stimuli, particularly in terms of psychometric scale development. Concerning the results, albeit effects were statistically significant, a small variance was found to be explained by our manipulated factors (contours, style). This implies that other factors may play a stronger role in the aesthetic and affective response variability. Given the complexity of environmental influences, with the present study only tapping into a few aspects of the visual domain, this is somewhat unsurprising. In addition, considering the acknowledged role of affect and/ or inter-individual differences in influencing the response to physical environments, future studies could balance their designs to account for variables such as mood, psychopathology, personality traits, and expertise, among others. As we asked our participants to report on their biological sex and did not assess sociological gender, we are unable to interpret whether the observed effects were the result of sex- or gender-related differences. However, we regard this issue critically and highlight the need to explore such effects beyond the limited perspective provided by the traditional binary definitions. Future works should assess gender identity together with biological sex (e.g., since birth) in a more differentiated way. Although our sample was considerably large when compared to similar studies, the fact that our participants were recruited online may affect the sample representation of a more general population, i.e., the sample was highly educated. Last but not least, with the absence of strong theoretical explanations – which presents one of the main challenges of the emerging fields investigating the psychological impact of architecture and design (Higuera-Trujillo et al., 2021) – it remains necessary to further explore these tendencies within different presentation modes, and with more objective paradigms that can better detect potential adaptive and unconscious responses and indicate more robust evidence on any source of this phenomenon.

Conclusions

In sum, the present study found differential evidence concerning aesthetic preference and stress response to contours in interior environments. On the one hand, the positive appreciation (beauty, liking) of curved compared to angular contours was found to be context (style) and sex-dependent (i.e., only in modern style, and only in participants who indicated female being their biological sex), suggesting that explicit aesthetic evaluations may vary meaningfully as a function of inter-individual and contextual (perhaps Zeitgeist) effects. On the other hand, the negative effects of angularity and edges on the stress responses (lower rest and higher stress), operationalized to resemble basic physiological/ affective states that may be triggered by environmental contexts, were robust, larger in magnitude, and not style or sex-dependent, also proposing a potentially adaptive response to curves, previously characterized as "biophilic." To the best of our knowledge, this is the first study that provides such evidence within fully-controlled yet ecologically valid settings (i.e., multiple photo-realistic images representing several perspectives of one space). Taken together, it could be speculated that the effects of contour in interior environments might be more generalizable with respect to psychological and physiological/ bodily responses than concerning the more conscious evaluations of aesthetics informed by experience and other cognitive mechanisms. Future works may want to focus on these dimensions which could be more relevant and especially important to informing designs intended for mental health promotion, however, using more implicit measures. On a last note, the significant results observed when presenting the same environments in the form of static stimuli (i.e., images, as opposed to VR immersion) raise the question of which exact role the modes of presentation and immersion play in aesthetic evaluations, stress, and other responses to contours and interior environments *per se* – a question which should be further followed upon.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: https://osf.io/mfpk2/.

Ethics statement

The studies involving human participants were reviewed and approved by Local Psychological Ethics Committee of the psychosocial center at Medical Center Hamburg-Eppendorf (LPEK-0215). The patients/participants provided their written informed consent to participate in this study.

Author contributions

NT and LA developed the experimental design idea and setup under supervision of SK. NT designed and provided the design stimuli, pre-processed the data, performed the analysis under supervision of LA and SK, and wrote the original first draft of the manuscript. LA and SK edited the first and all subsequent drafts. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.933344/full#supplementary-material

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Supplementary Material

1 Supplementary Information

1.1 Stimulus selection based on low-level features

Five low-level feature parameters (mean: edge density, hue, saturation, brightness, entropy) were extracted for each picture in Matlab R2017b using a script (ImageDecomposer, 2014) provided by Marc Berman and colleagues (available at: https://voices.uchicago.edu/bermanlab/stimuli-software/) (for background see Berman et al., 2014 and Kardan et al., 2015). Several rounds of stimulus generation and comparison (between angular vs. curved category pictures using t-tests) were conducted, as our goal was to create two sets of stimuli, that on average would not differ from one another in terms of the above-mentioned image features. Thereby, a simple matching procedure was used. The original picture pool included images taken from 15 different angles from each room (angular – modern, angular – classic; curved – modern, curved – classic), with a total of 60 stimuli. We selected five pictures to capture the rooms fully (i.e., from diverse perspectives), and checked whether there were any significant differences between the dimensions edgy vs. round. The results can be found in Table XX, which were all non-significant for all low-level feature parameters. Effect sizes for the contrast angular vs. curved were all small in magnitude. However, differences between design categories modern vs. classic, albeit all non-significant, were for hue of moderate effect size.

	T-value	**p-value (two-tailed)**	**Cohen's d**	**Mean (SD)**	**Mean (SD)**
	Angular vs. Curved			**angular**	**curved**
Hue (mean)	0.583	.567	.261	2.332 (0.315)	2.250 (0.313)
Brightness (mean)	0.136	.893	.061	0.512 (0.079)	0.507 (0.77)
Saturation (mean)	0.216	.832	.096	0.954 (0.027)	0.093 (0.028)
Entropy	0.048	.962	.021	7.392 (0.302)	7.386 (0.310)
Edge density	0.185	.406	.380	0.056 (0.015)	0.051 (0.010)
Green pixels (%)	0.151	.882	.068	0.021 (0.022)	0.020 (0.020)
	Modern vs. Classic			**modern**	**classic**
Hue (mean)	1.220	.238	.546	2.208 (0.307)	2.374 (0.302)
Brightness (mean)	0.967	.346	.433	0.526 (0.076)	0.493 (0.076)
Saturation (mean)	0.896	.382	.401	0.100 (0.030)	0.089 (0.248)
Entropy	0.106	.916	.048	7.396 (0.304)	7.382 (0.308)
Edge density	0.963	.352	.430	0.056 (0.016)	0.050 (0.008)
Green pixels (%)	0.877	.392	.392	0.025 (0.023)	0.017 (0.018)

1.2 Stimulus material

The stimulus material is available at https://osf.io/mfpk2/.

1.3 Inventory of objects and their properties in the different conditions (upper rows depict the modern category, and lower ones show the classic category)

Furniture	(width, height, depth) in meters	Angular	Curved
Armchair	(0.8, 0.9, 0.8)		
			

Basket	(0.4, 0.4, 0.4)		
			
Chair	(0.6, 0.8, 0.6)		
			
Couch	(2.6, 0.9, 0.9)		
			
Door	(1.0, 2.3, 0.1)		
			

Ceiling lamp	(0.2, 0.8, 0.2)		
			
Floor lamp	(1.1, 2.0, 0.4)		
			
Table lamp	(0.3, 0.4, 0.3)		
			
Painting	(1.5, 1.0, 0.04)		

			
Plant	(0.6, 0.7, 0.5)		
			
Center table	(1.4, 0.4, 0.8)		
			
Side table	(0.5, 0.5, 0.4)		
			
Window	(0.8, 2.0, 0.08)		

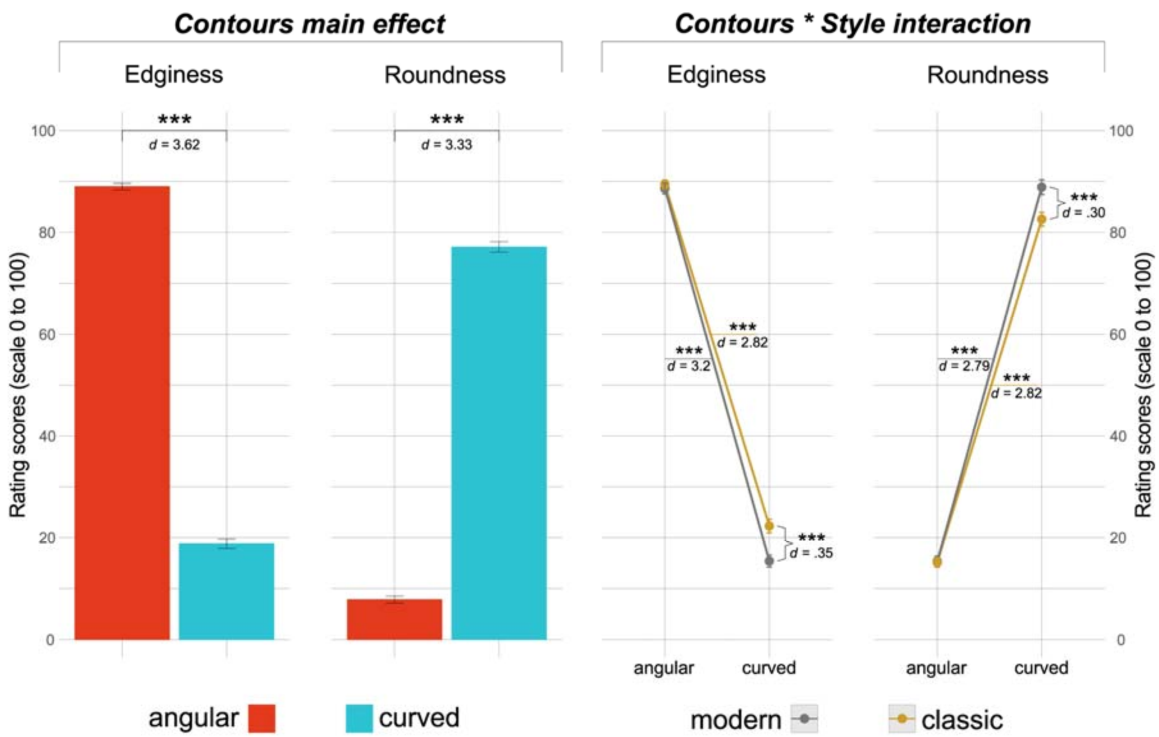
			
Vase	(0.1, 0.2, 0.1)		
			

1.4 Data

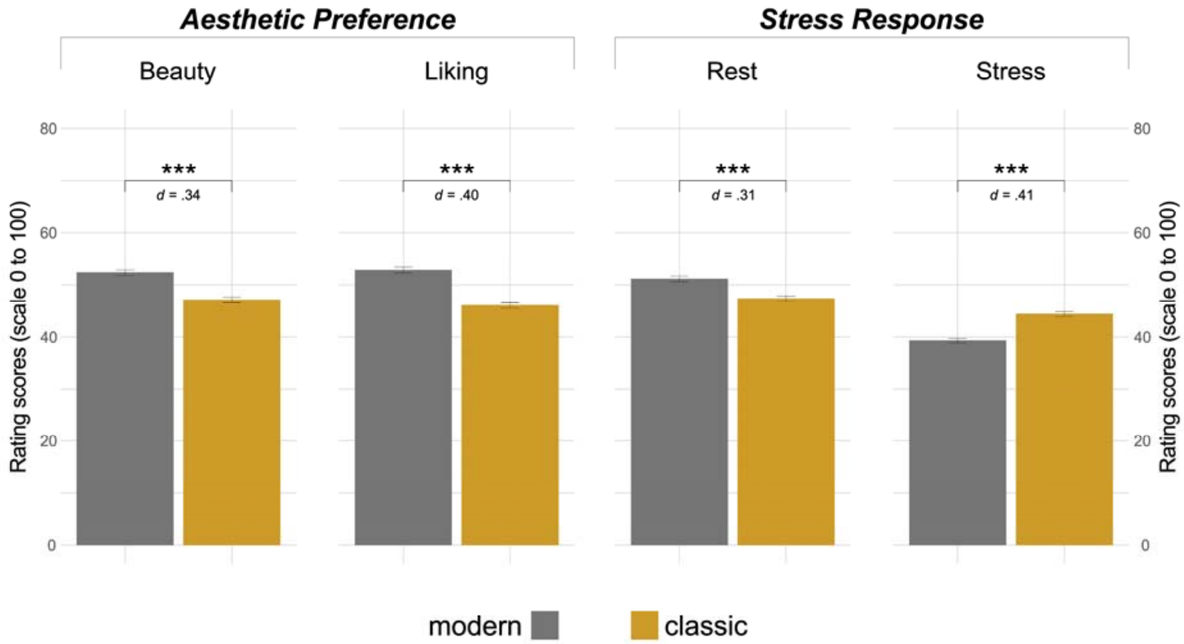
The data supporting the conclusions of this article is available at https://osf.io/mfpk2/.

2 Supplementary Figures and Tables

2.1 Supplementary Figures



Supplementary Figure 1. Results of the manipulation check. Left: There was a main effect of contours on both *edginess* and *roundness* scores. Images of angular contours were rated significantly higher on *edginess* and lower on *roundness* than those depicting curved ones. **Right:** Interaction effect of contours with style, showing consistency in ratings of *edginess* and *roundness* within the two styles. Scoring is on a range of 0-100. Bar graphs represent mean scores; error bars indicate standard errors. Asterisks represent significance, *p < .05, **p < .01, *** p < .001.



Supplementary Figure 2. Style main effect. Left to right: Results of the analyses comparing mean scores of images showing modern versus classic style on the four rating scales representing aesthetic preference (*beauty* and *liking*) and stress response (*rest* and *stress*) evaluations. Modern images were found to be more *beautiful*, more *liked*, more *restful*, and less *stressful* than classic ones. Scoring is on a range of 0-100. Bar graphs represent mean scores; error bars indicate standard errors. Asterisks represent significance, *p < .05, **p < .01, *** p < .001.

2.2 Supplementary Tables

2.2.1 Rating Tasks

Supplementary Table 1. Details of the two sets of rating tasks: set 1 (General Appraisal Scale, GAS), and set 2 (Aesthetic and Stress Response, AES) in the original German version (English translations can be found within the main manuscript).

Scale question	Anchored statements
GAS	
Edginess "Als wie eckig empfinden Sie diesen Raum?"	0="überhaupt nicht eckig" 100="sehr eckig"
Roundness "Als wie rund empfinden Sie diesen Raum?"	0="überhaupt nicht rund" 100="sehr rund"
Curiosity "Wie Neugierde erweckend erscheint Ihnen dieser Raum?"	0="überhaupt nicht Neugierde erweckend" 100="sehr Neugierde erweckend"
Novelty "Wie neuartig erscheint Ihnen dieser Raum?"	0="überhaupt nicht neuartig" 100="sehr neuartig'
Order/ Structure "Als wie strukturiert/ geordnet empfinden Sie diesen Raum?"	0="sehr unstrukturiert/ ungeordnet" 100="sehr strukturiert/ geordnet"
Complexity "Wie komplex erscheint Ihnen dieser Raum?"	0="überhaupt nicht komplex" 100="sehr komplex"
ASR	
Beauty "Bitte schätzen Sie die Schönheit/Ästhetik des Innenraums auf dem Bild ein."	0="überhaupt nicht schön" 100="sehr schön"
Liking "Wie gut gefällt Ihnen der Innenraum auf dem Bild?"	0="überhaupt nicht" 100="sehr gut"
Rest "Stellen Sie sich vor Sie wären in dem Innenraum auf dem Bild. Wie erholsam wirkt der Raum auf Sie?"	0="überhaupt nicht erholsam" 100="sehr erholsam"
Stress/ Emotion "Stellen Sie sich vor Sie wären in dem Innenraum auf dem Bild. Wie würden Sie ihre emotionale Reaktion beschreiben?"	0="entspannt" 100="gestresst"

2.2.2 Manipulation check

Supplementary Table 2. Results of the 2(contours) x 2(style) ANOVA for the dependent variable (rating score), shown separately for 'edginess' and 'roundness' scales.

Edginess

Predictor	df_{Num}	df_{Den}	SS_{Num}	SS_{Den}	F	p	η^2_g
(Intercept)	1	196	2287990.51	59760.74	7504.03	.000	.92
contours	1	196	969294.12	74006.13	2567.11	**.000**	.83
style	1	196	2897.36	35223.89	16.12	**.000**	.01
contours x style	1	196	1842.67	33285.58	10.85	**.001**	.01

Roundness

Predictor	df_{Num}	df_{Den}	SS_{Num}	SS_{Den}	F	p	η^2_g
(Intercept)	1	196	1422475.13	56499.87	4934.62	.000	.87
contours	1	196	944552.70	85180.30	2173.42	**.000**	.82
style	1	196	2021.12	35875.88	11.04	**.001**	.01
contours x style	1	196	1767.01	34115.99	10.15	**.002**	.01

Note. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. SS_{Num} indicates sum of squares numerator. SS_{Den} indicates sum of squares denominator. η^2_g indicates generalized eta-squared.

