Emotional Dimensions of the Cutaneous Rabbit Illusion in Virtual Reality: The Interplay of Visual and Tactile Stimuli

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Abstract. In this study, we explored the emotional impact of a visuo-tactile cutaneous rabbit effect (CRE) within a virtual reality (VR) context. Participants experienced tactile sensations on their forearms while interacting with 3D models of various visual stimuli (rabbit, kangaroo, spider, grasshopper, frog, flea, and sphere) in a VR environment hopping along a virtual arm, visually and positionally synchronized with the participant's real arm. The CRE was induced by delivering three successive bursts of tactile stimulation at different forearm locations. We manipulated the virtual experience by having the 3D models either hop thrice, mirroring the tactile stimuli, or nine times, creating a more distributed sensory illusion across the arm. Results show that the type of visual stimulus significantly influenced emotional responses. Spiders were consistently rated as more unpleasant than rabbits, kangaroos, and spheres. The frequency of hops also played a crucial role; fewer hops led to higher valence ratings for visually pleasant stimuli, consistent with previous findings. An increase in visual hops generally had a calming effect, particularly notable for stimuli like fleas. In terms of dominance, participants felt less in control with spider stimuli compared to spheres. Tactile feedback was pivotal in enhancing realism and emotional depth, with varying feedback patterns suggesting potential for more nuanced and realistic VR experiences. The findings suggest that tactile stimulation in VR can significantly alter emotional responses to different stimuli, highlighting the importance of effectively coordinated multisensory feedback in virtual environments.

Keywords: Cutaneous Rabbit Effect · Saltation · Multimodal CRE.

1 Introduction

To enhance the immersive quality of virtual reality (VR) and augmented reality (AR) technologies, the creation of emotionally engaging and contextually rich experiences is essential. These technologies have evolved beyond just visual and auditory stimulation and now aim to include a broader spectrum of human senses, such as touch, to achieve deeper immersion [1, 6]. The integration of emotional qualia—the subjective experience of emotions—is vital in replicating real-world interactions within virtual environments [16, 27]. This emotional dimension is not just an additive feature; it's a critical component that shapes the user's perception of realism and engagement in VR and AR [18, 21]. Emotional engagement in virtual environments can lead to more profound and memorable experiences [5, 10], mirroring those encountered in the real world. Such engagement is especially relevant in applications like virtual training, therapeutic interventions, and interactive gaming, where the emotional context can greatly enhance effectiveness and user satisfaction [13, 25].

Furthermore, understanding the interplay between different sensory modalities and their impact on emotional responses is crucial. In virtual environments, sensory stimuli need to be carefully orchestrated to ensure a cohesive and believable experience. Our work focuses on the cutaneous rabbit illusion (CRE) within a VR context and its emotional aspects. This work is grounded in the need to develop efficient haptic technologies that enhance user immersion in VR environments. Recognizing that emotional responses play a critical role in human interaction with virtual worlds, this paper explores how the CRE is influenced and transformed by visual stimuli. The primary objectives are twofold: first, to understand how visuo-tactile sensations are emotionally perceived; second, to provide design guidelines for integrating haptic technology into multimodal interfaces in a manner that is both user-acceptable and emotionally resonant. Specifically, this research examines the interplay between tactile and visual stimuli and their collective impact on emotional dimensions such as valence, arousal, and dominance.

2 Related Work

2.1 The Cutaneous Rabbit Illusion

The phenomenon known as the Cutaneous-Rabbit Illusion was first described in 1972 by Frank Geldard and Carl Sherrick [12]. Also referred to as somatosensory saltation or the cutaneous-rabbit effect (CRE), it occurs when participants feel a spread of sensation across a low acuity area like the forearm, even though tactile stimulation is applied only at specific points. This feeling of this illusion is often described as a small rabbit hopping along the arm. There are various forms of the CRE [19], including simplified versions [11]. CRE is distinct from apparent motion with the main difference lies in the timing of the tactile stimuli. In apparent motion, the onset of each new stimulation coincides with the offset of the previous one, creating a seamless sensation of continuous motion. However, in CRE, an added Inter-Burst Interval (IBI) between stimuli results in a hopping sensation, rather than a continuous motion as experienced in apparent motion [14, 30].

