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An integrative cognitive model for multisensory design: benefits and risks of AI-personalization

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In this paper, we examine the interplay between multisensory environments, cognitive performance, and artificial intelligence (AI)-enabled personalization. We propose an integrative cognitive model to better understand how the personalization of the sensory environment influences behavior, emotion, and cognition, drawing upon the Cognitive Capacity Hypothesis, Load Theory, Distraction-Conflict Theory, and the Strength and Vulnerability Integration model. Our integrative model delineates how the characteristics of the individual, the task, and the sensory stimuli interact through arousal modulation. Based on recent conceptual and empirical studies, this model proposes that (1) optimal arousal could improve distractor inhibition and task-focusing, (2) metacognitive misjudgments could lead individuals to select suboptimal sensory environments, and (3) aging alters sensory processing efficiency, necessitating tailored approaches. Within this theoretical proposition, we argue that sensory stimuli modulate arousal and available cognitive capacity, thereby influencing cognitive performance. Thus, when expanding to AI, personalized uni- and multisensory environments could demonstrate both benefits (e.g., enhanced attentional states, therapeutic applications) and risks (e.g., privacy erosion, metacognitive biases). Empirical evidence suggests that preferred background music can reduce mind-wandering, while olfactory stimuli, though underutilized in Western societies, hold untapped potential due to their strong links to memory and emotion. Whereas AI-personalized sensory environments open new perspectives into user experiences and therapeutic approaches (e.g., VR, music therapy, multisensory environment), they raise ethical concerns as the use of algorithms may polarize preferences and exploit behavioral data. Future research should address ethical AI design while leveraging cross-modal correspondences to enhance cognitive, emotional, and behavioral outcomes. Overall, this integrative model proposes an integrative framework by gathering all essential elements for creating a meaningful and coherent multisensory environment, which could be applied to researchers, artists, or marketers.

KEYWORDS

multisensory experiences, personalization, cognitive performances, behavior, artificial intelligence

1 Introduction

From the smells and sounds of morning breakfast to the softness of bed sheets and the melodies of music broadcast before sleeping, we are constantly immersed in multisensory environments. These environments are composed of countless sensory stimuli, whether voluntarily or involuntarily generated. Since each perceived stimulus requires cognitive processing, all multisensory settings inevitably shape our behavior and cognition. Reflecting the predominance of visual sensitivity in Western societies, studies investigating the influences of multisensory environments on human behavior and cognition claim the need to open the exploration of our other senses. Researchers should expand beyond sight and hearing to include smell, taste, and touch, fostering the development of tools and spaces that support social, cognitive, emotional, and behavioral growth (Baines, 2008; Spence, 2020b, 2020c, 2022; Vi et al., 2017). However, as Fulkerson (2020) argues, multisensory experiences are not merely the sum of individual sensory inputs but rather "the result of slightly more complex combinations of different sensory systems" (Sathian and Ramachandran, 2020, p. 54).

These intricate sensory interactions can be observed in both experimental studies and everyday life, from the visual influence of food coloring on taste perception (Spence et al., 2010), the deformation of phonemes by the impact of automatic lip-reading (McGurk and MacDonald, 1976), the influence of tactile, proprioceptive and visual stimuli on the feeling of a dummy limb embodiment (Bartoletti et al., 2023; Chancel and Ehrsson, 2023), or the correspondence between the shape or movement of an object or a sound (Corveleyn et al., 2012; Haggard and Cole, 2007; Ramachandran and Hubbard, 2001). Multisensory environments are not always involuntarily generated, as they can be deliberately designed to evoke specific impressions in individuals and groups (Parker et al., 2024; Velasco and Obrist, 2020). For example, the Tate Sensorium installation offered visitors a multisensory experience in which tactile, auditory, gustatory, visual, and olfactory sensibilities were brought to bear on the exploration of the paintings on display (Obrist et al., 2017; Pursey and Lomas, 2018). In earlier times, scented concerts were among the first spaces to blend multiple senses. If scents were originally diffused to camouflage the smell of crowds in concert halls, the joint diffusion of scents and music has gradually become a strategy to attract spectators (Crisinel et al., 2013; Spence, 2021a, 2021b). Such joint dissemination could overlook the need to match sensory modalities perception (e.g., perceived pleasantness) to create congruent multisensory experiences. Yet the phenomenon of correspondence between sensory modalities, also designed by cross-modal correspondence, occupies a considerable place in the study of the influences of multisensory environments on human behavior, emotion, and cognition.

1.1 Cross-modal correspondences in multisensory environments

Cross-modal correspondences may be semantic, statistical, structural, or affective in nature (Motoki et al., 2023; Spence, 2020a). Semantic and statistical correspondences are typically acquired through learning, either via language development or repeated exposure. In contrast, structural correspondences may be innate, emerging from the maturation of shared neural connections. For instance, the perceived familiarity of both odors and music has been linked to overlapping patterns of neural connectivity (Plailly et al., 2007), suggesting a shared multisensory neural network underlying these perceptual processes. Affective correspondences, on the other hand, arise from affective characteristics common to the sensory stimuli (e.g., perceived familiarity, intensity, arousal, or pleasantness of sensory stimuli). According to Motoki et al. (2023), these categories are not mutually exclusive and may often co-occur. In this regard, to elicit a "congruent effect" observable on behavioral or physiological measures, sensory stimuli should be selected according to their type of correspondence.

Psychological studies examining multisensory experiences often explore the effects of matched versus mismatched stimuli on affective perception (e.g., perceived pleasantness, familiarity, intensity, etc.), or on behavior, emotions, and cognition. Regarding the mutual influences of sensory stimuli, Seo and Hummel (2011) demonstrated a congruence effect between sounds and odors, likely grounded in statistical and affective correspondence. In their study, pairing a congruent sound (e.g., the crunch of potato chips) with the corresponding odor enhanced the perceived pleasantness of the odor compared to an incongruent pairing (e.g., the sound of coffee with the odor of chips). In a subsequent experiment, scientists demonstrated the existence of a halo effect, whereby the pleasantness of the sound influenced that of the odor, but not vice versa. A few years later, Seo et al. (2014) confirmed the role of olfactory-auditory correspondences in perceived pleasantness through three experiments, showing that congruent sounds not only enhanced odor pleasantness but also increased familiarity and identification. In another study conducted by Velasco et al. (2014), participants were asked to rate the pleasantness, intensity, and quality of six odors (blueberry, lemon, and orange considered pleasant, musk, dark chocolate, and smoke considered unpleasant) after listening to pleasant consonant music, unpleasant dissonant music, and white noise. While music did not directly influence olfactory perception, prior exposure to white noise reduced perceived pleasantness, sweetness, and moisture across all odors compared to the music conditions. In terms of arousal, olfactory modulation of musically induced arousal has also been observed in cases of affective correspondence (Zhou and Yamanaka, 2018).