Supplementary Table 3. Descriptive statistics for dependent variable (rating score) as a function of contours, shown separately for each of the edginess and roundness scales, meant as a manipulation check of the contour contrast in the stimulus set.

	contours				post-hoc			
	angular		curved		t-test			
N= 197	*M*	*SD*	*M*	*SD*	*df*	*t*	*p*	*d*
Edginess	88.96	11.22	18.81	14.68	196	50.67	**<.0001**	3.62
Roundness	7.87	10.26	77.11	16.00	196	-46.62	**<.0001**	3.33

Note. *M* and *SD* represent mean and standard deviation, respectively. Pairwise post-hoc analysis include degrees of freedom (*df*), the size of the difference relative to the variation (t), significance (*p*-value), and effect size (*d* = cohen's d).

Supplementary Table 4. Descriptive statistics for dependent variable (rating score) as a function of style, shown separately for each of the edginess and roundness scales.

	style				post-hoc			
	modern		classic		t-test			
N=197	*M*	*SD*	*M*	*SD*	*df*	*t*	*p*	*d*
Edginess	51.97	10.88	55.80	11.13	196	-4.02	**.0001**	.29

Roundness	44.09	11.04	40.89	10.66	196	3.32	**.0011**	.24

Note. *M* and *SD* represent mean and standard deviation, respectively. Pairwise post-hoc analysis include degrees of freedom (*df*), the size of the difference relative to the variation (t), significance (*p*-value), and effect size (*d* = cohen's d).

Supplementary Table 5. Means and standard deviations for dependent variable (rating score) as a function of a 2(contours) x 2(style) design, along with the results of the post-hoc pairwise t-tests, shown separately for each of the edginess and roundness scales.

		contours				post-hoc			
		angular		curved		t-test			
N=197	style	*M*	*SD*	*M*	*SD*	*df*	*t*	*p*	*d*
Edginess	modern	88.57	15.08	15.37	16.52	196	44.75	**<.0001**	3.20
	classic	89.35	13.20	22.26	18.90	196	39.52	**<.0001**	2.82
Roundness	modern	7.97	13.42	80.21	20.01	196	-39.08	**<.0001**	2.79
	classic	7.76	13.10	74.01	18.11	196	-39.86	**<.0001**	2.82

Note. *M* and *SD* represent mean and standard deviation, respectively. Pairwise post-hoc analysis include degrees of freedom (*df*), the size of the difference relative to the variation (t), significance (*p*-value), and effect size (*d* = cohen's d).

Supplementary Table 6. Means and standard deviations for dependent variable (rating score) as a function of a 2(style) x 2(contours) design, along with the results of the post-hoc pairwise t-tests, shown separately for each of the edginess and roundness scales.

		style				post-hoc			
		modern		classic		t-test			
N=197	contours	*M*	*SD*	*M*	*SD*	*df*	*t*	*p*	*d*
Edginess	angular	88.57	15.08	89.35	13.20	196	-0.63	.53	.04
	curved	15.37	16.52	22.26	18.90	196	-4.85	**<.0001**	.35
Roundness	angular	7.97	13.42	7.76	13.10	196	0.17	.86	.01
	curved	80.21	20.01	74.01	18.11	196	4.19	**.0001**	.30

Note. *M* and *SD* represent mean and standard deviation, respectively. Pairwise post-hoc analysis include degrees of freedom (*df*), the size of the difference relative to the variation (t), significance (*p*-value), and effect size (*d* = cohen's d).

2.2.3 Effects of contours, style, and their interaction

Supplementary Table 7. Results of the 2(contours) x 2(style) ANOVA for the dependent variable (rating score), shown separately for each dimension of the ASR.

Beauty

Predictor	df_{Num}	df_{Den}	SS_{Num}	SS_{Den}	F	p	η^2_g
(Intercept)	1	197	1958717.50	115721.99	3334.43	.000	.89
contours	1	197	3119.39	60933.62	10.09	**.002**	.01
style	1	197	5405.00	46324.85	22.99	**.000**	.02
contours x style	1	197	1764.64	14028.09	24.78	**.000**	.01

Liking

Predictor	df_{Num}	df_{Den}	SS_{Num}	SS_{Den}	F	p	η^2_g
(Intercept)	1	197	1936620.24	120929.97	3154.84	.000	.88
contours	1	197	2475.45	77137.60	6.32	**.013**	.01
style	1	197	9048.40	56945.21	31.30	**.000**	.03
contours x style	1	197	3362.08	14478.45	45.75	**.000**	.01

Rest

Predictor	df_{Num}	df_{Den}	SS_{Num}	SS_{Den}	F	p	η^2_g
(Intercept)	1	197	1918760.98	107523.00	3515.49	.000	.90
contours	1	197	27357.53	54341.73	99.18	**.000**	.12
style	1	197	2843.94	29824.36	18.79	**.000**	.01
contours x style	1	197	4319.47	9981.71	85.25	**.000**	.02

Stress/ Emotion

Predictor	df_{Num}	df_{Den}	SS_{Num}	SS_{Den}	F	p	η^2_g
(Intercept)	1	197	1384315.73	80517.01	3386.99	.000	.89
contours	1	197	15438.90	47668.32	63.80	**.000**	.08
style	1	197	5221.63	30678.99	33.53	**.000**	.03
contours x style	1	197	1486.94	11767.92	24.89	**.000**	.01

Note. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. SS_{Num} indicates sum of squares numerator. SS_{Den} indicates sum of squares denominator. η^2_g indicates generalized eta-squared.

Supplementary Table 8. Means and standard deviations for dependent variable (rating score) as a function of contours, along with the results of the post-hoc pairwise t-tests, shown separately for each dimension of the ASR.

	contours				post-hoc			
	angular		curved		t-test			
N=198	*M*	*SD*	*M*	*SD*	*df*	*t*	*p*	*d*
Beauty	47.75	15.07	51.72	14.87	197	-3.18	**.002**	.23
Liking	47.68	16.13	51.22	15.57	197	-2.51	**.01**	.18
Rest	43.34	15.30	55.10	13.30	197	-9.96	**<.0001**	.71
Stress/ Emotion	46.22	13.62	37.39	11.83	197	7.99	**<.0001**	.57

Note. M and SD represent mean and standard deviation, respectively. Pairwise post-hoc analysis include degrees of freedom (df), the size of the difference relative to the variation (t), significance (p-value), and effect size (d = cohen's d).

Supplementary Table 9. Means and standard deviations for dependent variable (rating score) as a function of style, along with the results of the post-hoc pairwise t-tests, shown separately for each dimension of the ASR.

	style				post-hoc			
	modern		classic		t-test			
N=198	*M*	*SD*	*M*	*SD*	*df*	*t*	*p*	*d*
Beauty	52.34	13.62	47.12	15.02	197	4.79	**<.0001**	.34
Liking	52.83	14.70	46.07	15.34	197	5.60	**<.0001**	.40
Rest	51.12	12.64	47.33	13.74	197	4.33	**<.0001**	.31
Stress/ Emotion	39.24	11.02	44.38	12.68	197	-5.790	**<.0001**	.41

Note. M and SD represent mean and standard deviation, respectively. Pairwise post-hoc analysis include degrees of freedom (df), the size of the difference relative to the variation (t), significance (p-value), and effect size (d = cohen's d).

Supplementary Table 10. Means and standard deviations for dependent variable (rating score) as a function of a 2(contours) x 2(style) design, along with the results of the post-hoc pairwise t-tests, shown separately for each dimension of the ASR.

		contours				post-hoc			
		angular		curved		t-test			
N=198	style	*M*	*SD*	*M*	*SD*	*df*	*t*	*p*	*d*
Beauty	modern	48.87	17.01	55.82	16.06	197	-5.21	**<.0001**	.37
	classic	46.63	16.87	47.61	19.27	197	-0.68	0.49	.05
Liking	modern	49.00	19.32	56.66	16.87	197	-5.07	**<.0001**	.36

	classic	46.36	17.46	45.78	20.13	197	0.38	0.71	.03
Rest	modern	42.90	16.76	59.33	14.07	197	-12.95	**<.0001**	.92
	classic	43.78	16.04	50.87	16.95	197	-5.45	**<.0001**	.39
Stress/	modern	45.03	15.13	33.45	12.77	197	9.43	**<.0001**	.67
Emotion	classic	47.42	14.90	41.33	15.88	197	4.90	**<.0001**	.35

Note. M and SD represent mean and standard deviation, respectively. Pairwise post-hoc analysis include degrees of freedom (df), the size of the difference relative to the variation (t), significance (p-value, corrected using the "FDR" method), and effect size (d = cohen's d).

Supplementary Table 11. Means and standard deviations for dependent variable (rating score) as a function of a 2(style) x 2(contour) design, along with the results of the post-hoc pairwise t-tests, shown separately for each dimension of the ASR.

		style				post-hoc			
		modern		classic		t-test			
N=990	style	*M*	*SD*	*M*	*SD*	*df*	*t*	*p*	*d*
Beauty	angular	48.87	17.01	46.63	16.87	197	2.04	**.057**	.15
	curved	55.82	16.06	47.61	19.27	197	5.98	**<.0001**	.43
Liking	angular	49.00	19.32	46.36	17.46	197	2.09	**.05**	.15
	curved	56.66	16.87	45.78	20.13	197	7.57	**<.0001**	.54
Rest	angular	42.90	16.76	43.78	16.04	197	-1.04	0.30	.07
	curved	59.33	14.07	50.87	16.95	197	7.34	**<.0001**	.52
Stress/	angular	45.03	15.13	47.42	14.90	197	-2.66	**0.008**	.19
Emotion	curved	33.45	12.77	41.33	15.88	197	-6.73	**<.0001**	.48

Note. M and SD represent mean and standard deviation, respectively. Pairwise post-hoc analysis include degrees of freedom (df), the size of the difference relative to the variation (t), significance (p-value, corrected using the "FDR" method), and effect size (d = cohen's d).

2.2.4 Results of the two-way interaction of contours*sex

Supplementary Table 12. Results of the mixed ANOVA with 2(contours) as within-subject factors and 2(sex) as a between-subject factor performed on the dependent variable (rating score), and shown separately for each dimension of the ASR.

Beauty

Predictor	df_{Num}	df_{Den}	SS_{Num}	SS_{Den}	F	p	η^2_g
(Intercept)	1	196	979358.75	57848.01	3318.25	.000	.92
sex	1	196	12.98	57848.01	0.04	.834	.00
contours	1	196	1559.69	28949.69	10.56	.001	.02
sex x contours	**1**	**196**	**1517.12**	**28949.69**	**10.27**	**.002**	**.02**

Liking

Predictor	df_{Num}	df_{Den}	SS_{Num}	SS_{Den}	F	p	η^2_g
(Intercept)	1	196	968310.12	60464.44	3138.85	.000	.91
sex	1	196	0.55	60464.44	0.00	.966	.00
contours	1	196	1237.73	36930.34	6.57	.011	.01
sex x contours	**1**	**196**	**1638.46**	**36930.34**	**8.70**	**.004**	**.02**

Rest

Predictor	df_{Num}	df_{Den}	SS_{Num}	SS_{Den}	F	p	η^2_g
(Intercept)	1	196	959380.49	53686.97	3502.50	.000	.92
sex	1	196	74.53	53686.97	0.27	.603	.00
contours	1	196	13678.76	25702.28	104.31	.000	.15
sex x contours	**1**	**196**	**1468.58**	**25702.28**	**11.20**	**.001**	**.02**

Stress

Predictor	df_{Num}	df_{Den}	SS_{Num}	SS_{Den}	F	p	η^2_g
(Intercept)	1	196	692157.86	39986.17	3392.75	.000	.92
sex	1	196	272.34	39986.17	1.33	.249	.00
contours	1	196	7719.45	23118.91	65.44	.000	.11
sex x contours	**1**	**196**	**715.24**	**23118.91**	**6.06**	**.015**	**.01**

Note. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. SS_{Num} indicates sum of squares numerator. SS_{Den} indicates sum of squares denominator. η^2_g indicates generalized eta-squared.

Supplementary Table 13. Means and standard deviations for dependent variable (rating score) as a function of a 2(contours) x 2(sex) design, along with the results of the post-hoc pairwise t-tests, shown separately for each dimension of the ASR.

		contours				post-hoc			
		angular		curved		t-test			
N=99	sex	*M*	*SD*	*M*	*SD*	*df*	*t*	*p*	*d*
Beauty	male	49.52	15.74	49.58	16.23	196	-0.03	.97	.002
	female	45.97	14.23	53.85	13.11	196	-4.56	**<.0001**	.33
Liking	male	49.75	17.48	49.22	16.76	196	0.27	.79	0.02
	female	45.61	14.45	53.21	14.09	196	-3.90	**.0005**	.28
Rest	male	45.70	15.97	53.61	15.07	196	-4.86	**<.0001**	.35
	female	40.98	14.28	56.59	11.13	196	-9.59	**<.0001**	.68
Stress/	male	44.05	14.45	37.91	12.89	196	3.98	**.0002**	.28
Emotion	female	48.40	12.41	36.88	10.70	196	7.46	**<.0001**	.53

Note. M and SD represent mean and standard deviation, respectively. Pairwise post-hoc analysis include degrees of freedom (df), the size of the difference relative to the variation (t), significance (p-value, corrected using the "FDR" method), and effect size (d = cohen's d). The terms 'male' and 'female' are used as grouping adjectives, as this was how participants were asked to (dichotomously) classify themselves.

Supplementary Table 14. Means and standard deviations for dependent variable (rating score) as a function of a 2(sex) x 2(contours) design, along with the results of the post-hoc pairwise t-tests, shown separately for each dimension of the ASR.

		sex				post-hoc			
		male		female		t-test			
N=99	sex	*M*	*SD*	*M*	*SD*	*df*	*t*	*p*	*d*
Beauty	angular	49.52	15.74	45.97	14.23	196	1.67	.13	.12
	curved	49.58	16.23	53.85	13.11	196	-2.04	.09	.15
Liking	angular	49.75	17.48	45.61	14.45	196	1.82	.09	.13
	curved	49.22	16.76	53.21	14.09	196	-1.82	.09	.13
Rest	angular	45.70	15.97	40.98	14.28	196	2.19	**.04**	.16
	curved	53.61	15.07	56.59	11.13	196	-1.59	.11	.11
Stress/	angular	44.05	14.45	48.40	12.41	196	-2.27	**.03**	.16
Emotion	curved	37.91	12.89	36.88	10.70	196	0.61	.54	.04

Note. M and SD represent mean and standard deviation, respectively. Pairwise post-hoc analysis include degrees of freedom (df), the size of the difference relative to the variation (t), significance (p-value, corrected using the "FDR" method), and effect size (d = cohen's d). The terms 'male' and 'female' are used as grouping adjectives, as this was how participants were asked to (dichotomously) classify themselves.

Supplementary Table 15. Correlation coefficients computed in R using the function 'rmcorr'. Following the guidelines provided in Bakdash and Marusich (2017), data was stored in long format with separate columns for participant and each of the four measures scores, and separate rows for each observation labeled by participant (N=198 with 3,960 observations in total). The function handles repeated measures data without violating independence assumptions or requiring first averaging the data. Paired correlations were computed separately for each of the possible pairs of the rating dimensions, and are reported in the matrix below.

N=198 participants **N=3,960 observation**	***Beauty***	***Liking***	***Rest***	***Stress***
Beauty	1			
Liking	0.78	1		
Rest	0.69	0.70	1	
Stress	−0.55	−0.57	−.58	1

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The curvature effect: Approach-avoidance tendencies in response to interior design stimuli

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ABSTRACT

Previous research suggests that curved vs. angular interior environments trigger affective (e.g., preference) and behavioural (e.g., approach-avoidance) responses. Yet, behavioural responses have mainly been assessed through explicit evaluations, such as self-reports. We aimed to investigate this phenomenon more 'implicitly' using a battery of reaction time (RT) paradigms, particularly focusing on approach-avoidance tendencies.