Figure 1 depicts the most commonly studied version that involves nine bursts of tactile stimuli at three equidistant points on the forearm, typically lasting

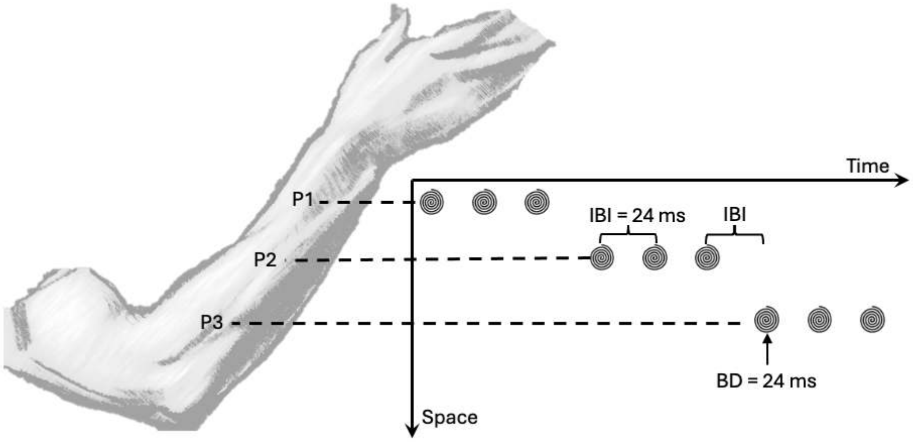

Fig. 1. The version of the CRE used in this work with three location points (P1, P2, and P3) on the forearm. Each point receives three bursts with a duration of 24 ms, separated by an inter-burst interval (IBI) of 24 ms.

between 300 and 500 milliseconds total-the duration when the illusion is most pronounced. In our study, each location on the forearm received three bursts, lasting 24 ms, with a 24-ms interval between bursts, totaling a duration of 408 milliseconds. Although our prior findings noted the importance of burst duration and interval on the CRE, shorter intervals (12 ms) proved too rapid for effective synchronization in VR, disrupting the multisensory experience, while (48 ms) diminished the illusion. Thus, 24 ms was optimal for balancing perceptual impact with VR integration constraints.

The Cutaneous Rabbit Effect offers an intriguing perspective in studying the spatiotemporal integration of somatosensory perception, both from phenomenological [7] and physiological [3, 15] standpoints. This illusion has sparked considerable interest in the field of spatial haptic sensation design, aiming to enhance user experiences across various applications. These applications range from drawing and gaming to tactile displays and even to creating out-of-body sensations [17], among others. This diversity underscores the potential of CRE in enriching sensory interactions in multiple contexts, including virtual and augmented reality.

2.2 Multimodal CRE

Several researchers showed that congruent visual movement with the tactile sensation enhances the illusion. While incongruent visual movement does not break the illusion, it modulates the perceived path of the virtual object, indicating a complex interaction between visual and tactile inputs in shaping the user's perception [2, 9, 26]. Ziat and colleagues have focused on the CRE interaction with visual stimuli and the resulting emotional dimensions [27–29]. In their 2017 study, they explored the impact of visual context on the perception of CRE, revealing that visual stimuli can modify the emotional interpretation of the tactile illusion [28]. Their subsequent work examined how variations in tactile stimulus duration, numerosity, and visual representations of motion influence the emotional dimensions of CRE, particularly in terms of valence and arousal [27, 29].

The authors highlighted the significance in shaping emotional responses within multimodal interaction frameworks, particularly in virtual and augmented reality contexts. Valence, especially in the context of very unpleasant stimuli, is predominantly influenced by visual factors. This is akin to the dynamics of human touch, where the perception and emotional response to touch are significantly affected by the welcome or unwelcome nature of the touch from another human, independent of the tactile quality of the touch itself [20, 22]. For moderately unpleasant or pleasant stimuli, the impact of visual stimuli on valence is less discernible, indicating a more intricate interplay between touch and vision. Additionally, their work reveals that both arousal and dominance dimensions can be effectively modulated by tactile stimuli, underscoring the role of tactile elements in shaping more nuanced aspects of emotional experience in these types of multimodal interactions.

3 Experiment

3.1 Participants

Twelve participants, comprising five females and seven males, aged between 22 and 39 years (Mean age = 25.75, Standard Deviation (SD) = 4.73), were recruited for the study. None of the participants had a history of insect phobia or arachnophobia. For their participation, each participant received a $20 gift card. All participants provided their informed consent, and the study was conducted with the approval of the Bentley University Institutional Review Board (IRB).