Uni- and multisensory stimulations are also investigated for their use in psychological interventions aimed at supporting preserved behavioral, emotional, and cognitive functions. Music, for example, is well known for its benefits over anxiety and depression disorders (Aalbers et al., 2017; Gutiérrez and Camarena, 2015), as well as in regulating emotions depending on both musical and individual characteristics (Moore, 2013). Similarly, multisensory environments have also been employed for elderly individuals with neurodegenerative diseases (De Oliveira et al., 2014). In advanced stages of such pathologies, where verbal communication is severely impaired, these interventions can be adapted to focus on aiding nonverbal interaction, emotional regulation, and physiological stabilization (Ansaldo et al., 2018; Clare et al., 2020; Maseda et al., 2018). However, the mechanism through which multisensory experiences can help to maintain or enhance behavior and cognition remains under debate. One promising research direction focuses on the type of cross-modal correspondences involved. For example, Baccarani et al. (2023) study represented a significant advance in the understanding of the influence of multisensory olfactory-auditory environments on physiological recovery following cognitive stress. Following cognitive stress induced by a battery of cognitive tasks, participants were assigned to unisensory (either slow-tempo classical music or lavender essential oil diffusion), multisensory (both sensory stimuli diffused together), or neutral (neither music nor odor diffused) environments. The results highlight the effectiveness of unisensory musical and olfactory environments on some of the physiological variables measured, compared with the neutral condition. While a multisensory gain could have been expected in the multisensory condition thanks to the structural matching of stimuli thought by Baccarani et al., no beneficial effect was observed on physiological measures. If declarative data (i.e., how participants felt

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relaxed) could be interesting to investigate in further studies, the results could suggest that semantic or structural correspondence may not be the most relevant match. The question then arises of an affective correspondence based on the personal experience and preferences of the participants.

Cross-modal correspondence represents one of many factors that can influence behavior, emotion, and cognition. Understanding the broader impact of multisensory environments remains a complex and challenging task. A starting point could be the theoretical cognitive models, which offer useful frameworks for conceptualizing how perceived sensory input shapes cognitive processes.

1.2 Human cognition models to help the understanding of uni and multisensory environments influences

Two recent articles have highlighted how a sensory stimulus (i.e., music in these articles) can influence cognitive performance by drawing on various cognitive models (Goltz and Sadakata, 2021; Gonzalez and Aiello, 2019). Before presenting these cognitive models, it is important to note that such influences can be broadly explained by the interaction of three categories of factors: the characteristics of the individuals involved, the characteristics of the task being performed, and the characteristics of the sensory stimulus.

Regarding individual characteristics, the Cognitive Capacity Hypothesis (Kahneman, 1973) provides insight into how a person may inhibit environmental information. According to this model, cognitive resources are limited and fluctuate based on the individual's arousal level. When arousal is moderately high as opposed to moderately low, their ability to inhibit distractors is enhanced, resulting in greater cognitive capacity for task performance. Conversely, a too low arousal level may prevent individuals from processing relevant environmental information, thus interfering with task completion or behavioral adjustment. This model emphasizes the risk of cognitive overload when a distractor draws on the same cognitive resources required for the activity or the task. In other words, cognitive capacity is modulated by environmental interactions, which in turn influence performance.

Complementary to the Cognitive Capacity Hypothesis, and intersecting individual and task characteristics, the Load Theory (Lavie, 2005, 2010) proposes that the impact of a distractor on task performance depends on the type of load, perceptual or cognitive, demanded by the task. When a task involves a high perceptual load, distractors could be easily blocked out since no perceptual resources would be available and orientable towards the distractors. In this case, the sheer number of perceptual events saturates the individual's processing capacity. However, in a task requiring high cognitive load, the current task could be interrupted by an irrelevant event similar to the activity being performed. For example, an activity that would require high visual attention capacities could be interrupted by a distractor relying on the same capacities. This model also includes the influence of aging on the capacities to inhibit distractors: a reduced perceptual capacity would attenuate sensitivity to irrelevant events, especially for tasks with low perceptual load. In other words, older adults would easily inhibit distractors during a low perceptual task due to impaired perception, compared to younger adults. This developmental perspective, which is necessary to adapt tools and spaces to people of different ages, can be found in other models or scales like the dynamic Neurocognitive Adaptation (Cieri et al., 2025; Cieri et al., 2025), which offers an interesting lifespan framework.

While Load Theory describes how distractions may impair performance, the Distraction-conflict Theory (Baron, 1986) offers a contrasting view, suggesting that distractors could exert a positive influence on cognitive performance. According to this theory, during simple or repetitive tasks with low cognitive demand, individuals could be less inclined to switch to a kind of mind-wandering thanks to a distractor (Goltz and Sadakata, 2021; Gonzalez and Aiello, 2019). Although mind-wandering has been shown to benefit important cognitive processes, such as episodic memory, empirical evidence suggests that it disrupts behavioral responses to immediate sensory external input, favoring intrinsic, self-generated thoughts (Baird et al., 2014; Poerio et al., 2017). In the case of mind-wandering during task completion, the distractor would create an attentional conflict, increasing both arousal and task-related cognitive load. People would therefore be more cognitively engaged, and the cognitive capacities for carrying out the task with the addition of the distractor would adjust to the cognitive load required for the completion of the current activity. Following this logic, in the case of a task requiring a very high cognitive load, the attentional conflict created by the distractor would add an additional cognitive load. Individuals' cognitive abilities would be overwhelmed, making task completion impossible. In short, distractions would create attentional conflicts that would increase activation and, depending on whether the task is simple or complex, would either support or hinder its completion.

Together, these three models frame environmental sensory stimuli as either distracting or facilitating influences on cognition and behavior, depending on factors such as arousal level and task complexity. Referring to the Cognitive Capacity Hypothesis, Goltz and Sadakata (2021) explored how listening to background music affects cognitive task performance. They argued that music may interfere with the cognitive processes required for task execution, especially when it contains lyrics in a familiar language, drawing on the same cognitive systems used for reading or vocabulary learning. In such cases, music would overload the information processing capacity (e.g., via saturation of the phonological loop, see Baddeley, 1996), disrupting the ongoing linguistic task. Musical characteristics such as lyrics, musical complexity, volume, and rhythm all contribute to the interference depending on the nature of the task. Unlike music, other sensory stimuli such as smells, light, or temperature do not typically compete for the same cognitive processes. Therefore, it remains difficult to argue that these stimuli interfere with tasks via similar mechanisms.