Online participants (initial N = 219) undertook four randomized tasks involving 20 photo-realistic living room images matched for contours (angular vs. curved) and styles (modern vs. classic). We intended to capture attentional (Dot Probe Task [DPT]), motoric (Approach Avoidance Task [AAT]), as well as associative-semantic (Implicit Association Task [IAT]) and -motoric (Stimulus Response Compatibility Task [SRCT]) biases towards contours.

The DPT and AAT showed no significant effects. However, we observed a significant congruency effect in the IAT ($F(1,192) = 97.51$, $p < .001$, $\eta^2 = 0.074$), whereby images were assigned faster into categories when those were curved-approach and angular-avoid (instead of curved-avoid, angular-approach). Additionally, we found a significant direction x contour interaction ($F(1,179) = 7.08$, $p = .009$, $\eta^2 = 0.004$) in the SRCT, attributable to within-curvature differences (faster approach compared to avoidance). Moreover, within-directions comparisons revealed a faster avoidance of angular than curved conditions.

Our findings confirmed an effect of contours on approach-avoidance tendencies using RT paradigms. We identified semantic associations between curvature and approach and angularity and avoidance behaviour. Furthermore, we demonstrated differential approach (faster) – avoidance (slower) representations in relation to curvature rather than an avoidance of angularity. These findings may hint towards (partially) automatic responses to contours in interior design, which in addition to self-reports, should be further researched concerning criterion validity, such as in correlation with physiological and psychological reactions to built spaces.

1. Introduction

As we navigate through our modern habitat, the built environment, we continuously perceive its physical properties and make judgments about them. While this process can be conscious or intentional, it appears that automatic response tendencies might generally govern one's behaviour in physical surroundings (Sussman & Hollander, 2014). Most stimuli, including environments, elicit immediate and unintentional affective responses (e.g., like vs. dislike) and behaviours (e.g., approach vs. avoidance) that are crucial to our general physiological and psychological state and wellbeing (Appleton, 1996; Elliot, 2008; Phaf, Mohr, Rotteveel, & Wicherts, 2014; Ulrich, 1983). Indeed, research has shown that the design of physical spaces can affect human emotions, cognition, and behaviour, subsequently influencing general mood states, mental health, and wellbeing (Burton, Cooper, & Cooper, 2014; Coburn et al., 2020; Evans, 2003; Evans & McCoy, 1998). While research has mainly relied upon explicit responses to design features such as via self-reports, the more immediate automatic responses they possibly induce are still understudied (Higuera-Trujillo, Llinares, & Macagno, 2021).

Among the influential features of design, curvature has been claimed as a "biophilic" parameter (Browning, Ryan, & Clancy, 2014; Kellert & Calabrese, 2015; Salingaros, 2015) that can have positive psychological and physiological effects on human beings (Coburn et al., 2020;

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Salingaros, 2019). Generally, the angular (or edgy/rectilinear) versus curved (or round/curvilinear) dichotomies have been extensively studied in many disciplines, repetitively demonstrating positive effects of curves. A variety of stimuli was tested, including abstract shapes and lines (Bertamini, Palumbo, Gheorghes, & Galatsidas, 2016; Gordon, 1909; Lundholm, 1921; Palumbo, Ruta, & Bertamini, 2015, 2021; Poffenberger & Barrows, 1924; Silvia & Barona, 2009), artwork such as typeface (Kastl & Child, 1968; Velasco, Woods, Hyndman, & Spence, 2015) and paintings (Ruta et al., 2021), as well as everyday objects (Bar & Neta, 2007; Chuquichambi, Palumbo, Rey, & Munar, 2021; Sinico, Bertamini, & Soranzo, 2021), commercial products (Carbon, 2010; Leder & Carbon, 2005; Pombo & Velasco, 2021; Westerman et al., 2012), and exterior (Ruta, Mastandrea, Penacchio, Lamaddalena, & Bove, 2019) and interior environments (Hesselgren, 1987; Küller, 1980; Madani Nejad, 2007; Tawil, Ascone, & Kühn, 2022; Vartanian et al., 2013, 2019). Everyday human-made artifacts (e.g., objects, built environments) were typically presented as line drawings (Chuquichambi, Palumbo, et al., 2021; Madani Nejad, 2007), photographs (Bar & Neta, 2006; Vartanian et al., 2013, 2019), three dimensional renders (Dazkir & Read, 2012; van Oel & van den Berkhof, 2013), and recently in Virtual Reality (Banaei, Hatami, Yazdanfar, & Gramann, 2017; Formiga, Rebelo, Cruz Pinto, & Gomes, 2022; Tawil, Sztuka, Pohlmann, Sudimac, & Kühn, 2021). However, most of the previously tested interior design image stimuli were either not matched or not realistically representative of a real-life scenario (e.g., greyscale, drawings).

Despite the extensive replication of the contour effect across different stimulus categories, consensus on its origins remains elusive (Corradi & Munar, 2019). An evolutionary perspective was proposed, as effects were observed in different cultures, e.g., western and non-western (Gómez-Puerto et al., 2018; Munar, Gómez-Puerto, & Gomila, 2014) although not in Japanese (Maezawa, Tanda, & Kawahara, 2020) and Chinese (Dai, Zou, Wang, Ding, & Fukuda, 2022) observers, however again across age groups (Fantz & Miranda, 1975; Hopkins, Kagan, Brachfeld, Hans, & Linn, 1976; Jadva, Hines, & Golombok, 2010), and even in non-human primates (Munar, Gómez-Puerto, Call, & Nadal, 2015; Schneirla, 1966). One view, the “threat hypothesis”, attributes these effects to appraisal mechanisms, possibly developed to quickly detect and behaviourally avoid potentially threatening edges (Bar & Neta, 2006, 2007), suggesting an association with avoidance behaviour. Other explanations proposed a “curvature effect”, attributable to an inherently attractive and pleasant appeal of curves (Bertamini et al., 2016),that are assumed to cause specific activations of sensorimotor mechanisms (Amir, Biederman, & Hayworth, 2011; Fantz & Miranda, 1975), including approach behaviour in particular (Palumbo et al., 2015). A third perspective argues that, although possibly pre-shaped by evolution, the preference for curves could be learnt as it was found to be modulated by a so-called “Zeitgeist effect” denoting time-related societal trends (Carbon, 2010). At least for more complex domains such as human-made objects, and using explicit ratings, cars with curved features were favoured only when the design belonged to an epoch in which curvature was trendy. However, further research is needed to address particularly the behavioural accounts using appropriate experimental paradigms that can inform specifically on the approach-avoidance reactions that have been discussed.

Generally, the literature reports effects of angular vs. curved everyday human-made artifacts onto multiple psychological domains. Using explicit rating formats, spaces, furniture, and objects with curved features were evaluated more positively compared to those with angular ones. These evaluations encompass multiple affective dimensions, including preference (Bar & Neta, 2006; Carbon, 2010; Tawil et al., 2022), pleasantness (Banaei et al., 2017; Dazkir & Read, 2012; Formiga et al., 2022; Hesselgren, 1987; Küller, 1980; Madani Nejad, 2007; Vartanian et al., 2013), attractiveness (Leder & Carbon, 2005), beauty (Tawil et al., 2022; Vartanian et al., 2013, 2019), safety (Madani Nejad, 2007), and stress responses (Madani Nejad, 2007; Tawil et al., 2022). On the behavioural level, approach vs. avoidance explicit decisions have been reported (Dazkir & Read, 2012; Vartanian et al., 2019). The scarce neuroimaging studies observed a consistent preference for curves, however, correlated with different brain activation patterns. In one study, edgy everyday objects activated stress-related regions (Bar & Neta, 2007), while in another, curvilinear spaces activated regions related to pleasantness and reward (Vartanian et al., 2013). Yet, to date, most research has mainly relied on explicit measures to study responses to angular vs. curved interiors, and the behavioural reaction tendencies they elicit remain understudied.

Reaction time (RT) experimental paradigms are utilized in social and cognitive psychology to assess hypothetical links. These paradigms strive to assess responses that are less influenced by conscious processes, reducing the impact of social desirability or other expectancy biases, including experimenter bias. They find utility in clinical studies aimed at examining response biases in individuals suffering from psychological disorders like addiction, phobias, or suicidality (Nock et al., 2010; Wiers, Eberl, Rinck, Becker, & Lindenmeyer, 2011). Hereby, participants typically respond to stimuli presented on a computer screen through mouse, joystick movements, or button presses. Hypothetical “automatic” response biases with respect to the feature of investigation can be detected, reflected in differential RTs or errors made in response to the stimuli of interest vs. suited control stimuli. Such paradigms have shown efficacy in testing the effects of environmental image stimuli, for instance in a study demonstrating a tendency in humans to approach nature and avoid cities (Schiebel, Gallinat, & Kühn, 2022). Research investigating contours has employed these paradigms, although exclusively with abstract shapes and patterns, demonstrating automatic effects concerning semantic (Palumbo et al., 2015), hedonic (Chuquichambi, Corradi, Munar, & Rosselló-Mir, 2021), and motoric, i.e., approach-avoidance (Bertamini et al., 2016; Palumbo et al., 2015) associations. Using an updated version of the implicit association task (IAT) (Greenwald, McGhee, & Schwartz, 1998), curved abstract shapes were associated with semantic concepts of positive valence and safety, and angular ones were related to opposite concepts (Palumbo et al., 2015). More recently, an affective stimulus-response compatibility (aSRC) task (Eder, Elliot, & Harmon-Jones, 2013) with non-verbal content (i.e., schematic faces instead of words) detected the compatibility of curved and symmetric patterns with positive hedonic tones (Chuquichambi, Corradi, et al., 2021). Furthermore, associations between contour shapes and approach-avoidance movements were demonstrated using adapted versions of the stimulus-response compatibility task (SRCT; De Houwer, Thomas, & Baeyens, 2001). These associations were driven by an approach tendency towards curved polygons rather than an avoidance of angular ones (Bertamini et al., 2016; Palumbo et al., 2015).

In this study, we investigated behavioural response tendencies towards contours using a set of photo-realistic living room images featuring varying contours (angular vs. curved) and styles (modern vs. classic). Explicit responses to the same images previously showed that curvature positively impacted aesthetic preference, while angularity was related to higher self-reported stress (Tawil et al., 2022). Here, we adopted an experimental testing strategy with RT tasks that can detect associations between mental representations and action/response tendencies. The ad-hoc test battery selection comprised the dot probe task (DPT; MacLeod, Soong, Rutherford, & Campbell, 2007), the approach-avoidance task in stimulus-irrelevant format (AAT; Wiers et al., 2011), the implicit association task (IAT; Greenwald et al., 1998), and the stimulus-response compatibility task (SRCT; De Houwer et al., 2001). These tests were selected based on previous studies focusing on abstract contours (SRCT, IAT) as well as a prior study on (city vs. natural landscape) environmental stimuli (DPT, AAT, and IAT), which identified response tendencies suggesting attentional and approach biases towards nature (Schiebel et al., 2022). Our particular focus was on approach-avoidance tendencies since these may best align with the different theories explaining the source of the contour effect (i.e., threat hypothesis vs. curvature appeal). To the best of our knowledge, implicit

RT paradigms have not yet been employed to evaluate responses to contours related to interior environments. Our primary goal was to mirror the contour effect with implicit paradigms (pre-registration can be retrieved from https://aspredicted.org/B65_HP6) and thus to tap into less aware responses (in contrast to self-reports), representing the 'behavioural component of emotional responding' (see Krieglmeyer & Deutsch, 2010). Furthermore, we explored whether other contextual (i.e., style) and individual (i.e., self-reported sex) factors affected the results, as previously observed for explicit measures (Tawil et al., 2022). Such findings could contribute to the understanding of (more) automatic responses to contours, facilitating a cost-effective, yet objective exploration of human reactions to interior design and architectural stimuli. Unravelling such tendencies in the long run could also inform design strategies aimed at considering immediate human responses, which may be particularly relevant to spaces intended to promote mental health and wellbeing, but also everyday environments.

2. Materials and methods

2.1. Participants

A total of N = 219 participants enrolled in the study via the crowdsourcing platform Prolific.[1] We determined the sample size based on results from an unpublished forerunner pilot of the AAT using similar stimuli (for detailed sample size calculations, see Tawil et al., 2022). To be included, participants had to confirm age (between 18 and 69 years old), absence of neurological/mental disorder requiring medication, no psychotic disorder, acute suicidal thoughts or tendencies, and no regular drug intake, no visual impairment unless appropriately corrected, German language proficiency, and the availability of an external computer mouse (for the AAT). The study was approved by the local psychological ethics board of the University Medical Center Hamburg-Eppendorf (LPEK-0215). The experiment lasted 1 hour on average and participants were compensated with approximately 10€.

2.2. Stimulus material

The stimulus material originated from a previous Virtual Reality study (Tawil et al., 2021). Four different living rooms were created and implemented in the gaming software Unity[2] (version 2019.2.1f1, 64-bit). Each of the four rooms included objects matched in their bounding sizes, materials, and colours, and contrasted exclusively according to the respective combination of the two study design factors "contours" and interior design "style". Rooms within the same pair were matched in all design features, except with respect to their contours (angular vs. curved). The contrast between pairs was style (modern vs. classic). We generated 80 images, with 20 images per room. Out of the respective 20 images, only those that showed insignificant differences in low-level image properties across the design factors were selected, resulting in five images per room (for more details, see Tawil et al., 2022). In total, 20 images were included in the final stimulus set (10 pairs of modern [5 angular, 5 curved], 10 pairs of classic [5 angular, 5 curved] stimuli). Stimulus examples are shown in Fig. 1a.

2.3. Experimental tasks and randomization

2.3.1. Dot probe task (DPT)

A keyboard input DPT was used (adapted from Schiebel et al., 2022). Each trial began with a 500ms central fixation cross, followed by a pair of matched images with angular vs. curved features, randomly presented on the right or left side. After a 500ms presentation, a probe ("X") appeared behind either the angular (hereafter defined as "congruent" condition) or the curved (hereafter defined as "incongruent" condition) stimulus (Fig. 1b). Participants had up to 1.000ms to identify the side on which the probe appeared by pressing the keyboard letters "E" (located on the left side of the keyboard) or "I" (right side). If no response was given, a red error message ("Fehler") would centrally show for 400ms. Trials were fully randomized, with 40 trials in total, therefore, each stimulus was presented four times (2 [left/right] x 2 [with/without probe appearing behind it]). Ten practice trials were conducted prior to the main trials, showing probes behind grey rectangles matching the size and positions of the stimulus pairs.

This paradigm resulted in two RT parameters of interest per participant: median RTs for the "congruent" and "incongruent" trials. Since the DPT is considered 'a gold standard in the field for investigating attentional bias to threat' (Kappenman, Farrens, Luck, & Proudfit, 2014), the label "congruent" was assigned to angular conditions in line with the threat hypothesis, which posits that attention is automatically drawn to angular compared to curved stimuli. Therefore, faster RTs could be expected for congruent conditions.

2.3.2. Approach Avoidance Task (AAT)

A stimulus-irrelevant AAT with mouse input was used (adapted from Schiebel et al., 2022), in which participants responded to the image orientation (Cousijn, Goudriaan, & Wiers, 2011). Each room image appeared four times, twice tilted to the left and twice to the right by 2° (see Fig. 1b). Participants completed 20 practice trials (with grey rectangles) then 80 main trials (with room images). In each trial, participants clicked on a central fixation cross before stimulus presentation to ensure a central initial position of the cursor. Using the mouse, they were instructed to pull the stimuli towards themselves (approach; whereby the image enlarges [zoom in until filling up nearly the entire screen]) or push it away (avoid; whereby the image shrinks to only a fraction of its original size [zoom out]), depending on its orientation (tilt), as quickly as possible. The stimulus disappeared after reaching its maximum (approach) or minimum (avoid) size, by the mouse cursor reaching the screen's upper or lower bound. The zoom feature mimics the stimulus moving towards or away from the self/participant (Fig. 1b). Incorrect cursor movements triggered a 400ms central red error message ("Fehler"). Instructions were randomized between participants (PULL-if-tilted-right & PUSH-if-tilted-left vs. PULL-if-tilted-left & PUSH-if-tilted-right). We evaluated two different AAT outcomes as typically done: initial (stimulus onset until mouse movement initiation) and movement (start of mouse movement until stimulus disappearance) RTs.