3.2 Apparatus and Stimuli

3.3 Apparatus

In our user study, we utilized the Unity game engine (version 2021.3) to develop the VR environment that was displayed through the Meta Quest Pro headset, offering a high-definition visual experience with a resolution of 1920 x 1800 per eye and a 90hz refresh rate. We operated the software on a high-performance Lenovo Legion 5PRO gaming computer, connected to the Quest Pro via an Oculus Link cable.

3.4 Tactile Stimuli

The haptic feedback was delivered using a custom-made flexible sleeve equipped with three C2 actuators. These actuators, each 3 cm in diameter, were meticulously positioned and separated by 5 cm from each other center-to-center to

Fig. 2. A participant wearing the headset and the sleeve

correspond with the virtual movements of visual stimuli in the VR environment, as depicted in Fig. 2. Vibrotactile feedback was generated using the Unity's audio player component and custom designed wave files. The sequence of vibrations was based on the CRE paradigm, illustrated in Fig. 1, which involves three sequential 24 ms bursts interspersed with 24 ms inter-burst intervals (IBI) at three distinct forearm locations - from the elbow to the wrist. The total duration of this feedback sequence was 432 ms, calculated as 3 locations × (3 × 24 ms burst + 3 × 24 ms (8 IBI including and 1 starting point)).

3.5 Visual Stimuli

The visual stimuli in our study were represented by 3D static models of saltatorial animals (Unity Asset Store). These animals are characterized by their hopping locomotion. The size of the 3D models were similar and were around 5 cm relatively to the arm that was about 60 cm. In the virtual environment, the animal performed a series of hops, the number of which varied based on one of two experimental conditions: either 3 hops or 9 hops. Figure 1 presents the five different animals (spider, flea, rabbit, kangaroo, frog) used in the experiment, along with a "sphere" representing a neutral stimulus (Fig. 3).

The key distinction between the two conditions lies in the visual representation of the number of times the animal hops on the arm. The duration of each hop was synchronized with the timing of the tactile stimulus. In the Three-hop condition, the animal hopped on three specific locations, directly matching the locations of the tactile stimuli. Conversely, in the Nine-hop condition (N9), the animal executed nine hops, creating a distributed visual sequence across nine

Fig. 3. The 3D models used: Top, from left to right) Spider, Flea, Rabbit. Bottom, from left to right) Kangaroo, Forg, and Sphere.

different locations. In both conditions, the total duration of the haptic feedback remained constant at 432 ms with nine actuation bursts in three distinct locations (as illustrated by Fig. 4).

3.6 Visual-Tactile Synchronization

To ensure precise synchronization, we meticulously coordinated the timings of visual and haptic feedback using system timers, verifying they met the required specifications. For haptic feedback, we addressed the latency issues found with Windows Multimedia Extensions (MME) - notably about 150-200 ms delay and unreliable multi-channel support for Unity - by employing ASIO4ALL. This freeware universal audio driver, compatible with Windows, supports the Audio Stream Input/Output (ASIO) protocol, known for its low-latency and high-fidelity sound transmission.

Since Unity does not inherently support ASIO, we utilized the 'Low-latency Multichannel Audio' plugin from DataTunnel, available on the Unity asset store. This enabled direct access to the external ESI GIGAPORT-HD+ USB Audio Interface. We chose the GIGAPORT HD+ for its support of 8 channels, dual independent stereo outputs, and a 24-bit/96 kHz D/A converter. This interface was connected to a Behringer Europower EPQ304 amplifier to enhance the signal of the C2 actuators, which were driven by a custom-designed wave file. The wave files utilized a sinusoidal actuation signal of 250Hz with 24ms on- and off- sequence, with the duration matching the visual stimuli of 432ms (3-point and 9-point jumping animation). The Behringer Europower EPQ304 amplifier is rated at 300 Watts total across each of its 4-channels, and each C2 tactors was driven within the manufacturer recommended wattage of 0.96 W (0.8 V/1.2 A), producing a peak amplitude of 1 mm.