However, according to the Cognitive Capacity Hypothesis, available cognitive capacities are modulated by arousal. Thus, other kinds of sensory stimuli could therefore indirectly influence the available capacities by modifying arousal. Odor perception, for example, is strongly linked to affective and emotional processing (Bensafi et al., 2002; Herz, 2002; Kontaris et al., 2020; Toet et al., 2020), and could impact cognitive capacity via changes in arousal. The hypothesis is inspired by the Mood and Arousal Hypothesis (Husain et al., 2002; Thompson et al., 2001), originally developed in music research but here extended to other sensory stimuli. According to this hypothesis, listening to music perceived as pleasant enhances positive mood and arousal, enhancing short-term cognitive performance. However, too pleasant music excerpts may over-activate and hamper cognitive performance, while listening to unpleasant music would have a negative impact on mood and arousal, impairing cognitive performance. Though promising, the Mood and Arousal Hypothesis has been tested in other sensory experiences, and empirical studies showed more nuanced results regarding the relationship between mood and arousal. Notably, cognitive performance can improve even in the absence of mood elevation from odor perception (Moss et al., 2008), and that trigeminal stimulation induced by certain odorant molecules could also influence cognitive performance (Lombion et al., 2009), and that unpleasant odors can enhance cognitive performance, and physiological arousal, including heart rate and skin conductance (Bensafi et al., 2002; Boesveldt et al., 2010; Brauchli et al., 1995). Such findings remind us that the relationship between mood, arousal, and sensory perceptions cannot be synthesized only by one factor, such as pleasantness.

Similarly, applying the Distraction-Conflict Theory to other sensory modalities seems challenging. For example, Ho and Spence (2005) demonstrated that peppermint odor obtained through a synthetic compound did not enhance vigilance in a simple sequential task. Instead, it improved concentration in a more complex dual-task condition. According to the authors, an increase in vigilance would have reduced reaction time without improving accuracy. However, accuracy improved only in the dual-task setting. This suggests the peppermint odor facilitated response inhibition in a complex multisensory context. It is important to note that during the dual task, the participant's response was dependent on processing multisensory information, not just uni-sensory input. Thus, according to Ho and Spence, peppermint odorant improved the accuracy of participants' responses by having a positive effect on the ability to inhibit dominant responses during a complex task requiring the processing of multisensory information.

To summarize, current cognitive models trying to represent the influences of sensory stimuli on cognition and behavior remain predominantly unimodal and incomplete. Although the effects of multisensory environments, such as olfactory-auditory ones, are still a matter of scientific debate, their use in multisensory designs is growing (Crisinel et al., 2013; Rey et al., 2023; Spence, 2020c, 2020d; Velasco and Obrist, 2020; Spence, 2022). Meanwhile, through the development and updating of cognitive models, it appears that the search for personalizing both uni- and multisensory experiences has been surprisingly neglected.

1.3 Personalization of sensory experiences and the implication of artificial intelligence (IA)

While traveling, cooking, walking, or engaging in sports, music accompanies us in numerous settings and supports diverse activities (Dibben and Williamson, 2007; Rentfrow, 2012). The simplified content dissemination and access to online and interactive music streaming services can partly explain the almost ubiquitous presence of music in our daily lives (Mazziotti and Ranaivoson, 2024). These platforms, operated by multinational corporations, curate information flow to optimize user engagement and profitability (Poell et al., 2019; van Dijck et al., 2019; Webster, 2023). In this manner, digital technologies supporting music streaming services have reinforced the notion of personalization, enabled by the fusion of social media, streaming services, causal inference, machine learning, and AI (Mazziotti and Ranaivoson, 2024). By suggesting music recommendations based on the ones previously listened to by the consumer, digital platforms extract and predict similarities in music taste. At a great scale, these processes are not without environmental impacts and social consequences, leading to polarization and exacerbation of class stratification (Webster, 2023; Zhuk, 2023).

When focusing on the consumer musical experience, the search for the song that will bring the most pleasure, that will help maintain a state of concentration, and physical performance are common behaviors today: out of 43,000 people surveyed by the International Federation of the Phonographic Industry (The International Federation of the Phonographic Industry, 2023), 63% of them claimed to search for specific songs in the last month, and 59% of them used personalized music lists. This trend has spurred scientific inquiry into the cognitive and behavioral effects of personalized background music. In two recent studies, Kiss et al. (2024) and Kiss and Linnell (2021) demonstrated that preferred background music (1) increases task-focused states while reducing mind-wandering ones, and (2) modulates these states (i.e., task-focusing and mind-wandering) through arousal modulation: in a context of background listening increasing arousal, the results suggested that mind-wandering states decreased, whereas task-focusing states increased. These findings highlight the influence of preferred and personalized sensory stimulation on cognition and behavior via individuals' arousal and open the possibility of investigating such influences with other kinds of uni- or multisensory experiences.

Like music or light, other kinds of sensory stimuli can be broadcast with a click on our smartphones. Although it is still considered a curiosity or even ignored by most of the population, the number of studies investigating the possibility of broadcasting smells with small technological devices, like smartphones, is growing (Huang and Chen, 2023; Maggioni et al., 2018, 2019; Matsukura et al., 2013). Within the next few years, we will likely be able to enhance the mastering of our olfactory environment. However, the underestimated importance of the sense of smell in contemporary Western societies may delay its development (Herz and Bajec, 2022; Schifferstein, 2006; Wrzesniewski, 1999), although olfaction is a sense that develops early in humans, supporting the development of vision (Rekow and Leleu, 2023; Schaal et al., 2020). A question might arise while reading the last sentences: what is the link between personalization of our sensory environment and the development of olfactory research? Beyond being an important cultural and identity marker (Boswell, 2008; Majid, 2015), smells participate in our social life and provide important health indicators (Schwambergová et al., 2024), influence our emotional state (Villemure et al., 2003), and are at the center of sensory strategies to try to influence consumer behavior (Doucé and Janssens, 2013; Nibbe and Orth, 2017; Spence, 2015; Teller and Dennis, 2012; Yang and Cai, 2024). Odors bring personal information, and their cognitive processing is intrinsically linked to our autobiographical memory (Hackländer et al., 2019; Rey et al., 2023; Willander and Larsson, 2006). The literary anecdote of Proust's madeleine illustrates an emotional and memory phenomenon that everyone can experience: a smell can trigger the revival of an emotion linked to a particular autobiographical memory. Numerous studies support that odor-evoked emotion can be particularly intense and that the memory recovered by olfactory stimulation could be linked to old moments in life, sometimes belonging to the first 10 years of life marketing (Chu, 2000; Herz, 2016; Jellinek, 2004; Larsson et al., 2006; Toffolo et al., 2012; Willander and Larsson, 2007). For all these reasons, the development of smell diffusion cannot neglect the concept of personalization and cannot only focus on common affective characteristics such as pleasantness, familiarity, or irritability.