The paradigm results in four RT parameters of interest per participant, by means of which an interaction of [2] direction (approach vs. avoidance) and [2] contour (angular vs. curved) can be computed, and reflects the main analysis of interest. Significant interactions could manifest as between- and/or within-contour differences. Faster approach RTs towards curved vs. angular stimuli (between-difference) could be detected. Approach (vs. avoidance reactions) towards curved stimuli (within-difference) should be faster. Conversely, faster avoidance RTs of angular vs. curved stimuli (between-difference) could be observed. Avoidance (vs. approach) reactions towards angular stimuli (within-difference) should be faster.

2.3.3. Implicit association task (IAT)

The IAT (adapted from Schiebel et al., 2022) comprised 7 blocks. In the first (categorization) block, participants quickly assigned each centrally presented stimulus to either "angular" ("Eckig") or "curved" ("Rund") categories (shown on the screen's upper left and right sides) by pressing a left ("E) vs. right ("I") button on the keyboard [block 1; 20 trials]. In the second (attribute practice) block [block 2; 20 trials], five "approach", e.g., "to touch" ("berühren") and five "avoidance" words, e.g., "to dodge" ("ausweichen") were each centrally presented (twice), and participants sorted them into their respective categories ("Annäherung" and "Vermeidung" which respectively translate as

[1] www.prolific.co.

[2] www.unity.com.

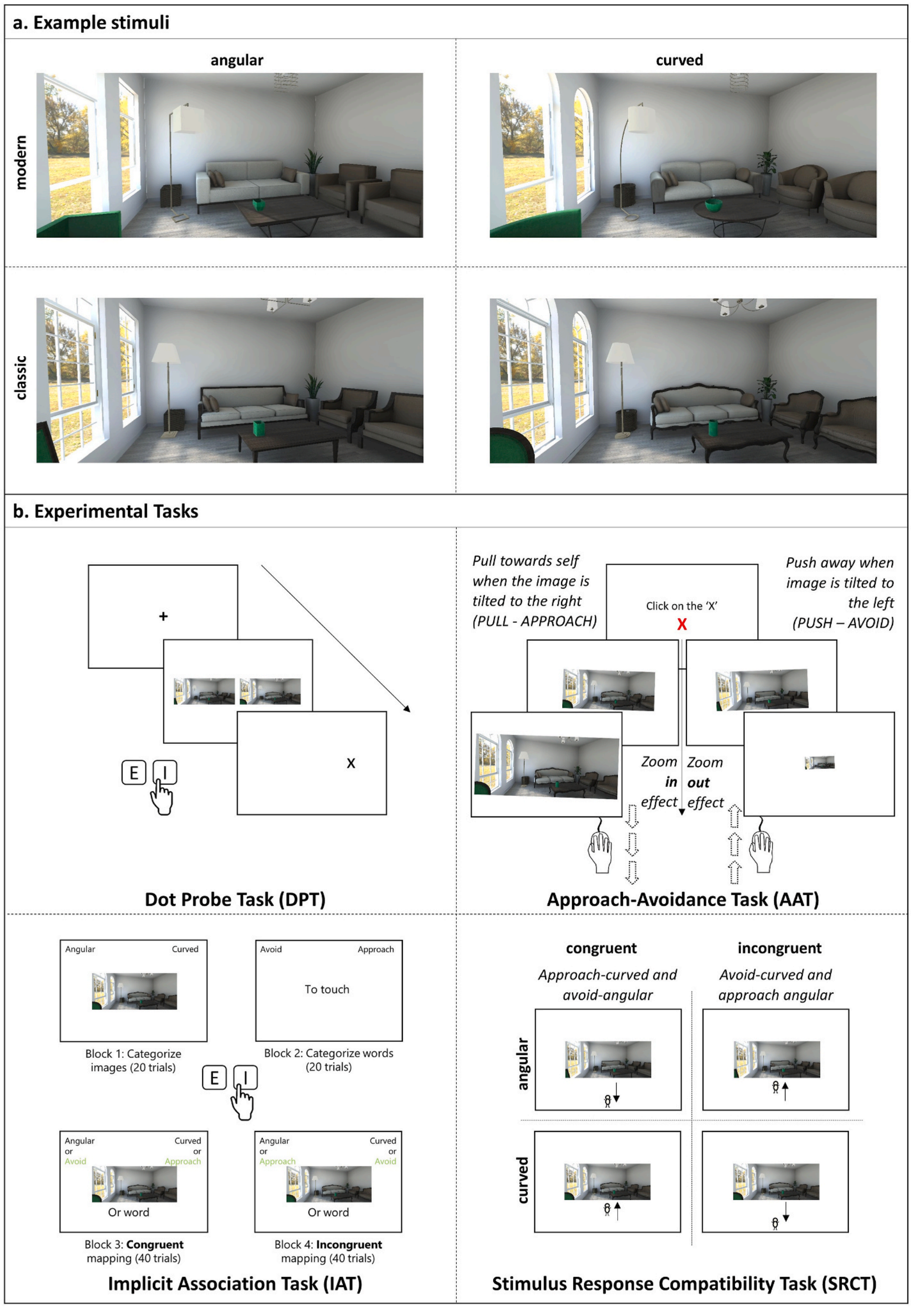

Fig. 1. Stimuli and experimental tasks. **a.** Example stimuli showing the same view according to the design factors contour (angular vs. curved) and style (modern vs. classic). The generated image size was set to 5075 × 2160 pixels, 4 K resolution with ratio 21:9. **b.** Example slides showing the four experimental tasks.

"approach" and "avoidance"). During the next two blocks [3–4; 40 trials each], participants assigned the 20 images (each once) and ten words (each twice), alternately displayed, into the combined categories in an "incongruent" ("curved-avoid", "angular-approach") or "congruent" ("curved-approach", "angular-avoid") pairing (see Fig. 1b). Next, they repeated the categorization task from block 1, but with the sides of "angular" and "curved" categories switched [block 5; 20 trials]. The remaining pairings (opposite to block 3–4) were then presented in the last two blocks [6–7; 40 trials each]. A 200ms red error message appeared if participants pressed the wrong button, requiring correction. The intertrial interval was 250ms. The total number of trials was n = 220. The main outcomes were RTs for "congruent" vs. "incongruent" pairings across blocks 3–4 and 6–7. Only RTs related to image stimuli were evaluated.

This paradigm results in two RT parameters of interest per participant: the "congruent" and "incongruent" median RTs forming the "congruency" factor. The congruent condition is hypothesized to match participants' semantic associations (curved conditions with the approach category and angular conditions with the avoidance category), and thus faster responses can be expected.

2.3.4. *Stimulus response-compatibility task (SRCT)*

A keyboard input SRCT was utilized (adapted from the millisecond download library[3]). Participants initially viewed a black screen for 1000ms, followed by a randomly selected stimulus with a manikin placed (randomly) above or beneath it. Depending on the manikin location, they pressed the "up" or "down" (arrow) keyboard buttons to

[3] https://www.millisecond.com/download/library.

make the manikin approach or avoid the stimulus based on its depicted contour content (Fig. 1b). Two main blocks were presented in random order, in which participants were instructed to approach images of curved interiors and avoid those of angular ones in one block (20 trials, each stimulus presented once), and vice versa in the other block (20 trials). Two distractor blocks (each with 20 trials) were randomly presented either before or after the main blocks, where participants had to move the manikin to the left or right (curved-move-right, angular-move-left vs. curved-move-left, angular-move-right). Errors (moving the manikin into the wrong direction) were flagged with a 1000ms message ("Fehler"). Each block had 10 practice trials (images from the same rooms, not included in the main experiment).

This paradigm results in four RT parameters of interest per participant: two median RTs respectively for [2] direction (approach vs. avoidance) and [2] contour (angular vs. curved). The interaction between direction and contour was the focus of the analysis, which in the post-hoc tests could plausibly manifest within-contours (faster approach & slower avoidance of curvature; slower approach & faster avoidance towards angularity) or within-directions (faster approach towards curvature vs. angularity; faster avoidance of angularity vs. curvature), or both.

2.4. Procedure

The experiment was conducted online using Inquisit 6 software.[4] Participants were recruited via Prolific. First, they were informed about the aims (examining perception of different interior designs) and provided informed consent. Eligibility criteria were later checked, before administration of the four tasks, which were presented in quasi-random order. The DPT and AAT were always introduced first, and the IAT and SRCT thereafter, as the latter two tasks included explicit instructions regarding how to respond to curved vs. angular stimuli. Hence, showing IAT and SRCT first would have enhanced awareness concerning the stimuli classification (curved vs. angular) which could have interfered with the DPT and AAT, in which participants were unaware of the stimulus type concerning contours. Upon completing the tasks, participants filled out a sociodemographic survey (age, biological sex, school degree, net income, and occupational status), including questions about environmental exposure (nature vs. urban exposure and landscape preferences, home environment and preferences), expertise in arts and architecture through part A of the Vienna Art Interest and Art Knowledge Questionnaire (VAIAK; Specker et al., 2020) and another version adapted to architecture, psychopathology levels with the depression, anxiety, and stress scale (DASS-21; Lovibond & Lovibond, 1995), as well as personality traits (BFI-10; Rammstedt & John, 2007). In the last section, participants rated the stimuli on different visual analogue scales concerning aesthetics and stress response evaluations (for details and results see Tawil et al., 2022).

2.5. Statistical analyses

We followed a data preparation and analysis approach similar to a prior study (Schiebel et al., 2022) for our four RT tasks results.

Mixed effects (repeated measures) ANOVA models were used with different factors (and their interactions) depending on the task and corresponding hypothesis (for more details, see respective descriptions of the experimental tasks above). Post hoc t-tests were conducted for significant effects of interest. *P*-values were checked for false discoveries using the False Discovery Rate method (FDR) (Benjamini & Hochberg, 1995), corrected according to the total number of relevant comparisons across each task. We considered this to be a good compromise given the explorative character of the study (i.e., little previous evidence and novelty of the stimulus material). As correction had no substantial impact on the significance, we report the uncorrected values within the manuscript and the corrected ones within the Supplementary Material (SM).

Data pre-processing was conducted in Python (version 3.8.3; see section 1 in SM for details). Data analysis was conducted with RStudio-v4.2.1 (RStudio, Boston, MA, USA). We fitted the models and produced inferential statistics using the function "ez_aov" from the package "afex" (Singmann et al., 2022). We used the packages "emmeans" (Lenth et al., 2022) for pairwise comparisons and "effectsize" (Ben-Shachar, Lüdecke, & Makowski, 2020) for effect sizes.

Moreover, in order to enhance the robustness and generalizability of our findings, we opted to conduct a sensitivity analysis. To that end, we complemented the ANOVA approach with a linear mixed-effects modelling (LME) approach. LME models effectively accommodate both the between-subject and within-subjects effects of the independent variable while also providing the capacity to consider random effects associated with subjects and stimuli (Baayen, Davidson, & Bates, 2008; Judd, Westfall, & Kenny, 2012). The raw, unaggregated data was used for the sensitivity analysis. We used the "lmer" function from the "lme4" package to fit the models (Bates, Mächler, Bolker, & Walker, 2015) and the package "emmeans" to produce the inferential statistics and *p*-values, as well as to obtain predicted means for the fixed effects.

3. Results

3.1. Descriptive sample data

The dataset contains information from 197 to 205 participants depending on the questionnaire. Table 1 describes the sample in terms of biological variables, education, knowledge and expertise in architecture, general (aesthetic) preferences, and psychopathology.

3.2. Experimental tasks

3.2.1. DPT

The 2 × 2 × 2 ANOVA with factors "congruency" (congruent vs. incongruent), "contour" (angular vs. curved), and "style" (modern vs. classic) did not yield the expected significant congruency effect ($F(1,207) = 0.42$, $p = .52$, $n2 < 0.001$). For a more detailed analysis, including other main effects and interactions, see Supplementary Table 1 (inferential statistics) and 2 (descriptive statistics).

Similarly, another ANOVA on error rates with the same factors as reported above, revealed no significant main effects ($p > .05$).

3.2.2. AAT

The 2 × 2 × 2 ANOVA with factors "direction" (approach vs. avoid), "contour" (angular vs. curved), and "style" (modern vs. classic) revealed that the main interaction of interest, namely contour x direction, was non-significant for both initial ($F(1,118) = 1.11$, $p = .30$, $n2 < 0.001$) and movement ($F(1,115) = 0.31$, $p = .58$, $n2 < 0.001$) RTs. No significant main or interaction effects were observed beyond the main effect of direction, that exclusively showed in movement RT ($F(1,115) = 8.87$, $p = .004$, $n2 = 0.004$), indicating participants were generally faster in avoiding than approaching stimuli. For further details, see Supplementary Tables 3 and 4 (inferential statistics), and 5 (descriptive statistics).

In line with the RT response, the analysis of the error rates also revealed an effect of direction, but no significant interaction of direction x contour.

3.2.3. IAT

The 2 × 2 × 2 ANOVA including factors "congruency" (congruent vs. incongruent), "contour" (angular vs. curved), and "style" (modern vs. classic) revealed a significant main effect of congruency ($F(1, 192) = 97.51$, $p < .0001$, $n2 = 0.074$). Pairwise comparisons showed that, on average, RTs were faster during congruent ($M = 720.93 \pm 133.28$) compared to incongruent ($M = 809.38 \pm 151.00$) test blocks with

[4] www.millisecond.com.

Table 1
Sample characteristics.

	N	Range [a]	Median	SD	freq.	%
Biological Variables	*200*					
Age		18–69	28.0	10.83	–	–
Self-reported sex [b]						
Male		–	–	–	101	50.5
Female		–	–	–	99	49.5
Handedness						
Right		–	–	–	170	85.0
Left		–	–	–	25	12.5
Ambidextrous		–	–	–	5	2.5
Vision correction (yes/no)						
Yes		–	–	–	91	45.5
No		–	–	–	109	54.5
Education	*200*					
Years of education [c]		5–13	12	1.34	–	–
Nominal level of education [d]						
No school degree		–	–	–	1	0.5
Hauptschulabschluss (9)		–	–	–	2	1.0
Realschulabschluss (10)		–	–	–	14	7.0
Polytechnische Oberschule (10)		–	–	–	5	2.5
Fachhochschulreife, Abschluss Fachoberschule (12)		–	–	–	[e]2	11[f]0
Allgemene Hochschulreife/ Abitur (12–13)		–	–	–	156	78.0
Architectural/aesthetics knowledge	*205*					
Architecture/design related profession (yes)		–	–	–	5	2.4
VAIAK architecture [e]		0–41	7	7.42	–	–
Interior design – interest VAS [f]		0–100	61.0	27.3	–	–
Interior design – knowledge VAS [f]		0[d]100	23.0	23.66	–	[c]
General aesthetic preferences						
Preferred interior design style	*198*					
No preference		–	–	–	2	1.0
Classic/traditional		–	–	–	19	9.6
Modern		–	–	–	104	52.5
No predominant style/ mixed		–	–	–	69	34.9
Other		–	–	–	4	2.0
Green colour rating – VAS [g]	*197*	0–100	75	22.99	–	–
Psychopathology	*198*					
DASS21- stress [h]		0–36	10.0	7.21	22	11.1
DASS21 – anxiety [h]		0–28	4.0	5.30	39	19.7
DASS21 – depression [h]		0–42	8.0	7.91	48	24.2

[a] Observed value range.
[b] The terms “male” and “female” are used as grouping adjectives, as this was how participants were asked to (dichotomously) classify themselves.
[c] School and professional education.
[d] Based on German education system. Years of education for each qualification are mentioned in brackets.
[e] A 7-item version of the interest subscale of the VAIAK (Vienna Art Interest and Knowledge Questionnaire) adapted to focus on architecture and interior design.
[f] Visual analogue scale (0–100) to rate interest or knowledge concerning architecture and interior design.
[g] Visual analogue scale (0–100) to rate the green colour as the only non-neutral colour presented in the rooms.
[h] DASS21 = Depression, Anxiety and Stress Scale 21. Values under the frequency column are the number of subjects reaching a clinically meaningful cut-off (i.e., moderate severity).

medium effect size ($t(192) = -9.88$, $p < .0001$, $d = 0.71$); (see Fig. 2). No significant two- or three-way interactions with neither contour (e.g., congruency x contour: $F(1,192) = 0.35$, $p = .557$, $\eta 2 < 0.001$) nor style were observed (see Supplementary Table 9). For further inferential and descriptive statistics, see Supplementary Tables 9–11.