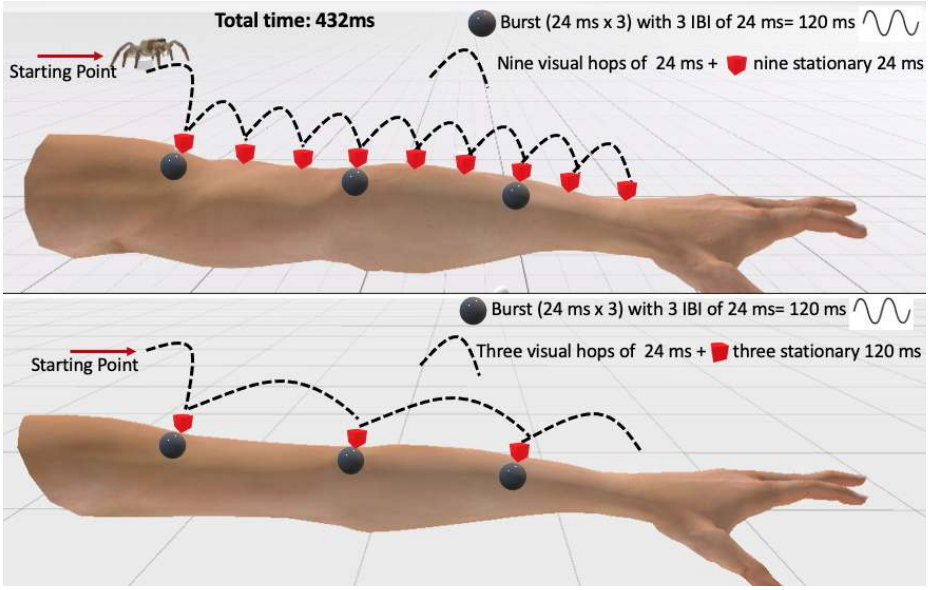

Fig. 4. The two hopping conditions: Top) The animal jumps nine time on a male arm. Bottom) The animal jumps three times on a female arm. The landing positions on the arm are shown by the red cube. The tactile stimulation, shown by the black sphere, remains the same in both conditions.

3.7 Procedure

Before beginning the experiment, participants were introduced to the Self Assessment Manikin (SAM) scale, a 7-point tool used to evaluate three affective dimensions: Valence, Arousal, and Dominance (illustrated in Fig. 5). Each participant was asked to sit at a table and put on a sleeve equipped with three C2 voice coils on their left forearm. They then put on a VR headset, which displayed a virtual arm corresponding to their real arm's position. Participants were able to adjust their seat height for comfortable alignment of their left forearm with the virtual arm on the table. They also had the choice to select the gender of the virtual arm (male or female).

After ensuring proper alignment between the physical and virtual worlds, the experiment started. It was divided into four blocks, each containing 12 trials (6 visual stimuli × 2 hopping conditions), resulting in 48 trials in total. The first block served as a baseline, involving only visual stimuli without any tactile feedback. The subsequent three blocks featured a combination of visual and tactile stimuli, presented synchronously. The sequence of stimuli presentation was randomized for every participant. This design employed a limited number of repetitions per condition to optimize data quality while minimizing participant fatigue and mitigating the risk of VR-induced motion sickness.

In each trial, participants observed one of the six 3D models appearing beside their arm and performing a hopping motion on the arm. Following this, they were prompted to provide their emotional response using the SAM scale, displayed within the VR environment. Responses were articulated verbally, with ratings ranging from 1 (symbolizing feelings of happiness, excitement, or control) to 7 (denoting feelings of unhappiness, calmness, or being controlled). Upon completion of all trials, participants were invited to share their overall impressions of the experiment. The average duration of the experimental session was approximately 30 minutes per participant, with the VR interaction lasting no more than 15 minutes.

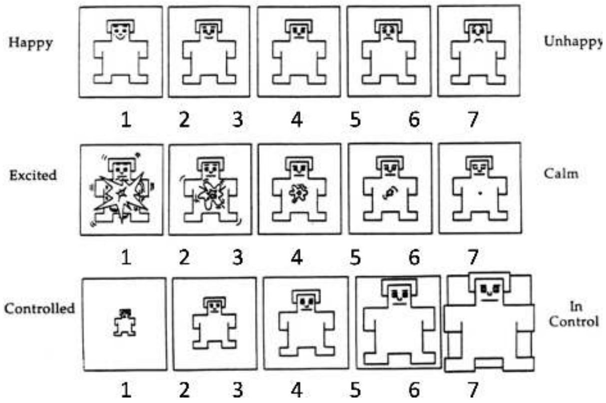

Fig. 5. The Self-Assessment Manikin(SAM) with 7-point scale for valence (top), arousal (middle), dominance (bottom) [4].