The global influence of personalized sensory stimulation is still poorly understood in psychology, possibly due to the difficulty of adapting scientific protocols, but also due to the absence of a consensus regarding a method to personalize sensory stimuli. For example, studies exploring the effects of participants' musical preferences have selected preferred music excerpt based on choices that were constrained: from a sample of musical excerpts of varying lengths, the music that induces the most pleasure or displeasure can be considered as preferred and personalized (Huang and Shih, 2011; Johansson et al., 2012; Nemati et al., 2019; Perham and Sykora, 2012). Reconsideration of musical personalization is recent and uncommon in this field of research, with participants being asked to bring their favorite CD or playlist and listen to it while performing a cognitive task (Darrow et al., 2006; Mori et al., 2014). Those studies suggest that listening to favorite, personalized music has a positive influence on certain cognitive performances, particularly attention by modifying the arousal state of the participant (Darrow et al., 2006; Kiss and Linnell, 2021; Mori et al., 2014). In other studies, the positive effect of preferred and personalized music on cognitive performance is based on factors related to the cultural background of the participants (Kotsopoulou and Hallam, 2010; Mohan and Thomas, 2020). The recent and growing interest in the use of personalized sensory stimuli for therapeutic applications (Grifoni et al., 2023), notably regarding Virtual Reality (Lee et al., 2024; Pardini et al., 2022; Pizzoli et al., 2022; Solcà et al., 2021), led researchers to investigate the importance and influences of sensory stimuli personalization. Choosing a preferred sensory stimulus over a panel or bringing one into laboratory experiments (e.g., a music excerpt) involves its evaluation and comparison. Choosing a preferred sensory stimulus over a panel or bringing it into laboratory experiments (like a music excerpt) involves its evaluation and comparison. Scientists investigate the importance of people's metacognitive judgments on evaluations and choices regarding musical background during working, learning, or study conditions. These studies are complementary to research on individual preferences, firstly because metacognitive judgments characterize the perceived propensity of a stimulus, such as music, to help or distract a person in performing a task. Secondly, by studying the incidence of retrospective metacognitive judgments, a positive correlational link has been demonstrated between the perceived pleasantness of music and the likelihood of judging it as improving cognitive performance (Bell et al., 2023b).

In the Bell et al. (2023a) study, participants' objective cognitive performance in serial recall tasks was impacted by the presence of music and whether the music was liked. At the same time, Bell et al. (2023a) investigated the validity of metacognitive judgments about the effects of irrelevant auditory stimuli (piano melodies and Mozart's sonata) on cognitive task performance. The authors aimed to confirm one of two theories: (1) the direct-access account, according to which people base their metacognitive judgments on direct and conscious access to the distracting or helpful features of an auditory stimulus, and (2) the processing-fluency account, according to which people base these same metacognitive judgments on similar past experiences, whether conclusive or not. According to these two theories, the repetition of irrelevant auditory stimuli would lead to increasingly less negative metacognitive judgments. Yet, unlike the direct access explanation, fluent processing theory does not require knowledge of the precise helping or distracting characteristics of a stimulus, so an individual can make metacognitive judgments that conflict with the objectively and scientifically provable effects of a stimulus on their abilities. Through two experiments, the scientists manipulated the processing fluency of musical excerpts while maintaining their musical complexity. The scientists assumed that people are familiar and accustomed to the sound of music played in the normal direction of listening (i.e., forward), rather than in reverse (i.e., backward). The authors aimed to create an illusion of fluidity in the processing of musical stimuli and hypothesized that participants would have the illusion of performing better on a cognitive task with music played "forward" despite its complexity compared to the same music played "backward." In other words, the scientists expected participants to wrongly judge music played "forward" as less distracting than music played "backward. Bell et al. (2023a) demonstrate that direct experience of performing a task with music helped attenuate the illusion of metacognitive judgment without eliminating it. In other words, participants modified their judgment about the distracting nature of the sensory stimuli (i.e., the background music broadcasted during the cognitive task) after the experience. Besides, participants judged the same music "backward" as being more distracting than in a normal listening mode. Finally, these results showed that human metacognitive judgments about the suitability of music to aid cognitive task performance are based on fluid processing.

This discovery highlights the potential for poor metacognitive judgments about environmental conditions that would promote good cognitive performance. In other words, we should be cautious about how a sensory stimulus, perceived as pleasant and potentially chosen among others based on metacognitive judgments, has a genuinely positive influence on our cognition and behavior. However, the lack of knowledge about the influences of personalized sensory stimuli on cognition, emotion, and behavior does not deter from the growing interest and use of AI to personalize experiences. Technological advances, such as computing power, machine learning, or data storage are combined with theoretical developments, helping researchers transform theoretical concepts into applications. The personalization of communication content and user experience is not only "based on individuals' preferences, interests, demographics, and past behavior, item features and characteristics, or similar tastes of others, but also on psychological factors—the method of psychological targeting" (Hermann, 2022, p. 5). Individual psychological traits, such as personality traits and emotional states, are also computationally predicted by algorithms thanks to their purchase history and digital footprint (Matz et al., 2017; Matz and Netzer, 2017; Gao and Liu, 2023).

Yet, if a growing body of research gathers many fields like marketing, economy, welfare and public policy, computer sciences, and statistics, it appears that psychology could give interesting insights through theoretical models, practical feasibility, and therapeutic applications. Based on the cognitive models presented above and the research focusing on metacognitive judgments, we propose a cognitive model to represent the potential influences of uni- and multisensory stimuli on cognition and behavior.

1.4 Proposal for a cognitive model representing the influences of uni- and multisensory stimuli on cognitive performances

The structure of this model (Figure 1) is based on the Cognitive Capacity Hypothesis (Kahneman, 1973), which posits that task performance relies on an individual's limited and variable available capacity, modulated by their arousal. By integrating Load Theory (Lavie, 2005, 2010), we account for the influence of cognitive and perceptual loads from both tasks and distractors, while also considering task complexity and cognitive aging effects. Further incorporating Distraction-Conflict Theory (Baron, 1986; Gonzalez and Aiello, 2019) allows for the inclusion of potential beneficial effects of distractors on arousal. Finally, the Strength and Vulnerability Integration model (Charles, 2010), addresses age-related differences in arousal regulation. The proposed model comprises several interconnected modules (Figure 2).