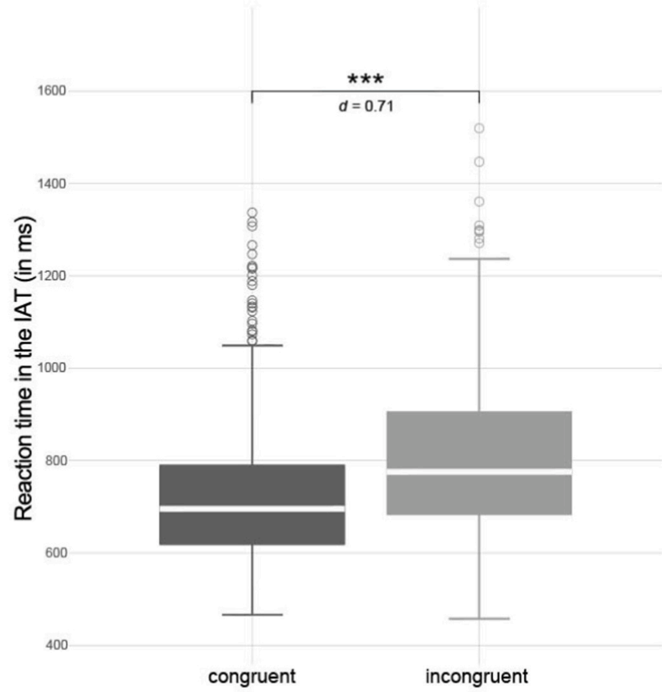

Fig. 2. Results of the IAT. Error bars represent standard errors.

Patterns of error aligned with those of RTs, indicating that the number of errors was higher in incongruent than congruent trials.

3.2.4. SRCT

The 2 × 2 × 2 ANOVA, incorporating factors “direction” (approach vs. avoid), “contour” (angular vs. curved), and “style” (modern vs. classic), revealed a significant two-way interaction of direction x contour ($F(1,179) = 7.08$, $p = .009$, $\eta 2 = 0.004$), as depicted in Fig. 3a. In terms of within-contour contrasts, pairwise comparisons showed that participants were faster approaching ($M = 937.93 \pm 246.68$) than avoiding ($M = 1027.33 \pm 252.88$) images showing curved interiors with small effect size ($t(179) = -5.42$, $p < .0001$, $d = 0.40$). Conversely, they were indifferent with respect to (approaching or avoiding) images with angular contours, as evident from the insignificant pairwise-comparison ($t(179) = -0.95$, $p = .35$, $d = 0.07$). Regarding the within-direction effects, while participants approached curvature descriptively faster than angularity, the effect was statistically insignificant. However, participants avoided angularity ($M = 974.73 \pm 223.11$) significantly faster than curvature ($M = 1027.33 \pm 252.88$), with small effect size ($t(179) = -3.09$, $p = .002$, $d = 0.23$); see Supplementary Tables 6–8 for more details.

The triple-interaction effect of direction x contour x style was also significant ($F(1,179) = 4.84$, $p = .03$, $\eta 2 = 0.001$), as illustrated in Fig. 3b. Post-hoc comparisons revealed different patterns depending on the interior design style. While similar trends as those described above were observed within the classic style, the within-curvature difference (faster approach and slower avoidance) remained similarly significant within the modern style ($t(179) = -5.32$, $p < .0001$, $d = 0.40$), while the within-angularity indifference further descriptively increased ($t(179) = 0.04$, $p = .097$, $d < 0.0001$). This resulted in significantly both faster approach ($t(179) = 2.9$, $p = .004$, $d = 0.22$) and slower avoidance ($t(179) = -2.82$, $p = .005$, $d = 0.21$) of curved compared to angular interiors. For further details, see Supplementary Tables 6–8.

Error rates analyses mirrored the results above, revealing a significant two-way interaction effect of direction and contour on participants RT responses. Specifically, error rates were the highest when avoiding images of curved vs. angular interiors, as well as when compared to

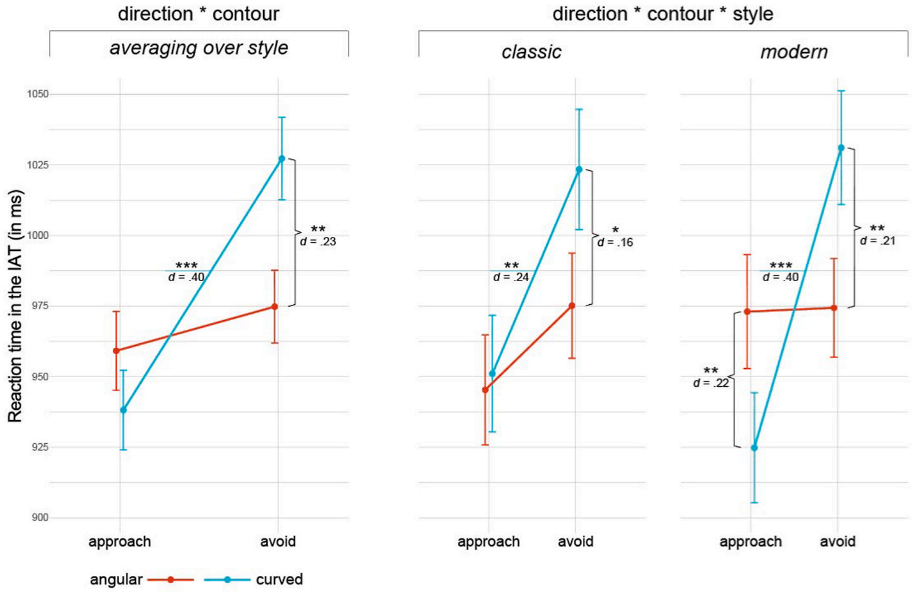

Fig. 3. Results of the SRCT. Error bars represent standard errors.

approaching them. The three-way interaction with style was also significant.

3.3. Interaction effects with self-reported sex

Interaction effects with "self-reported biological sex" (male vs. female; referred to hereafter as sex) were computed for exploratory purposes only when the main effect/interaction of interest was significant. This was the case for the IAT and the SRCT. Therefore, the two ANOVA models were updated by adding the factor "sex".

3.3.1. IAT

The 2 × 2 × 2 × 2 ANOVA revealed a significant main effect of "sex" on the IAT RTs ($F(1, 191) = 7.47, p = .007, n2 = 0.025$). Faster responses were generally observed in the female compared to male subgroup (see Supplementary Tables 13 and 14). There was a significant interaction effect of congruency x sex ($F(1, 191) = 8.88$, $p = .003$, $n2 = 0.007$). Pairwise comparisons indicated significant "congruency" effects within both groups, meaning, participants of both reported sexes were faster assigning images according to the congruent as opposed to incongruent instruction. When looking into between-group effects, RTs during congruent test blocks were faster for female ($M = 682.86 \pm 105.33$) compared to male ($M = 758.60 \pm 147.20$) participants with small effect size ($t(191) = 4.11$, $p = .0001$, $d = 0.30$). The groups did not differ in their response to incongruent trials ($t(191) = 1.08$, $p = .28$, $d = 0.08$). See Fig. 4 for a graphical depiction of the results, and Supplementary Tables 12–14 for more details on inferential and descriptive statistics.

No other significant two- or three-way interactions with neither contour nor style were observed (see Supplementary Table 12).

3.3.2. SRCT

When accounting for the effects of the factor sex on the SRCT RTs, we observed no main or interaction effects on any of our variables of interest, e.g., direction x contour x sex: $F(1, 177) = 1.16$, $p = .28$, $n2 < 0.001$ (see Supplementary Tables 15 and 16 for complete inferential and descriptive statistics).

3.4. Sensitivity analysis

For each of the four tasks, we estimated a model with the same ANOVA variables (experimental factors) and their interactions as fixed-

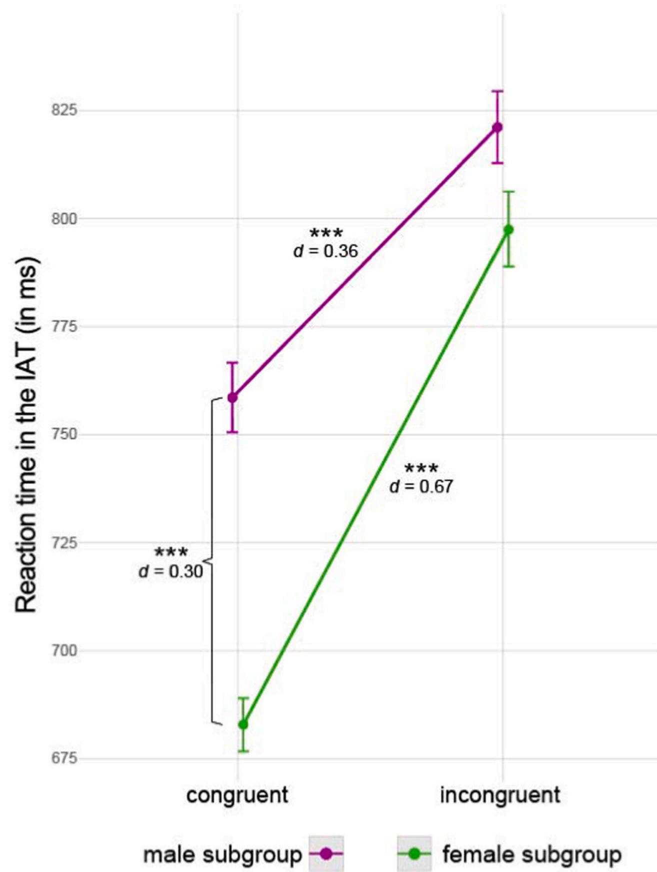

Fig. 4. Results of the interaction of congruency and sex in the IAT. Error bars represent standard errors.

effects and we estimated the related relevant random intercepts and slopes for participants and stimuli (see section 2.3 in the SM). Results of the LME models mirrored those of the ANOVA approach, confirming null results in the case of the DPT and AAT, and significant results for the IAT and SRCT that are of the same type (i.e., main effects or interactions) and direction as in the ANOVAs. Please see section 2.3 of the SM for more information regarding the LME results.

4. Discussion

Contour shapes are thought to play an influential role in how physical environments are perceived and evaluated, with a noted positive effect of curved vs. angular stimuli. The main explanations focused on either automatic appraisals or sensorimotor system responses (Corradi & Munar, 2019), with some attributing the effect to an avoidance of angularity (the threat hypothesis) (Bar & Neta, 2007), while others emphasize the attractiveness of curves (the curvature effect) (Bertamini et al., 2016; Vartanian et al., 2013). Another view highlighted the role of design trends in moderating this preference, at least within human-made domains (Carbon, 2010). Since previous research mainly relied on self-reports, we tested behavioural response tendencies towards contours in interior environments using a battery of four RT tasks that could detect potential automatic biases.

4.1. DPT

The "threat hypothesis" proposes that humans have evolved to prefer curvature due to their need to quickly detect and avoid edginess (Bar & Neta, 2007). We used the DPT as a marker of potentially biased attention and speculated that if angles would be perceived as "threatening", participants' attention would be drawn to angular conditions, leading to a faster detection of probes behind those. However, we observed no effects of contours on the DPT RTs, as participants' responses were independent of whether the probe appeared behind angular or curved stimuli.

There are several possible explanations for the null finding. Despite the demonstrated salience of angles/corners (Bertamini, Helmy, & Bates, 2013; Cole, Skarratt, & Gellatly, 2007), research suggests that scene gist is processed faster than individual objects, and understanding scene context might be more fundamental to threat judgement than object perception per se (Hochstein & Ahissar, 2002; Oliva & Torralba, 2006). It is possible that learning and exposure might have led to angular cues losing their threatening nature in living environments (Vartanian et al., 2013). Additionally, the contour differences in our stimuli may have been too subtle for participants to detect. The images represented overall room views in a relatively small size when compared to real-life scenarios, and also relative to the image size in the other tasks. Future research could compare environments with sharper angles or systematically vary the extent of angularity to explore whether the degree of edginess will affect participants' responses, as proposed in recent studies with abstract shapes (Clemente, Penacchio, Vila-Vidal, Pepperell, & Ruta, 2023).

Of note, defining the angular condition as "congruent" might be viewed critically, albeit aligning with the origins of the DPT as a task to detect threat-related attentional biases (Kappenman et al., 2014). Some studies proposed that curves, more common in natural environments in which the visual system has evolved, are processed more fluently and can be responded to faster than angles (Bertamini, Palumbo, & Redies, 2019; Chuquichambi et al., 2020). Unlike angles, which are defined by a set of vertices with abrupt orientation changes, curved shapes have a continuous changes along their contour, enhancing the efficiency of contour integration (Bex, Simmers, & Dakin, 2001; Field, Hayes, & Hess, 1993). Still, we also found no evidence for faster responses to curved conditions.

4.2. AAT

We assessed potential automatic behavioural/motoric biases towards curvature vs. angularity using an AAT with stimulus-irrelevant design. This means that participants responded to image orientation (instead of contours) by pulling a stimulus towards themselves (approach) or pushing it away (avoidance). As in the DPT, we expected contour to be a relevant feature, even when participants were not explicitly instructed to attend to it. Unlike hypothesized, we did not find evidence of any motoric biases or tendencies to approach or avoid either of the contours.

Overall, these results are in line with literature mostly reporting non-significant effects using the AAT when instructions are implicit, i.e., participants are not made aware of differential stimulus characteristics (Phaf et al., 2014). A study investigating contour and symmetry in abstract patterns similarly found that the responses to an affective stimulus-response compatibility (aSRC) task were only influenced when participants were instructed to think of one of the two features when responding (Chuquichambi, Corradi, et al., 2021). In fact, some argue that when stimulus features are task-relevant, compatibility effects can be better detected since the processing of irrelevant information is reduced (Fujita, Gollwitzer, & Oettingen, 2007; Gollwitzer, 2012). As mentioned above, it could be that the differences between our contour conditions were too subtle to be detected by participants without having to consciously take note of the contour. Future research may investigate whether making the contour more extreme or applying explicit instructions would reveal significant effects. However, it is worth noting that both the DPT and AAT could have been carried out without being consciously aware of not only the contour content, but also the images per se, whereby participants may have been rather solely focusing on the image orientation (AAT) or expected probe (DPT).

4.3. IAT

We conducted an IAT to capture semantic associations with the approach-avoidance concept. Participants categorized stimuli into hypothetical congruent (curved-approach and angular-avoid) and incongruent (angular-approach and curved-avoid) pairings. As predicted, we observed significantly faster responses in congruent trials, indicating that participants were faster sorting the images when curved and approach as well as angular and avoid categories were mapped together in pairs. The pattern suggests that participants associated these concepts in these specific mappings more intuitively, therefore, these links seem to be stronger in their mental representation, than the opposite, hypothetically incongruent pairings.

The findings confirm the previously reported positive effect of curved objects (Bar & Neta, 2006; Leder & Carbon, 2005) and interiors (Dazkir & Read, 2012; Madani Nejad, 2007; van Oel & van den Berkhof, 2013; Vartanian et al., 2013, 2019), in particular with respect to the same stimulus set (Tawil et al., 2022). The results are also in line with earlier evidence supporting a self-reported tendency to approach curved vs. angular furniture (Dazkir & Read, 2012) and spaces (Vartanian et al., 2019). In addition to the previously detected biases to associate contours with affective concepts (valence, safety) (Palumbo et al., 2015), we demonstrated semantic associations with a behavioural/motoric outcome, namely, approach-avoidance words.

While the interior design style (modern vs. classic) did not affect RTs, we observed a significant effect of participants' reported sex. The curved-approach and angular-avoid associations were more pronounced in female participants, who were also generally faster with the task. This higher sensitivity to contours in female participants aligns with prior research on children (Munroe, Munroe, & Lansky, 1976) and abstract shapes (Palumbo, Rampone, & Bertamini, 2021). It also manifested in the explicit preference response to the same stimulus material (Tawil et al., 2022). To note, the literature reports general sex differences in semantic processing (Wirth et al., 2007). For instance, studies have found that women process natural categories faster and more fluently while it is easier and quicker for men to process human-made categories (Bermeitinger, Wentura, & Frings, 2008; Capitani, Laiacona, & Barbarotto, 1999; Laws, 1999). Moreover, it appears that the two subgroups categorize the same common objects in systematically different ways (Pasterski, Zwierzynska, & Estes, 2011). Although both angular and curved conditions constitute man-made artifacts, curvature is considered a closer representation of nature (Coburn et al., 2020; Salingaros, 2015). However, we cannot say if curvature was indeed perceived as more natural as we have not explicitly tested for this.

We interpret the IAT effects as evidence for semantic/conceptual processes related to where such concepts are stored. The fact that effects were amplified in female participants reiterates the observation with explicit measures. In view of recent evidence suggesting that women may benefit more from salutogenic effects of natural environments (Sudimac & Kühn, 2022), further research is required to uncover societal and/or biological origins of this sensitivity to curved (interior) designs. Although the identified patterns might hint at a potential biophilic aspect of curves, the task was not designed to explain whether the effects relate to a tendency to approach curvature or conversely, to avoid angularity.

4.4. SRCT

The last measure to assess approach-avoidance tendencies was the SRCT. Hereby, participants were explicitly instructed to move a manikin towards/away from a stimulus, based on the depicted contours. As hypothesized, we observed a significant interaction between direction and contour, indicating that whether interiors had curved or angular features influenced how participants associated them with approach or avoidance movements: images of curved interiors were responded to with faster approach and slower avoidance responses, while images of angular interiors were approached and avoided equally fast. Additionally, angularity was always avoided faster than curvature. It seems that the effect lied within curvature yielding differential responses by instruction, whereas participants responded to angularity indifferently, regardless of instruction.

The results of the SRCT expand our knowledge from previous reports of an influence of contour on approach avoidance behaviour, further identifying the source of the effect. When comparing the findings with earlier evidence from studies that used a similar task to test abstract shapes (Bertamini et al., 2016; Palumbo et al., 2015), we confirmed consistent patterns in response to different contours, but with interior design stimuli. In particular, previous research also found faster approach and slower avoidance of curved abstract stimuli, and insignificant differences within angular ones, even when polygons had the most pronounced vertices (Palumbo et al., 2015).

There was also a significant interaction with style, similar to the effects found with explicit ratings of the same images, which revealed a preference for curves only within images depicting modern (compared to classic) style (Tawil et al., 2022). Here, modern style further descriptively increased the indifference towards angularity, but this time elicited both faster approach *and* slower avoidance towards curved vs. angular conditions. The findings, therefore, may propose a role of Zeitgeist in moderating responses to contours (Carbon, 2010). However, we note that objects in the modern and classic rooms included some differences in their geometrical properties, for instance the contrasting frames in the classic style, which might have affected participants' evaluations. Therefore, the effects should be further explored with a wider variety of styles.

Unlike the IAT, which demonstrated an influence of participant sex on how fast they associated contours with movement words, the SRCT yielded insignificant effects. This indicates that although these concepts were more strongly semantically connected in female participants' mental representations, this did not manifest in faster associative movements.

Our main interpretation of the SRCT findings supports a positive/pleasant effect of curved interior features (Vartanian et al., 2013), and hence motoric-approach-associations, rather than a negative/threatening effect of angular features. Although participants approached both contours generally similarly, it seems that it required them more effort to respond to images depicting curved features with an avoidance behaviour (slowest RTs), which suggests a tendency to come closer to curvature and stay longer compared with angularity. This also implies a biophilic aspect of curves (Browning et al., 2014; Salingaros, 2015).

4.5. Limitations and directions for future research

This study has limitations to consider. First, due to technical errors, the sample for the AAT was reduced by 75 participants from the original sample. Moreover, given the high rate of errors (67% of the original pool eventually qualified for evaluation), it remains uncertain whether all participants used a mouse (as instructed), especially since we did not assess compliance with this requirement. Second, the subtleness of our contour manipulation might have prevented us from detecting some expected effects in stimulus-irrelevant paradigms. However, as indicated by our previously reported manipulation check and participants' explicit ratings (Tawil et al., 2022), as well as the as-expected responses to the IAT and SRCT, the contour contrast was likely sufficiently pronounced. The absence of significant effects in both the DPT and AAT could hence be due to numerous other reasons. For instance, the SRCT may be better suited than the AAT to detect approach-avoidance reactions and biases, as it has previously shown better criterion validity in that it has been demonstrated to be significantly associated with self-reports for fear of spiders (Krieglmeyer & Deutsch, 2010). This difference may be attributed to inherent properties of the tasks, such as the intuitive nature of moving the manikin body towards or away from a stimulus in the SRCT, compared to directly moving the stimulus in the AAT, with the zoom feature potentially being perceived as an abstract effect. This taps into a more general, urgently needed critical discussion about implicit measures per se. The terms 'implicit' or 'automatic' should be used cautiously, as they formally require to be produced with explicit goals, awareness, substantial cognitive resources, and time (see De Houwer, Teige-Mocigemba, Spruyt, & Moors, 2009). In this paper, we used the term 'automatic' which is often used interchangeably with 'implicit'. However, we cannot rule out explicit goals and awareness. Concerning cognitive and time resources, we would argue that these were inherently limited by the task setup – albeit we cannot formally prove this claim. Especially in the two tasks where participants were made aware of attending and responding to the contour dimensions (IAT, SRCT), significant effects were found, which may call into question the 'implicitness' or 'automaticity' of responses and, arguably, providing a less clear distinction from explicit approaches such as self-reports.

A few last critical methodological remarks shall be made. Since the study was conducted on a platform dedicated for research, a sample bias might limit the generalizability of the results (i.e., highly educated sample, experienced with experiments). Similarly, the presented stimuli are limited in terms of representativeness. For one, we used static stimuli to generate conclusions about a dynamic experience. For another, we investigated the living room space, which, although multi-functional, is not representative of every other space. Future research may want to include more styles and target different functional spaces as well as different presentation modes to determine whether the effects can be exhibited similarly or ultimately differently.

5. Conclusion

In sum, this study confirmed effects of curved vs. angular interior designs using RT paradigms. Results identified associative biases with approach-avoidance words (IAT) and movements (SRCT), but neither attentional (DPT) nor motor biases (AAT), whereby findings were consistently shown with both reaction times and error rates as outcome parameters. The IAT demonstrated semantic associations indicating that curvature and approach, and angularity and avoidance were closely connected concepts in participants' mental representations. This is held especially true for women, who are perhaps more prone to the positive effects of (biophilic) curves. The SRCT particularly indicated weaker curvature-avoidance (as compared to relatively stronger curvature-approach) representations, similar to previous findings from abstract shapes. This effect was pronounced in modern style, now additionally yielding a significant difference concerning faster approach towards curved relative to angular interior designs.

Overall, this study provides evidence in favour of an attractive and pleasant intrinsic effect of curved interior designs rather than a threat afforded by angular ones, using behavioural measures hypothetically less influenced by conscious evaluations and expectancies in comparison to self-reports. More research is needed to study the criterion validity of the detected effects, such as for example in how far they relate to in-situ physiological and psychological responses in interior settings. In addition, a systematic approach to implicit task selection is needed to pinpoint hypothetical underlying psychological processes.

CRediT author statement

Nour Tawil: Conceptualization; Investigation; Methodology; Formal analysis; Project administration; Visualization; Writing - original draft; Writing – review and editing.

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Simone Kühn: Conceptualization; Methodology; Supervision; Writing – review and editing.

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Data availability statement

The datasets presented in this study along with the statistical codes can be found on: https://osf.io/vmw4f/.

Ethics statement

The studies involving human participants were reviewed and approved by Local Psychological Ethics Committee of the psychosocial center at Medical Center Hamburg-Eppendorf (LPEK-0215). The participants provided their written informed consent to participate in this study.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2023.102197.

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The curvature effect: Approach-avoidance tendencies in response to interior design stimuli

Supplementary Material

1. Pre-processing

Data preparation and pre-processing were conducted with Python version 3.8.3.

DPT. The DPT had an original sample of N=219, of which N=9 were excluded due to prematurely quitting the experiment and N=2 participants for having less than 75% initially correct trials. This resulted in a final sample of N=208 participants (95% of original sample), and n=8320 trials. Again, only correct trials were regarded as valid leaving n=8200 trials (corresponding to 94% of the original data pool final eligible sample size N=208). As this task has an upper limit of 1.000 ms per trial, after which an error message is shown and the next trial begins, no outlier correction was necessary.

Medians were computed for each combination of factors: [2] congruence (congruent = probe appearing at site of angular stimuli; incongruent = probe appearing at side of curved stimulus) x [2] style (modern vs. classic), resulting in four parameters.

AAT. An original sample of N=148 participants started with the AAT task. A script error caused the task not to appear to participants with even IDs, in addition to N=27 participants undertaking the task twice. Of those, five participants (Mac OS users – AAT program incompatible) were unable to move the cursor correctly and reattempted the task on a windows computer. The first attempts for these users were excluded. For the other N=22 (windows users), their first attempt was chosen for the analysis to avoid bias by repetition/ learning. Seven participants quit the experiment prematurely and N=22 participants had fewer than 75% correct trials (i.e., correct and no change of direction during the movement), and were all subsequently excluded (remaining=80% from the original sample; final eligible sample size N=119). This left an initial data pool of n=9520 RTs of interest. RTs of interest were a) the initial RT (time to initiation of movement after stimulus appearing) and b) the movement RTs (time needed to complete the approach/ avoidance movement) in response to the interior design stimuli. Only trials with correct responses and no change of direction were selected for computing median RT scores resulting in further reductions of the original pool of raw data (remaining=71% from original data, n=8383 trials). As preregistered, a cut-off criterion of > Q1 – IQR*3 and < Q3 + IQR*3 was defined for the RTs to detect and exclude outliers. After excluding outliers separately, for the initial and movement RTs, 69% of the original data pool was eligible, leaving a final sample of n=8172 trials (N=119) to evaluate the initial RTs; and 67% of the original pool with final sample of n=7922 trials (N=119) to evaluate the movement RT for the AAT.

In sum, 16 median RTs were computed; factors: [2] direction (approach/ avoidance) x [2] stimulus type (curved vs. angular) x [2] style (modern vs. classic) [=8], once for the initial and once for the movement RT [=16] were thereafter computed per participant.

IAT. An original sample of N=208 participants took part in the IAT. Ten participants quit the experiment prematurely and N=5 participants were excluded as they had less than 75% correct responses in the 'target trials' (remaining = 93% from the original sample; final eligible sample size N=193). 'Target trials' refer to RTs for sorting the interior design picture stimuli into categories from four blocks á 20 trials: two blocks assorting the stimuli into the congruent categories 'curved/approach' or 'angular/avoid'; and two blocks assorting the picture stimuli into the incongruent categories 'curved/avoid' or 'angular/approach'. There were hence initially n=15440 trials (RTs) available for analysis. Of those, only correct trials were considered, leaving n=14659 trials (corresponding to 95% from the initial data pool). After jointly applying these criteria, 94% of the initial data pool was eligible, leaving a final RT sample of n=14458 trials to evaluate the IAT (N=193).

The RT average of the two medians per congruent and incongruent conditions (blocks 3-4 and 6-7) were computed, resulting in a total of 4 median RT scores, factors: [2] congruence (congruent = curved/approach - angular/avoid; vs. incongruent = curved/avoid - angular/approach) x [2] style (modern vs. classic). The main effect of interest was the main effect of congruence, i.e., faster reactions of participants hypothesized in the case of congruent category pairings.

SRCT. The SRCT had an original sample of N=214 participants. Of those, n=14 participants with incomplete data and N=19 participants with less than 75% correct trials were excluded (remaining=85% from the original sample; final eligible sample size N=181). There was initially n=6626 correct trials eligible for analysis. Hereby, only the RTs to either approach or avoid curved/ angular stimuli, as explicitly instructed, were evaluated. After removing outliers, 81% of the original data pool was eligible with a total of n=6520 trials (final RT data pool, N=181).

In sum, 8 median RTs were computed; factors: [2] direction (approach/avoid) x [2] stimulus type (curved vs. angular stimuli) x [2] style (modern vs. classic) per participant.

2. Results

2.1. Experimental Tasks

2.1.1. DPT

Supplementary Table 1. Inferential statistics (main and interaction effects) of the DPT.

ANOVA factors	F value	Num DF	Den DF	P value	η^2
Congruence	0.42	1	207	0.518	<0.001
Style	0.09	1	207	0.765	<0.001
Congruence x style	0.59	1	207	0.445	<0.001

Supplementary Table 2. Descriptive reaction time data for the DPT.

congruent		incongruent	
M=357.06 SD=54.08		M=356.31 SD=55.74	
CI=350, 364		CI=349, 364	
classic	**modern**	**classic**	**modern**
M=357.35 SD=54.58	M=356.76 SD=56.47	M=355.67 SD=55.47	M=356.96 SD=58.53
CI=350, 365	CI=349, 364	CI=348, 363	CI=349, 365

Note: Congruent = probe behind angular conditions, incongruent = probe behind curved conditions.
M = mean, SD = standard deviation, CI = confidence intervals (95%).

2.1.2. AAT

Supplementary Table 3. Inferential statistics (main and interaction effects) of the AAT.

INITIAL RT					
ANOVA factors	**F value**	**Num DF**	**Den DF**	**P value**	**η^2**
Direction	0.53	1	118	0.466	<0.001
Contour	1.02	1	118	0.315	<0.001
Style	1.60	1	118	0.208	<0.001
Direction x contour	1.11	1	118	0.295	<0.001
Direction x style	0.03	1	118	0.869	<0.001
Contour x style	0.21	1	118	0.651	<0.001
Direction x contour x style	1.34	1	118	0.250	<0.001
MOVEMENT RT					
ANOVA factors	**F value**	**Num DF**	**Den DF**	**P value**	**η^2**
Direction	**8.87**	**1**	**115**	**0.004**	**0.004**
Contour	0.81	1	115	0.369	<0.001
Style	0.06	1	115	0.801	<0.001
Direction x contour	0.31	1	115	0.581	<0.001
Direction x style	0.55	1	115	0.459	<0.001
Contour x style	0.59	1	115	0.443	<0.001
Direction x contour x style	0.27	1	115	0.604	<0.001

Note. Num DF indicates degrees of freedom numerator. Den DF indicates degrees of freedom denominator. η^2 indicates generalized eta-squared.

Supplementary Table 4. Pairwise comparisons for of the significant effects identified for the AAT RTs (direction in movement RT).

Pairwise comparisons N=116	**T value**	**Uncorrected P value**	**Corrected P value**	**Cohen's D**
Direction: approach vs. avoid (Movement RT)	**2.98**	**0.004**	**0.007**	**0.22**

Supplementary Table 5. Descriptive reaction time data for the AAT.