1.4.1 Possible activities and tasks

The model begins with the "Activities and tasks" module (module "1" in Figure 2). All activities and tasks are dependent on an input, which is the available capacity. According to the Cognitive Capacity Hypothesis model, an activity carries a cognitive load, a consideration also found in the Load Theory model: a task carries a cognitive load and a perceptual one, just like potential distractors. By linking the two models, a task that would have a high perceptual load could be provided with available capacity, thus saturating the stock of available capacity. Distractors with a perceptual load equivalent to the task could not be processed. In the case of a task with a high cognitive load and low perceptual load, the latter could be interrupted by one or more diverse environmental determinants, which would be endowed with the same type of load or having a greater perceptual load.

The Cognitive Capacity Hypothesis model suggests that successfully performing multiple activities simultaneously would depend on the capacity required to perform each of them separately; the complexity of the activity or task is therefore important to consider. A simple activity or task would be poorly demanding in available capacity and would have a low cognitive load, whereas a difficult activity would be very demanding in cognitive capacity and would have a high cognitive load. If the activity or task exceeds the individual's available capacity, its execution would therefore be hindered. Less available capacity provided would cause a deterioration in performance compared to the standard expected for its completion, and an activity or task that had a capacity demand higher than the individual's cognitive limit would be impossible to undertake. Moreover, the perceived complexity of an activity varies according to an individual's arousal and therefore errors made during the task can provide information regarding the variation in activation state with the difficulty of the activity performed. Unused capacities reduced by the difficulty of the task would be proven by failure to detect a signal that is normally detected easily or a slower response.

Important points:

- A task with high perceptual load may saturate available capacity, preventing concurrent processing of distractors with similar loads.
- A task with high cognitive load but low perceptual load remains vulnerable to interruption by environmental determinants (e.g., distractors) of comparable or greater perceptual load.
- Simple tasks require minimal capacity and exhibit low cognitive loads.
- Complex tasks demand substantial capacity; exceeding an individual's limits leads to performance failure.

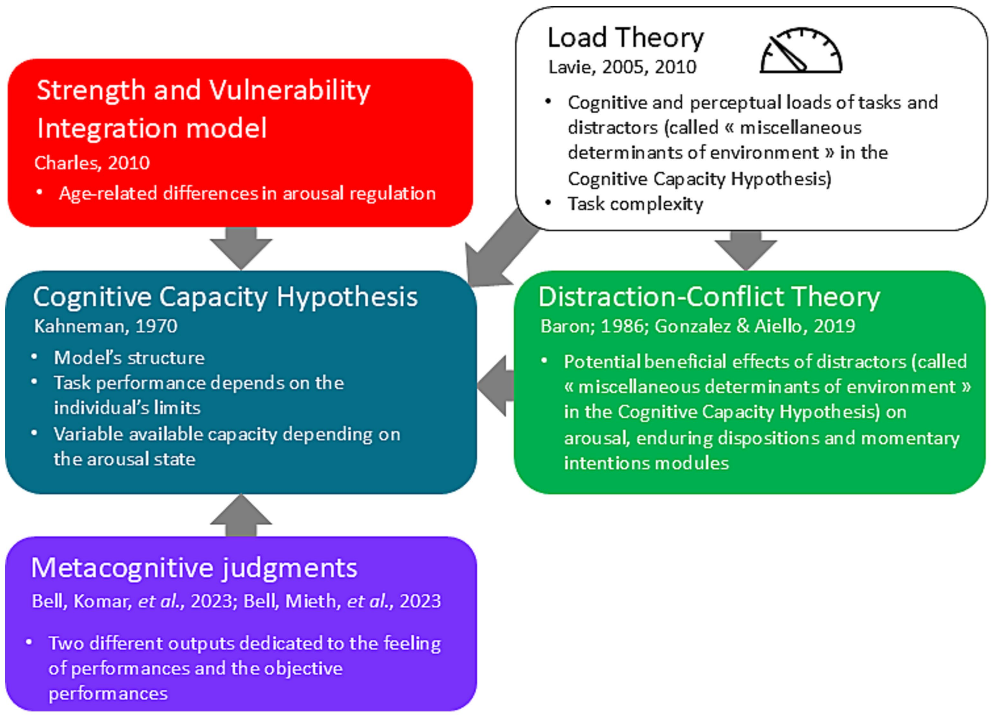

FIGURE 1
Synthesized interactions between the different theories and models used to develop the Model of the influence of uni and multisensory environments on cognitive performances.

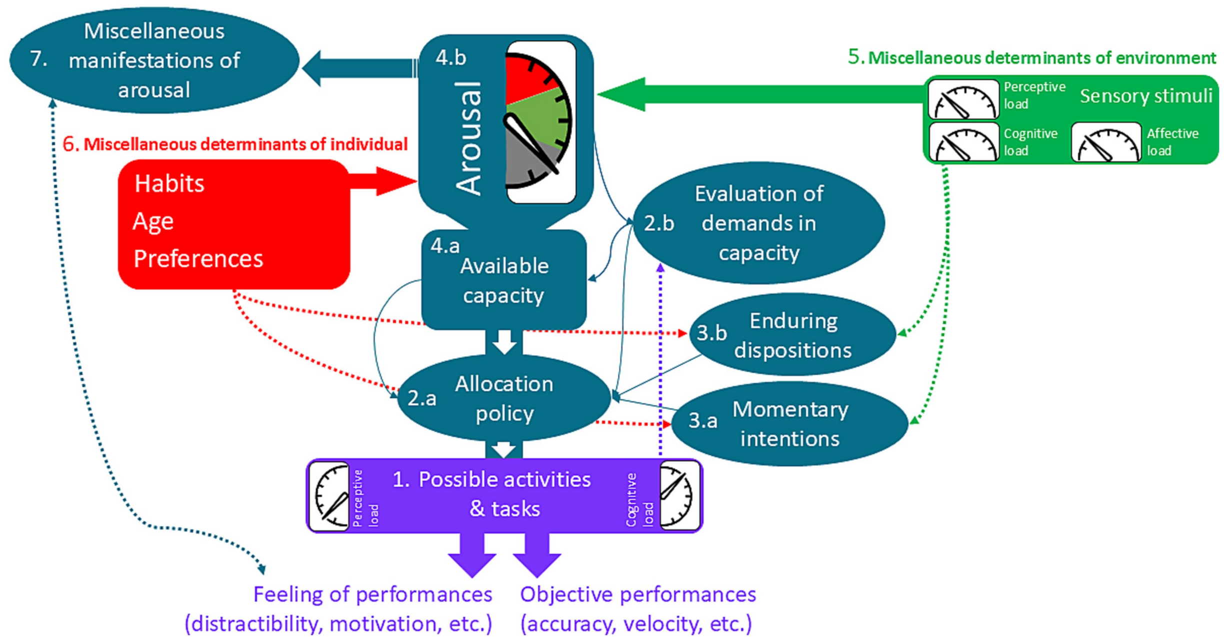

FIGURE 2
Model of the influence of uni and multisensory environments on cognitive performances. The numbers indicate the reading order.