<table>
<tr><th colspan="8">INITIAL RT</th></tr>
<tr><th colspan="4">approach</th><th colspan="4">avoid</th></tr>
<tr><td colspan="4">M=569.55
SD=96.99</td><td colspan="4">M=566.31
SD=85.59</td></tr>
<tr><td colspan="4">CI=552, 587</td><td colspan="4">CI=551, 582</td></tr>
<tr><th colspan="2">curved</th><th colspan="2">angular</th><th colspan="2">curved</th><th colspan="2">angular</th></tr>
<tr><td colspan="2">M=572.94
SD=105.08</td><td colspan="2">M=566.16
SD=95.8</td><td colspan="2">M=566.26
SD=94.04</td><td colspan="2">M=566.35
SD=83.54</td></tr>
<tr><td colspan="2">CI=554, 592</td><td colspan="2">CI=549, 584</td><td colspan="2">CI=549, 583</td><td colspan="2">CI=551, 582</td></tr>
<tr><th>classic</th><th>modern</th><th>classic</th><th>modern</th><th>classic</th><th>modern</th><th>classic</th><th>modern</th></tr>
<tr><td>M=567.69
SD=108.04</td><td>M=578.19
SD=126.38</td><td>M=566.47
SD=103.58</td><td>M=565.84
SD=96.84</td><td>M=565.85
SD=93.97</td><td>M=566.68
SD=108.87</td><td>M=563.14
SD=84.16</td><td>M=569.56
SD=91.52</td></tr>
<tr><td>CI=548,
587</td><td>CI=555,
601</td><td>CI=548,
585</td><td>CI=548,
583</td><td>CI=549,
583</td><td>CI=547,
586</td><td>CI=548,
578</td><td>CI=553,
586</td></tr>
<tr><th colspan="8">MOVEMENT RT</th></tr>
<tr><th colspan="4">approach</th><th colspan="4">avoid</th></tr>
<tr><td colspan="4">M=119.84
SD=50.82</td><td colspan="4">M=113.75
SD=45.18</td></tr>
<tr><td colspan="4">CI=110, 129</td><td colspan="4">CI=105, 122</td></tr>
<tr><th colspan="2">curved</th><th colspan="2">angular</th><th colspan="2">curved</th><th colspan="2">angular</th></tr>
</table>

M=121.62 SD=55		M=115.77 SD=50.7		M=122.53 SD=53.88		M=115.4 SD=47.22	
CI=110, 129		CI=111, 130		CI=105, 122		CI=106, 122	
classic	**modern**	**classic**	**modern**	**classic**	**modern**	**classic**	**modern**
M=119.89 SD=52.19	M=118.51 SD=53.61	M=120.1 SD=53.07	M=120.84 SD=50.81	M=113.25 SD=46.74	M=113.91 SD=47.62	M=113.46 SD=44.55	M=114.4 SD=44.5
CI=110, 129	CI=109, 128	CI=110, 130	CI=111, 130	CI=105, 122	CI=105, 123	CI=105, 122	CI=106, 123

Note: M = mean, SD = standard deviation, CI = confidence intervals (95%).

2.1.3. IAT

Supplementary Table 6. Inferential statistics (main and interaction effects) of the IAT.

ANOVA factors	F value	Num DF	Den DF	P value	η^2
Congruence	**97.51**	**1**	**192**	**<0.0001**	**0.074**
Contour	0.35	1	192	0.557	<0.001
Style	0.37	1	192	0.546	<0.001
Congruence x contour	1.1	1	192	0.296	<0.001
Contour x style	0.06	1	192	0.807	<0.001
Congruence x style	1.28	1	192	0.260	<0.001
Congruence x contour x style	1.6	1	192	0.207	<0.001

Note. Num DF indicates degrees of freedom numerator. Den DF indicates degrees of freedom denominator. η^2 indicates generalized eta-squared.

Supplementary Table 7. Pairwise comparisons for of the significant effects identified for the IAT RTs (congruence).

Pairwise comparisons N=193	T value	Uncorrected P value*	Corrected P value	Cohen's D
Congruence: congruent vs. incongruent	**-9.88**	**<0.0001**	**<0.0001**	**-0.71**

Supplementary Table 8. Descriptive reaction time data for the IAT (RT means and standard deviations).

congruent				**incongruent**			
M=720.93 SD=133.28				M=809.38 SD=151			
CI=702, 740				CI=788, 831			
angular		**curved**		**angular**		**curved**	
M=717.49 SD=133.46		M=724.36 SD=143.16		M=810.31 SD=158.31		M=808.45 SD=156.94	
CI=699, 736		CI=704, 745		CI=788, 833		CI=786, 831	
classic	**modern**	**classic**	**modern**	**classic**	**modern**	**classic**	**modern**
M=719.25 SD=143.54	M=715.73 SD=139.62	M=729.60 SD=154.81	M=719.12 SD=145.78	M=811.93 SD=166.70	M=808.7 SD=171.75	M=804.88 SD=165	M=812.03 SD=167.68
CI=699, 740	CI=696, 736	CI=708, 752	CI=698, 740	CI=788, 836	CI=784, 833	CI=781, 828	CI=788, 836

Note: Congruent = probe behind angular conditions, incongruent = probe behind curved conditions.
M = mean, SD = standard deviation, CI = confidence intervals (95%).

2.1.4. SRCT

Supplementary Table 9. Inferential statistics (main and interaction effects) of the SRCT.

ANOVA factors	F value	Num DF	Den DF	P value	η^2
Direction	**37.53**	**1**	**179**	**<0.001**	**0.009**
Contour	2.26	1	179	0.135	<0.001
Style	0.08	1	179	0.783	<0.001
Direction x contour	**7.08**	**1**	**179**	**0.009**	**0.004**
Direction x style	0.01	1	179	0.904	<0.001
Contour x style	2.77	1	179	0.098	<0.001
Direction x contour x style	**4.84**	**1**	**179**	**0.029**	**0.001**

Note. Num DF indicates degrees of freedom numerator. Den DF indicates degrees of freedom denominator. η^2 indicates generalized eta-squared.

Supplementary Table 10. Pairwise comparisons for the significant effects identified for the SRCT RTs (direction, contour x direction, and contour x style x direction).

Pairwise Comparisons N=179	T value	Uncorrected P value	Corrected P value	Cohen's D
Direction				
approach vs. avoid	**-6.13**	**<0.0001**	**<0.0001**	**-0.46**
Direction x Contour				
approach-curved vs. avoid-curved	**-5.421**	**<0.0001**	**<0.0001**	**-0.41**
approach-angular vs. avoid-angular	-0.948	0.345	0.383	-0.07
approach-angular vs. approach-curved	1.436	0.153	0.191	0.11
avoid-angular vs. avoid-curved	**3.089**	**0.002**	**0.005**	**0.23**
Direction x Contour in Modern				
approach-curved vs. avoid-curved	**-5.323**	**<0.0001**	**<0.0001**	**0.40**
approach-angular vs. avoid-angular	0.035	0.972	0.972	<0.0001
approach-angular vs. approach-curved	**2.903**	**0.004**	**0.008**	**0.22**
avoid-angular vs. avoid-curved	**-2.823**	**0.005**	**0.009**	**0.21**
Direction x Contour in Classic				
approach-curved vs. avoid-curved	**-3.193**	**0.002**	**0.004**	**0.24**
approach-angular vs. avoid-angular	-1.725	0.086	**0.115**	0.13
approach-angular vs. approach-curved	-0.433	0.666	**0.701**	0.03
avoid-angular vs. avoid-curved	**-2.188**	**0.03**	**0.043**	**0.16**

Supplementary Table 11. Descriptive reaction time data for the SRCT (RT means and standard deviations).

approach				**avoid**			
M=949.02 SD=221.96				M=1001.03 SD=211.81			
CI=915, 980				CI=967, 1028			
angular		**curved**		**angular**		**curved**	
M=960.71 SD=246.82		M=937.93 SD=246.68		M=974.73 SD=223.11		M=1027.33 SD=252.88	
CI=923, 994		CI=900, 973		CI=940, 1006		CI=986, 1057	
classic	**modern**	**classic**	**modern**	**classic**	**modern**	**classic**	**modern**
M=942.02 SD=260.21	M=973.15 SD=269.71	M=950.96 SD=278.37	M=922.06 SD=259.65	M=973.64 SD=252.58	M=972.50 SD=236.58	M=1017.32 SD=274.6	M=1024.91 SD=258.40
CI=905, 981	CI=934, 1013	CI=911, 993	CI=884, 961	CI=937, 1011	CI=937, 1007	CI=976, 1058	CI=987, 1064

Note: M = mean, SD = standard deviation, CI = confidence intervals (95%).

2.2. Interaction effects with self-reported sex

2.2.1. IAT

Supplementary Table 12. Inferential statistics (main and interaction effects including sex) of the IAT.

ANOVA factors	F value	Num DF	Den DF	P value	η^2
Congruence	**101.82**	**1**	**191**	**<0.001**	**0.076**
Contour	0.34	1	191	0.561	<0.001
Style	0.36	1	191	0.549	<0.001
Sex	**7.47**	**1**	**191**	**0.007**	**0.025**
Congruence x contour	1.11	1	191	0.294	<0.001
Congruence x style	1.27	1	191	0.262	<0.001
Contour x style	0.06	1	191	0.810	<0.001
Congruence x sex	**8.88**	**1**	**191**	**0.003**	**0.007**
Contour x sex	1.22	1	191	0.271	<0.001
Style x sex	0.37	1	191	0.542	<0.001
Congruence x contour x style	1.59	1	191	0.209	<0.001
Congruence x contour x sex	0.85	1	191	0.359	<0.001
Contour x style x sex	0.34	1	191	0.562	<0.001
Congruence x style x sex	1.99	1	191	0.160	<0.001
Congruence x contour x style x sex	0.55	1	191	0.459	<0.001

Note. Num DF indicates degrees of freedom numerator. Den DF indicates degrees of freedom denominator. η^2 indicates generalized eta-squared.

Supplementary Table 13. Pairwise comparisons for of the significant sex effects identified for the IAT RTs (sex and congruence x sex).

Pairwise Comparisons N=193	T value	Uncorrected P value	Corrected P value	Cohen's D
Sex				
male vs. female	**2.73**	**0.007**	**0.0106**	**0.20**
Congruence x sex				
congruent-male vs. congruent-female	**4.107**	**0.0001**	**0.0003**	**0.30**
incongruent-male vs. incongruent-female	1.077	0.2828	0.3327	0.08
congruent-male vs. incongruent-male	**-5.041**	**<0.0001**	**<0.0001**	**-0.36**
congruent-female vs. incongruent-female	**-9.219**	**<0.0001**	**<0.0001**	**-0.67**

Supplementary Table 14. Descriptive reaction time data for the IAT with sex interaction (RT means and standard deviations).

<table>
<tr><th colspan="4">male</th><th colspan="4">female</th></tr>
<tr><td colspan="4">M=789.81
SD=133.99</td><td colspan="4">M=740.24
SD=117.37</td></tr>
<tr><td colspan="4">CI=765, 815</td><td colspan="4">CI=715, 766</td></tr>
<tr><th colspan="2">congruent</th><th colspan="2">incongruent</th><th colspan="2">congruent</th><th colspan="2">incongruent</th></tr>
<tr><td colspan="2">M=758.6
SD=147.2</td><td colspan="2">M=821.02
SD=144.73</td><td colspan="2">M=682.86
SD=105.33</td><td colspan="2">M=797.62
SD=156.96</td></tr>
<tr><td colspan="2">CI=733, 784</td><td colspan="2">CI=791, 851</td><td colspan="2">CI=657, 709</td><td colspan="2">CI=767, 828</td></tr>
<tr><th>curved</th><th>angular</th><th>curved</th><th>angular</th><th>curved</th><th>angular</th><th>curved</th><th>angular</th></tr>
<tr><td>M=762.46
SD=159.49</td><td>M=754.73
SD=145.99</td><td>M=824.34
SD=151.33</td><td>M=817.71
SD=154.56</td><td>M=685.88
SD=112.85</td><td>M=679.86
SD=107.75</td><td>M=792.39
SD=161.61</td><td>M=802.84
SD=162.47</td></tr>
<tr><td>CI=735, 790</td><td>CI=729, 780</td><td>CI=793, 856</td><td>CI=786, 849</td><td>CI=658, 714</td><td>CI=654, 706</td><td>CI=761, 824</td><td>CI=771, 835</td></tr>
</table>

Note: The terms “male” and “female” are used as grouping adjectives, as this was how participants were asked to (dichotomously) classify themselves.
Congruent = categories mapped into angular-avoid and curved-approach, incongruent = categories mapped into angular-approach and curved-avoid.
M = mean, SD = standard deviation, CI = confidence intervals (95%).

2.2.2. SRCT

Supplementary Table 15. Inferential statistics (main and interaction effects including sex) of the SRCT.

ANOVA factors	F value	Num DF	Den DF	P value	η^2
Sex	1.28	1	177	0.259	0.004
Direction	**36.82**	**1**	**177**	**<0.001**	**0.009**
sex x direction	2.62	1	177	0.107	<0.001
Contour	2.26	1	177	0.135	<0.001
Sex x contour	0.00	1	177	0.961	<0.001
Style	0.06	1	177	0.808	<0.001
Sex x style	1.49	1	177	0.224	<0.001
Contour x direction	**7.15**	**1**	**177**	**0.008**	**0.004**
Sex x direction x contour	1.16	1	177	0.284	<0.001
Style x direction	0.03	1	177	0.873	<0.001
Sex x style x direction	0.15	1	177	0.697	<0.001
Style x contour	2.59	1	177	0.110	<0.001
Sex x contour x style	0.89	1	177	0.347	<0.001
Contour x style x direction	**5.08**	**1**	**177**	**0.025**	**0.001**
Sex x direction x contour x style	0.79	1	177	0.375	<0.001

Note. Num DF indicates degrees of freedom numerator. Den DF indicates degrees of freedom denominator. η^2 indicates generalized eta-squared.

Supplementary Table 16. Descriptive reaction time data for the SRCT with sex interaction (RT means and standard deviations).

male				female			
M=954.96 SD=203.41				M=989.90 SD=209.75			
CI=912, 998				CI=947, 1033			
approach		**avoid**		**approach**		**avoid**	
M=923.62 SD=220.62		M=986.29 SD=201.26		M=971.77 SD=220.68		M=1008.03 SD=211.56	
CI=877, 970		CI=943, 1029		CI=926, 1018		CI=965, 1051	
curved	**angular**	**curved**	**angular**	**curved**	**angular**	**curved**	**angular**
M=920.13 SD=242.41	M=927.11 SD=233.15	M=1003.66 SD=224.18	M=968.93 SD=217.36	M=953.81 SD=252.09	M=989.74 SD=252.05	M=1038.99 SD=254.62	M=977.07 SD=230.03
CI=868, 972	CI=876, 978	CI=953, 1054	CI=922, 1016	CI=902, 1005	CI=939, 1040	CI=989, 1089	CI=931, 1024

Note: The terms “male” and “female” are used as grouping adjectives, as this was how participants were asked to (dichotomously) classify themselves.
M = mean, SD = standard deviation, CI = confidence intervals (95%).

2.3. Sensitivity Analysis

2.3.1. DPT

Since no significant effects (as hypothesized) of the DPT were found in the ANOVA, we limited our sensitivity analyses to models without exploration of the effect of sex. In any case, if the main effect of interest (congruency) became significant in the LME sensitivity analysis approach, sex would have been analyzed additionally.

In the analysis of the DPT data, we aimed to predict reaction times (RTs) based on congruency (congruent vs. incongruent), style (modern vs. classic), and the interaction between congruency and style as factors of fixed effects. We used the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) fit criteria (ANOVA in R) to compare models. The best-fitting model included random intercepts for subjects and stimuli (m_DPT = RT ~ 1 + congruency * style + (1|subject) + (1|stimulus)).

As with the initial ANOVA analysis, the main effect of interest (congruency) as well as the interaction congruency * style were not significant. See Supplementary Table 17 for more details. In sum, the sensitivity analyses broadly replicate the findings as reported in the main paper.

Supplementary Table 17. DPT Model

Model	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	363.4899	4.3099	126.7582	84.338	<2e-16 ***
congruenceincongruent	-1.0445	1.8104	7985.2421	-0.577	0.564
stylemodern	-0.3274	1.8067	7985.1487	-0.181	0.856
congruenceincongruent:stylemodern	2.8174	2.5548	7985.1674	1.103	0.270

2.3.2. AAT

Similar to the DPT, we did not initially consider the effect of sex when fitting the AAT models.