- Performance errors (e.g., missed signals or delayed responses) reflect fluctuations in arousal relative to task difficulty.
- Fatigue or hyperarousal can impair the evaluation of capacity demand, disrupting capacity distribution.

1.4.2 Evaluation of demands on capacity and allocation policy

The "Evaluation of Capacity Demands" (module "2.a" in Figure 2) and "Allocation Policy" modules (module "2.b" in Figure 2) are central elements of the Cognitive Capacity Hypothesis model. The function of the evaluation of demands on capacity is to assess the capacity required to achieve an activity or task, based on the arousal and available capacity, which vary together. This module can therefore be considered as a governance system that informs the allocation policy of the available capacity. The evaluation of demands can, however, suffer from an individual's fatigue or agitation, and therefore from an activation state that is too low or too high. The evaluation of demands manages the stock of available capacity and its distribution. Together with the evaluation of demands, the allocation policy recalls the role played by the supervisory system in Shallice's (1988) model, which regulates and selects alternative response patterns, and thus allows behavioral adaptation during a non-routine situation. The allocation policy is directly influenced by the evaluation of demands on capacity, but also by enduring dispositions, momentary intentions, and arousal. According to the Cognitive Capacity Hypothesis, the attribution strategy system favors perceptual activities that require a large available capacity to the detriment of less demanding perceptual ones. This can be compared to tasks with a high perceptual load compared to low perceptual load ones.

Important points:

- Perceptual activities with higher capacity demands are prioritized by the allocation priorities over fewer demanding ones.

1.4.3 Enduring dispositions and momentary intentions

Two other modules influence the allocation policy. First, the "Enduring dispositions" (module "3.a" in Figure 2), described by Kahneman as involuntary attention. It would allow a transient effort to process and analyze the stimulus that captured attention, but also the inhibition of current activity as well as the attentional orientation of the individual toward future sources of relevant information. Then, the "Momentary intentions" (module "3.b" in Figure 2) refers to a phenomenon of voluntary and active attention, close to selective attention. These two direct the attention paid to stimuli, and therefore to environmental determinants. While many empirical experiments demonstrated that attention can be influenced and redirected in a voluntary or involuntary way by the pop-up of environmental stimuli (Carretié, 2014; Cloutier et al., 2020; Nadon et al., 2021), Kahneman's model does not indicate a link of influence between attentional modules and environmental determinants. Finally, in our model, individual determinants also provide information on the individual's activation state and modulate attention. The functioning of these two attentional modules therefore varies according to determinants internal and external to the individual, which influences the allocation policy of available capacity.

Important points:

- Enduring disposition facilitates transient stimulus processing and inhibit ongoing activities to orient toward salient information.
- Momentary intention reflects goal-directed focus, analogous to selective attention.
- Both are influenced by environmental and individual determinants.

- While Kahneman's original model omitted these linkages, we explicitly integrate them to reflect empirical evidence on attentional modulation by external/internal stimuli.

1.4.4 Available capacity and arousal

The "Available capacity" (module "4.a" in Figure 2) is central, its mobilization does not depend on the individual's intention but on the "Arousal" (module "4.b" in Figure 2) required to perform an activity, which itself varies depending on miscellaneous environmental determinants. The arousal level varies from a low state (gray area of the gauge) in which distractors cannot be inhibited, which can manifest as a state of mind wandering, to a high state (red area) in which the inhibition of relevant environmental determinants would prevent the adaptation of individuals' behaviors, being visible with a state of agitation or perseveration. A moderately high state (green area) allows for the inhibition of distractors and the consideration of relevant information to perform an activity with success. The Strength and Vulnerability Integration model adds nuance by modulating arousal with aging. This model argues that aging negatively impacts physiological flexibility and, consequently, maintaining and returning to a moderate homeostatic state would be more difficult compared to younger adults. Thus, when miscellaneous environmental determinants negatively impact homeostatic balance, the activation state of older adults remains too high for a prolonged period, inducing the inhibition of miscellaneous relevant environmental determinants.

Here, AI could be used to detect the real-time fluctuation of arousal. Several physiological signals governed by the autonomic nervous system can be monitored, and peripheral sensors such as electrocardiogram, photoplethysmography, pupillometry, electrodermal activity, skin temperature, respiratory cycle, or electromyogram can be used individually or in combination (Paniagua-Gómez and Fernandez-Carmona, 2025; Pelagatti et al., 2025). These peripheral sensors are suitable for continuous and unobtrusive monitoring (e.g., electrodes, eye tracking, patches, and wristbands), but the collected data could be, at the same time, confounded by behavioral factors like posture or physical activity. To grasp the multidimension of arousal, some behavioral indicators like facial expressions, postures, physical activity, computer interaction patterns, or voice characteristics could be combined with physiological signals (Reid et al., 2025). Personalization of these physiological and behavioral measures could be done using user-specific calibration, person-specific models, and adaptive to obtain personalized thresholds, training separate models for each individual, and dynamic models being able to adjust to individual baseline physiological levels over time (e.g., circadian rhythms, changes in health status, etc.) (Paniagua-Gómez and Fernandez-Carmona, 2025). However, if AI could help to monitor multiple behavioral and physiological signals, it is essential to have total transparency of all the procedures, and to ensure the protection of the collected data. In this manner, models must have the possibility to unlearn from one individual's data, who would use his or her right to be forgotten (Paniagua-Gómez and Fernandez-Carmona, 2025).

Important points:

- Available capacity is non-volitionally mobilized by arousal, which fluctuates with environmental and individual determinants, and prior activities.
- Arousal states can be low (poor distractor inhibition, manifesting as mind-wandering), moderately high (optimal distractor inhibition and task-relevant information processing), or high (inhibition of relevant inputs, causing agitation or perseveration).
- The Strength and Vulnerability Integration model adds nuance: older adults exhibit reduced physiological flexibility, prolonging high arousal states and impairing homeostasis.

1.4.5 Miscellaneous environmental and individual determinants

Available capacity is dependent on the individual's arousal and cannot be modulated voluntarily. Just like ongoing activities and tasks, the "Miscellaneous environmental determinants" (module "5" in Figure 2) and the "Miscellaneous individual determinants" (module "6" in Figure 2) modulate arousal states. When arousal is low, environmental and individual determinants are not blocked. In this condition, mental wandering induced by fatigue or by a simple task can hinder performance with a moderate or low perceptual or cognitive load. Conversely, when the arousal is high, the inhibition of potentially relevant environmental and individual determinants is not processed. Finally, a moderately high arousal state allows the inhibition of distractors and the consideration of relevant information. The Cognitive Capacity Hypothesis highlights the potential overload of cognitive capacity when miscellaneous determinants rely on the same capacities as the activity or task. Thus, the evaluation of demands on capacity and the allocation policy can direct available capacity toward the attentional processing of miscellaneous determinants, an individual's sensory environment can therefore influence its cognitive performances. Kahneman provided very few details about diverse environmental determinants, giving few examples like the intensity of stimulation, the physiological effects of drugs, or training. This module could group an infinite number of stimuli, including sensory stimuli potentially considered as distractors. By gathering the Load Theory to it, the perceptual and cognitive loads of each distractor would influence individuals' available capacities, capacities that would then be allocated for the performance of activities and tasks according to their cognitive and perceptual demands.

The Load Theory does not allow us to consider a positive influence of music, smells, or other sensory stimulations, which are then considered as distractors, irrelevant information with perceptual and cognitive loads that can compete with those of the activity. However, in the Distraction-Conflict Theory, it is possible to propose an alternative. During a simple task, distractors with a low cognitive load could create a slight attentional conflict, increasing and maintaining the arousal moderately high. This conflict would prevent the arousal from decreasing too low, which could result in a state of mind wandering. Consequently, a distractor would adjust the arousal state to the cognitive load required by the task to be performed. According to the Distraction-Conflict Theory, performing a complex task with high cognitive load could not be aided by a distractor, because the cognitive loads of the task and the distractor would compete, creating an attentional conflict that would excessively increase the activation state. The Distraction-Conflict Theory, revised by Gonzalez and Aiello (2019), models the influence of music with a low or high cognitive load but does not propose the existence of a perceptual load. According to the Load Theory, all distractors carry a cognitive and perceptual load. In the case of music, it is possible to hypothesize that an increase in a perceptual load (e.g., volume, rhythm) would consequently induce an increase in cognitive load. In the case of odors or other sensory stimuli, it is difficult to grant with certainty the existence of a cognitive load. While perceptual load may be related to its intensity, the cognitive load of a sensory stimulus, such as a smell, may vary depending on an individual's experience. Therefore, it seems necessary to assume that affective load, in addition to perceptual and cognitive load, may also influence individuals' arousal.

Our model postulates that environmental determinants include sensory stimuli. Depending on whether they are perceived as favorable or unfavorable for cognitive performance, whether they are uni- or multi-sensory, personalized or imposed, with cross-modal correspondences or not, we assume that sensory stimuli do not influence in the same way the performances felt by individuals and the performances achieved by them. Thus, each sensory stimulus would have, on the one hand, perceptual and cognitive loads dependent on characteristics specific to them, and on the other hand, an affective load dependent on the miscellaneous individual determinants of each person perceiving the stimuli. The presence of an output dedicated to performance feelings, therefore, marks the difference between performance feelings and real performances, which could be differently affected by individual characteristics (miscellaneous individual determinants), the activity or task to achieve, and the stimuli (miscellaneous environmental determinants). This proposal is supported by the studies that investigated metacognitive judgments (Bell et al., 2023a; Bell et al., 2023b), which assume a difference between individuals' metacognitive judgments regarding the influence of sensory stimuli on their cognitive performance and objectively achieved performance.

Finally, as Goltz and Sadakata (2021) observed, a greater frequency of musical listening during cognitive activities is a habit found significantly more often among younger adults compared to older adults. Age influences the habits of use and modification of sensory environments, which could modulate the arousal and the modules of enduring dispositions and momentary intentions when carrying out a cognitive task. It therefore seems important that the model we propose in this article includes a dimension of miscellaneous individual determinants that brings together daily habits, age, or even sensory preferences.

Important points:

- Miscellaneous environmental and individual determinants interact with arousal.
- Miscellaneous environmental determinants (e.g., sensory stimuli) compete for capacity based on perceptual and cognitive loads. Kahneman's sparse examples (e.g., drug effects) are expanded here to include multisensory distractors.
- Miscellaneous individual determinants (e.g., age, habits) modulate arousal thresholds and attentional biases (e.g., younger adults more frequently use music during tasks).
- The Load Theory posits that all distractors have perceptual and cognitive loads, but affective loads (e.g., odor valence) may also shape arousal. Crucially, a feeling of performance (subjective) may diverge from actual performance (objective) due to metacognitive biases.

1.4.6 Miscellaneous manifestations of arousal

The miscellaneous manifestations of arousal (module "7" in Figure 2) are addressed by Kahneman (1973) only in the form of illustrations. No textual details are provided, except for a list of possible observations of the disruption of the homeostatic state of individuals, with examples cited: increased heart rate, pupil dilation, and skin conductance. The use of physiological measures would allow for more objective measurements of changes in the activation state induced by the diffusion of sensory stimuli. The goal would be a better understanding of the influence of these changes on cognitive performance, notably depending on age. However, these manifestations of arousal should not be limited to the measurement of physiological constants. Through this model, we propose to extend these manifestations to the affective and emotional states experienced by individuals, feeding a bidirectional relationship with the feelings of performance. In this manner, the miscellaneous manifestations of arousal would directly inform people's feelings of performance, and the latter could have a retroactive action of regulating emotions (Egloff et al., 2006; Gross, 2002).

Important points:

- Kahneman (1973) briefly cited arousal indicators (e.g., heart rate, pupillometry). Our integrative model extends these to include miscellaneous manifestation of arousal, bidirectionally linked to feeling of performances.
- Physiological metrics could provide objective arousal measures to disentangle sensory influences across age groups.