2.3.2.1. AAT initial RT

To predict RTs, we included direction (push vs. pull), contour (angular vs curved), style (classic vs modern), and interaction terms between these three variables as factors of fixed effects. The best fitting model, according to model fit indices, additionally included random slopes within subjects' random effect (m_AAT_initial = RT ~ 1 + direction * contour * style + (1 + direction|subject) + (1|stimulus)).

The effects of interest, i.e., direction*contour (or triple interaction direction*contour*style), were generally non-significant, replicating the null-findings based on the ANOVA.

Supplementary Table 18. AAT initial RT model

Model	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	600.509	9.917	176.083	60.556	<2e-16 ***
directionpush	-10.139	6.835	631.443	-1.483	0.139
contourcurved	-2.186	6.049	8862.248	-0.361	0.718
stylemodern	-2.549	6.058	8869.389	-0.421	0.674
directionpush:contourcurved	4.164	8.370	8859.361	0.497	0.619
directionpush:stylemodern	4.479	8.376	8865.033	0.535	0.593
contourcurved:stylemodern	10.016	8.552	8863.246	1.171	0.242
directionpush:contourcurved:stylemodern	-12.800	11.842	8860.429	-1.081	0.280

2.3.2.2. AAT movement RT

Movement RTs were also evaluated. Similar to the AAT initial RT model, the best-fitting model included random slopes within subjects' random effect (m_AAT_movement = RT ~ 1 + direction * contour * style + (1 + direction|subject) + (1|stimulus)).

Direction exhibited a significant negative effect. This directional effect was also confirmed between push and pull conditions (Z = 4.52, p <.0001, d = 0.38). Although this was not an effect of interest, the results of the LME confirm the post-hoc results from the ANOVA. However, the effects of interest, i.e., direction*contour (or triple interaction direction*contour*style) were generally non-significant, replicating the null-findings based on the ANOVA.

Supplementary Table 19. AAT movement RT model

Model	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	137.08452	5.30536	148.32535	25.839	< 2e-16 ***
directionpush	-14.74139	3.36265	153.90263	-4.384	2.15e-05 ***
contourcurved	-1.21815	1.60966	8551.19849	-0.757	0.449
stylemodern	-1.02259	1.61232	8552.60515	-0.634	0.526
directionpush:contourcurved	0.16856	2.22353	8548.47442	0.076	0.940
directionpush:stylemodern	0.08138	2.21990	8550.83637	0.037	0.971
contourcurved:stylemodern	-0.05126	2.27122	8550.51456	-0.023	0.982
directionpush:contourcurved:stylemodern	2.97478	3.13649	8548.93540	0.948	0.343

2.3.3. IAT

We fitted a model to predict IAT RTs based on "congruency" (congruent vs. incongruent), "contour" (angular vs. curved), "style" (modern vs. classic), and the interaction between these three factors as fixed effects. Since we observed a significant effect of sex with the ANOVA approach, we added sex when fitting and comparing the models. According to the models fit indices, the best fitting model also included sex as a fixed effect and random slopes within subjects' random effect (m_IAT = latency ~ 1 + congruence * contour + congruence * style + congruence * sex + (1 + congruence|subject) + (1|stimulus)). .

As in the ANOVA results reported in the main paper, the following main effects and interactions of interest were significant (congruency, congruency * sex). Post-hoc t-tests (emmeans) were conducted to follow up on these effects. Pairwise comparisons for the congruency main effect showed that, on average, RTs were faster during congruent (M = 763 ± 19.5) compared to incongruent (M = 849 ± 20.1) test blocks (Z = -9.81, p < .0001, d = 0.40).

Concerning the interaction congruency * sex, post-hoc tests revealed a significant difference between male and female participants' RTs during congruent trials (Z = 4.83, p < .0001, d = 0.43) with female participants being faster on average (M = 717 ± 21.7) compared with male participants (M = 809 ± 21.6). Significant differences were also found between congruent and incongruent trials when looking at male and female participants separately (Z = -4.53, p < .0001, d = 0.26) for male, and (t = -9.33, p < .0001, d = 0.54) for female.

Supplementary Table 20. IAT model

Model	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	809.564	21.922	10.721	36.929	1.20e-12 ***
typeincompatible	55.164	13.358	256.149	4.130	4.92e-05 ***
contourcurved	6.372	5.041	14066.064	1.264	0.206200
stylemodern	-8.387	5.040	14065.443	-1.664	0.096088 .
sex	-91.568	18.968	190.303	-4.828	2.83e-06 ***
typeincompatible:contourcurved	-5.301	7.180	14067.530	-0.738	0.460379
typeincompatible:stylemodern	7.139	7.179	14066.672	0.994	0.320010
typeincompatible:sex	60.074	17.556	189.154	3.422	0.000762 ***

2.3.4. SRCT

In the analysis of the SRCT data, the best fitting model included parameters for direction (approach vs. avoid), contour (angular vs. curved), style (classic vs. modern), the interaction between these variables, and random intercepts for subjects and stimuli (m_SRCT = latency ~ 1 + direction * contour * style + (1|subject) + (1|stimulus)). Adding sex as a fixed effect did improve the model fit.

In line with the ANOVA analysis, there was a significant interaction of direction*contour. Pairwise comparisons confirmed significant differences between avoid-angular and avoid-curved RTs (Z = -5.96, p <.0001, d = 0.21) as well as between approach-curved and avoid-curved RTs (Z = -9.26, p = <.0001, d = 0.33). There were no further significant differences for the interaction direction*contour.

Supplementary Table 21. SRCT model

Model	**Estimate**	**Std. Error**	**df**	**t value**	**Pr(>|t|)**
(Intercept)	979.605	25.632	14.126	38.217	1.16e-15 ***
directionavoid	17.459	14.264	6329.043	1.224	0.22101
contourcurved	9.057	14.387	6329.572	0.630	0.52903
stylemodern	19.774	14.295	6328.205	1.383	0.16663
directionavoid:contourcurved	64.983	20.472	6330.001	3.174	0.00151 **
directionavoid:stylemodern	-2.771	20.207	6329.064	-0.137	0.89093
contourcurved:stylemodern	-53.693	20.214	6328.211	-2.656	0.00792 **
directionavoid:contourcurved:stylemodern	27.591	28.761	6328.757	0.959	0.33743

D: Declaration of own share

Annex Declaration pursuant to Sec. 7 (3), fourth sentence, of the Doctoral Study Regulations regarding my own share of the submitted scientific or scholarly work that has been published or is intended for publication within the scope of my publication-based work.

1. Last name, first name: Tawil, Nour
   Institute: Max Planck Institute for Human Development, Berlin
   Doctoral study subject: Psychology
   Title: MU2 in Neuroscience Applied to Architectural Design; B.A. in Architectural Engineering

2. **Numbered listing of works submitted (title, authors, where and when published and/or submitted):**

   2.1 Tawil, N., Sztuka, I. M., Pohlmann, K., Sudimac, S., & Kühn, S. (2021). The living space: Psychological well-being and mental health in response to interiors presented in virtual reality. *International Journal of Environmental Research and Public Health*, *18*(23), Article 12510. doi: 10.3390/ijerph182312510

   2.2 Tawil, N., Ascone, L., & Kühn, S. (2022). The contour effect: Differences in the aesthetic preference and stress response to photo-realistic living environments. *Frontiers in Psychology, 13*, Article 933344. doi: 10.3389/fpsyg.2022.933344

   2.3 Tawil, N., Elias, J., Ascone, L., & Kühn, S. (2024). The curvature effect: Approach-avoidance tendencies in response to interior design stimuli. *Journal of Environmental Psychology, 93*, Article 102197. doi: 10.1016/j.jenvp.2023.102197

3. **Explanation of own share of these works:**
   The amount of the work completed by myself is evaluated on the following scale: all – the vast majority – most – part.

   Regarding 2.1: Experimental design (the vast majority), method development (the vast majority), data collection (all), data analysis and programming (the vast majority), data visualization (all), interpretation and discussion of results (all), preparing the manuscript (all).

Regarding 2.2: Experimental design (most), method development (the vast majority), data collection (all), data analysis and programming (the vast majority), data visualization (all), interpretation and discussion of results (all), preparing the manuscript (all).

Regarding 2.3: Experimental design (most), method development (the vast majority), data collection (all), data analysis and programming (the vast majority), data visualization (all), interpretation and discussion of results (the vast majority), preparing the manuscript (all).

4. **Names and e-mail addresses for the relevant co-authors:**

Regarding 2.1: Izabela Maria Sztuka (sztuka@mpib-berlin.mpg.de),
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Regarding 2.2: Leonie Ascone (l.ascone-michelis@uke.de),
Simone Kühn (see above).

Regarding 2.3: Jordan Elias (elias@mpib-berlin.mpg.de),
Leonie Ascone (see above),
Simone Kühn (see above).

Berlin, April 2024

Nour Tawil

E: Declaration of independent work

I hereby declare in lieu of oath:

- that I have written this dissertation independently and without unauthorised assistance,
- that I have not submitted this dissertation to any other university and that I do not hold a doctoral degree in the subject of psychology, and
- that I am aware of the doctoral regulations for the degree of Dr.rer.nat. / Ph.D. in the Department of Education and Psychology at the Freie Universität Berlin, as amended on August 8th 2016 (official gazette of the Freie Universität Berlin 35/2016).

Hiermit erkläre ich an Eides statt,

- dass ich die vorliegende Arbeit selbstständig und ohne unerlaubte Hilfe verfasst habe,
- dass ich die Dissertation an keiner anderen Universität eingereicht habe und keinen Doktorgrad in dem Promotionsfach Psychologie besitze und,
- dass mir die Promotionsordnung zum Dr. rer. nat./Ph. D. des Fachbereichs Erziehungswissenschaft und Psychologie der Freien Universität Berlin vom 8. August 2016 (Amtsblatt der Freien Universität Berlin 35/2016) bekannt ist.

Berlin, April 2024

Nour Tawil

F: Curriculum vitae

Nour Tawil

Max Planck Institute for Human Development

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Education and Training

03/2022 – Present	Freie Universität Berlin, Berlin, Germany Doctoral Student
04/2020 – Present	International Max Planck Research School on the Life Course (LIFE) Fellow
11/2017 – 10/2018	Università Iuav di Venezia, Venice, Italy Master Universitario 2 - Neuroscience Applied to Architectural Design (grade: 16/16) Thesis: A Neurophenomenological Approach to Architectural Design in Psychiatric Settings - An Application on the Interior Spaces of Villa San Pietro (Trento, Italy)
09/1998 – 06/2003	Beirut Arab University, Beirut, Lebanon Bachelor - Architectural Engineering (grade: 73.01/100)

Research positions

04/2020 – Present	Pre-Doctoral Fellow, Lise Meitner Group for Environmental Neuroscience, Max Planck Institute for Human Development Berlin, Germany
10/2019 – 06/2022	Tutor, Neuroscience Applied to Architectural Design program (NAAD master), Università Iuav di Venezia, Venice, Italy

Publications

In press	**Tawil, N.,** & Kühn, S. (in press). The built environment and the brain: Emerging methods to investigate the impact of viewing architectural design. In S. Kühn (Ed.), *Environmental Neuroscience*. Springer.

2024	**Tawil, N.,** Elias, J., Ascone, L., & Kühn, S. (2024). The curvature effect: Approach-avoidance tendencies in response to interior design stimuli. *Journal of Environmental Psychology, 93*, Article 102197. https://doi.org/10.1016/j.jenvp.2023.102197
2023	Olszewska-Guizzo, A., Russo, A., Roberts, A. C., Kühn, S., Marques, B., **Tawil, N.,** & Ho, R. C. (2023). Editorial: Cities and mental health. *Frontiers in Psychiatry*, 14, Article 1263305. https://doi.org/10.3389/fpsyt.2023.1263305
2022	**Tawil, N.,** Ascone, L., & Kühn, S. (2022). The contour effect: Differences in the aesthetic preference and stress response to photo-realistic living environments. *Frontiers in Psychology, 13*, Article 933344. https://doi.org/10.3389/fpsyg.2022.933344
2022	Roessler, K. K., Weber, S., **Tawil, N.,** & Kühn, S. (2022). Psychological attributes of house facades: A graph network approach in environmental psychology. *Journal of Environmental Psychology, 82,* Article 101846. https://doi.org/10.1016/j.jenvp.2022.101846
2021	**Tawil, N.,** Sztuka, I. M., Pohlmann, K., Sudimac, S., & Kühn, S. (2021). The living space: Psychological well-being and mental health in response to interiors presented in virtual reality. *International Journal of Environmental Research and Public Health*, *18*(23), Article 12510. https://doi.org/10.3390/ijerph182312510

Invited Talks and Panels

02/2024	Hochschule Darmstadt, Germany Talk: *The intersection of neuroscience and architectural design: Towards healthier built environments.*
03/2023	Leuphana University, Lüneburg, Germany Leuphana conference week, “Our turn”. Panel: *Building a sustainable future: Integrating perspectives from psychology, anthropology and architecture for climate action and resilient human well-being.*
06/2022	Università IUAV di Venezia, Venice, Italy Panel: *Prison spaces.*
03/2022	University Medical Center Hamburg-Eppendorf, Germany Symposium on Virtual and Augmented Reality (AR/VR) methods in the intersection of Computer Science and Neuroscience. Talk: *Home environment and the brain: Psychological*

	responses to architectural parameters.
04/2021	Università IUAV di Venezia, Venice, Italy Talk: *Curved or angular? Exploring human reactions to architecture.*
11/2020	The Center for Conscious Design Conscious Cites Festival 2020: Sensing our City, Warsaw, Poland Talk: *Environmental neuroscience: Insights for architectural practice?*
01/2020	Università IUAV di Venezia, Venice, Italy Talk: *Sensory designs, well-being, and the human experience.*
11/2019	The European Federation of Psychology Students' Association, Prague, Czech Republic Talk: *Mental health and architecture.* Panel: *Architecture, design, and urban planning.*

Conferences

11/2023	Università IUAV di Venezia, Venice, Italy Conference chair: *Brain principles and urban design: Memory and emotions.*
06/2023	International Conference on Environmental Psychology, Aarhus, Denmark Talk: *Neural correlates underlying the effects of architectural stimuli: The case of contours.* Symposium chair: *Environmental neuroscience: An emerging field investigating human-environment interactions.*
05/2023	Association for Psychological Science, Washington D.C., USA Poster: *The implicit preference for curves: Approach-avoidance tendencies in response to interior design stimuli.*
07/2022	International Association People-Environment Studies, Lisbon, Portugal Talk: *Curvy or edgy? Differences in the explicit and implicit responses to simulated indoor environments.*
03/2022	The 9th MinBrainBody Symposium, Leipzig, Germany Poster: *Is curvature preferred over angularity? Exploring psychological responses to indoor environments presented in Virtual Reality.*
10/2021	International Conference on Environmental Psychology, Syracuse, Italy

	Talk: *Home environment and the brain: Psychological responses to architectural parameters.*
11/2020	Agora Caumme, Cairo, Egypt Talk: *Fast urban growth, human psycho-socio-ecological needs and 'enactivism': The future of cities.*
09/2020	City Streets 4 – Ljubljana, Slovania Talk: *Transition streets: A view from psychological sustainability perspective.*
06/2019	European Healthcare Design Congress, London, UK Poster 1: *Architectural elements for an improved healing process in psychiatric settings.* Poster 2: *Attention: The link between aesthetic features of the built-environment and its restorative properties.*
11/2018	The Visual Science of Art, Trieste, Italy Poster: *A neurophenomenological approach to architectural design.*

Funding

12/2023	Max Planck Dahlem Campus of Cognition, Cross-group collaboration (1600 Euros for participants' renumeration) Project: *Do you see a face? Neural representations underlying psychological responses to face-likeness in architectural facades.*
04/2020 – 03/2024	International Max Planck Research School on the Life Course (LIFE) Project: *Affective and behavioural mechanisms underlying the response to architectural stimuli.*

Advising

Lukas Stockmaier, Tom Kohrs, Kira Pohlmann**, Jordan Elias, Natalie Kreppner*, Jiaona Hu**

*Bachelor thesis mentee, **Master's thesis mentee