2 Discussion

We aimed to propose an integrative cognitive model to better understand how the personalization of the sensory environment influences behavior, emotion, and cognition. The integration of the Cognitive Capacity Hypothesis, the Load Theory, the Distraction-Conflict Theory, and the Strength and Vulnerability Integration model provides insights into how individual characteristics, environmental factors, and task demands collectively shape cognitive and behavioral outcomes. However, their explanatory power remains limited when applied to complex multisensory contexts, as opposed to unisensory experiences. While these models can be useful, they rely on a linear and static view of the interactions between cognitive load, arousal, and performance, without finely integrating affective load or the combined effects of multiple sensory modalities. The study by Baccarani et al. (2023) provides an illustrative example: although one might expect a "multisensory gain" from combining relaxant music and scent, two structurally congruent stimuli, no additional benefit was observed compared to unisensory conditions. This outcome challenges the assumption of a simple additive effect of sensory inputs and encourages the adoption of more integrative models, which consider the type of correspondence (affective, structural, or semantic), the arousing properties of the sensory stimuli used, and their effect on the individual's arousal state. Furthermore, the model proposed in this article offers a valuable conceptual contribution: drawing on the Strength and Vulnerability Integration model, it introduces interindividual variability, notably age-related differences, in the ability to modulate arousal. This aspect could be crucial, as Goltz and Sadakata (2021) have shown that younger adults more frequently engage in active modulation of their sensory environment (e.g., listening to music while working) than older adults. Any model attempting to explain cognitive performance in sensory environments should therefore account for these developmental and contextual differences.

The growing trend toward personalization of uni- and multisensory environments has attracted significant scientific attention, as it emerges as a potential critical factor, capable of modulating an individual's cognitive performances. However, recent findings by Bell et al. (2023b) and Bell et al. (2023a) offer a nuanced perspective. While participants reported that familiar music improves their performance, these metacognitive judgments do not always align with objectively measured outcomes: the familiarity of a music excerpt creates an illusion of improved performance, whereas objective results demonstrate no benefits compared to music perceived as more distractive. This distinction highlights the methodological need to further link experimental research with the analysis of metacognitive and affective judgments. Doing so would not only enhance our understanding of cognitive adaptation in real-life contexts but also improve the evaluation of personalized sensory strategies. In this sense, individual preferences should not merely be seen as matters of taste, but rather as complex vectors of emotional, motivational, and cognitive regulation. The model proposed in this article integrates this tension between subjective and objective performance by introducing two distinct cognitive outputs: one for objectively assessed performance and another for subjective experience.

Another important concept of this model is the modification of the sensory environment to create an attentional conflict during repetitive or simple cognitive tasks, resulting in increased arousal and the interruption of mind-wandering. In this manner, this attentional conflict prevents the disruption of responses to immediate external inputs by mind-wandering. In this case, mind-wandering is considered to impair behavioral responses and cognitive engagement in the task. However, this phenomenon also has its benefits and should not be fully avoided during activities. Mind-wandering is associated with a large-scale neural network called the Default Mode Network (DMN). DNM involves regions which are thought to be more devoted to encoding scenes and context, to abstract thinking, memory representation and retrieval, generated experiences, and less to the treatment of input information from the external world (Buckner and Krienen, 2013; Poerio et al., 2017; Smith et al., 2018; Spreng et al., 2009). If the use of sensory stimuli could be promising for disrupting mind-wandering, it has also been shown that fast or slow-paced music and evoked emotions modulate DNM's activity, with potential effects on internally oriented cognition (Taruffi et al., 2017). As empirical experiences suggest that DNM activation has potential value for creativity and prospective memory (Smallwood and Schooler, 2015), various strategies could be used to minimize the disruptive effects of mind-wandering during tasks without totally avoiding it.

Finally, the development of AI raises questions regarding its role in personalizing experiences, leading researchers from different backgrounds to investigate how AI could contribute to the massification of personalization content, which may yield both beneficial and detrimental consequences. On the one hand, it paves the way for sensory environments optimized to support focus, emotional regulation, or cognitive performance. Personalized approaches hold significant promise for enhancing user experiences, therapeutic interventions, and optimizing the sensory environment. For example, in cases of neurodegenerative diseases where verbal communication is impaired, personalized sensory therapies (e.g., music therapy) could be tailored by leveraging real-time emotional feedback from facial expressions, physiological activation patterns, and other physiological markers (Panahi, 2025; Sakamoto et al., 2013). Also, cognition and intellectual growth can also be supported by AI chatbots, which can reinforce executive functioning (i.e., planning, organization, strategy implementation) through personalized and interactive training (Pergantis et al., 2025). The integration of AI into these approaches offers the promise of continuous, real-time personalization, not just fixed interventions, thereby improving care. Such applications underscore the potential of AI to bridge gaps in traditional therapeutic practices while respecting ethical boundaries. On the other hand, it also reinforces social distinction, as highlighted by Webster (2023), which may lead to polarization of preferences and a narrowing of sensory experiences. Nowadays, through the personalization of communication content and user experience, firms often promote improvements in consumer and social welfare, but at the expense of consumer privacy (e.g., user tracking and behavioral targeting) (Hermann, 2022; Rafieian and Yoganarasimhan, 2023). The ethical considerations surrounding the AI-enabled personalization of sensory environments are notably addressed to prevent issues related to transparency, autonomy, and privacy, as well as ownership, access, control, and retention of the data collected (Hao et al., 2025). For example, in the food industry, scent marketing, or air design, the data collected from AI-enabled personalization should not be used for pervasive and targeted advertising to "manipulate consumer behavior by unconsciously raising emotions and consequently manipulating purchase decisions" (Emsenhuber, 2011, p. 344). We should also be careful about respecting copyright and cultural diversity, as AI is used to create digital representations of fragrances, aided by real analyses of the chemical composition of actual odors (Hao et al., 2025; Sinha et al., 2023). Overall, a foundational understanding of AI algorithms and their welfare implications must be objectively defined and standardized, and AI-enabled personalization of multisensory experiences must be supported by rigorous ethical safeguards, regulatation especially in vulnerable populations.

By integrating insights from cognitive psychology and AI, the model proposed in this article provides a valuable framework for understanding and designing personalized, adaptive, and evidence-based sensory environments. It offers promising directions for both fundamental research and therapeutic innovation, while also urging caution. Further empirical studies and theoretical propositions based on this model should also consider arousal as a multidimensional perspective, which is missing in this first version. To conclude, AI-personalization of our sensory perceptions remains entangled with ethical, cognitive, and subjective considerations that must be addressed within a truly interdisciplinary framework.

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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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