4 Results

4.1 Data Analysis

We conducted three separate three-way repeated measures ANOVAs to examine the effects of Animal (spider, rabbit, kangaroo, flea, frog, sphere), Modality (Visual, Visual-Haptic), and Number of Hops (3 or 9) on each of the three dependent variables: Valence, Arousal, and Dominance. Each variable was rated on a 7-point scale. Prior to the ANOVA, tests for normality and sphericity were conducted. When the assumption of sphericity was violated, the Greenhouse-Geisser correction was applied to adjust the degrees of freedom. For post-hoc comparisons, we utilized Dunn's Multiple Comparison Test with a Bonferroni correction. This approach involves adjusting the obtained p-values by multiplying them by the number of comparisons made, to control for the increased risk of Type I errors [8]. Gender was included as a covariate to assess its influence on the dependent measures. It was not found to significantly interact with other factors, nor did it show a main effect on Valence, Arousal, or Dominance.

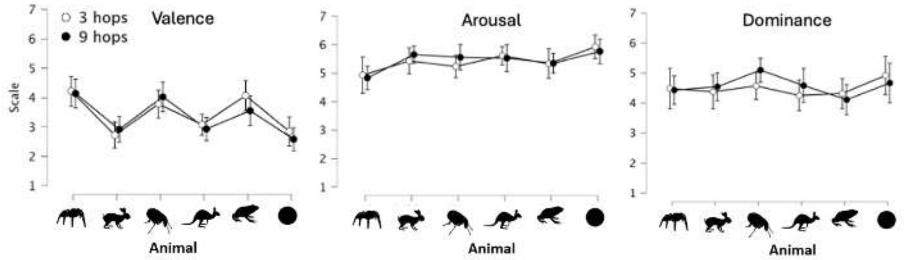

Fig. 6. Ratings for Valence, Arousal, and Dominance for the two hopping conditions, for the six 3D models.

4.2 Valence

A significant main effect of animal type on valence was observed, F(5, 55) = 7.733, $p < .001$, $\eta_p^2 = 0.413$. This suggests that different animals significantly influenced the valence ratings, with a moderate effect size (Fig. 6). The interaction between the number of hops and animal type was also significant, F(5, 55) = 3.216, p = .013, $\eta_p^2 = 0.226$, indicating that the impact of the number of hops on valence ratings varied depending on the animal type. This interaction effect shows a small to moderate effect size. No additional effects were found.

In the post-hoc pairwise comparisons examining the interaction effect between the number of hops and animal type on valence ratings, several significant differences were found. Regardless of the number of hops, spiders were consistently rated significantly higher in valence compared to rabbit, kangaroo, and sphere ($p < 0.001$), suggesting a distinct perception of valence associated with spiders. For the 3-hop condition, rabbit was significantly rated more pleasant than frog with 3 hops ($p < 0.011$) and flea with 9 hops ($p < 0.017$). This indicates that the effect of the number of hops is particularly relevant when comparing a visual stimulus like a rabbit with less pleasant visual stimuli such as frog or flea. Finally, a significant difference was observed between frog with three hops and both 3-hop and 9-hop sphere conditions, underscoring how animal type, coupled with the number of hops, can distinctly affect valence ratings.

4.3 Arousal

The main effects of Modality, Number of Hops, and Animal were not significant (Fig. 6). Similarly, the interaction effects between Modality and Number of Hops, and Modality and Animal, were also not significant. However, the interaction between Number of Hops and Animal was significant, F(5, 55) = 2.685, $p < .031$,

$\eta_p^2 = .2$. This indicates that the combination of Number of Hops and Animal had a meaningful impact on arousal ratings. Simple main effects of the factors Hop and Animal revealed that the Flea with three hops (4.67) were rated significantly more exciting than nine hops (5.42), suggesting increasing visual hops has a calming effect.

4.4 Dominance

The only significant results was observed for the factor of Animal (F(5, 55) = 3.436, p = .009, $\eta_p^2 = .238$). Post-hoc analysis revealed a significant difference between Spider and Sphere (p = 0.004) with the dominance rating for Spider significantly lower than for Sphere. Other comparisons, although not statistically significant, showed some trends. Spiders differed from Kangaroos by a mean of 0.69 (p = 0.095), and from Rabbits by a mean of 0.67 (p = 0.10). However, these differences did not reach statistical significance after Holm's adjustment for multiple comparisons.

4.5 Circumplex Models

We utilized the circumplex model of emotion and the Geneva Emotion Wheel to compare different emotional dimensions. The circumplex model, developed by James Russell, arranges twelve emotions in a two-dimensional space, with arousal on the vertical axis and valence on the horizontal axis [23]. In contrast, the Geneva Emotion Wheel positions valence and dominance within a circular space, distinguishing 20 emotions [24]. Applying our data to these models provides us with additional insights into the dynamics of the CRE in a VR setting.

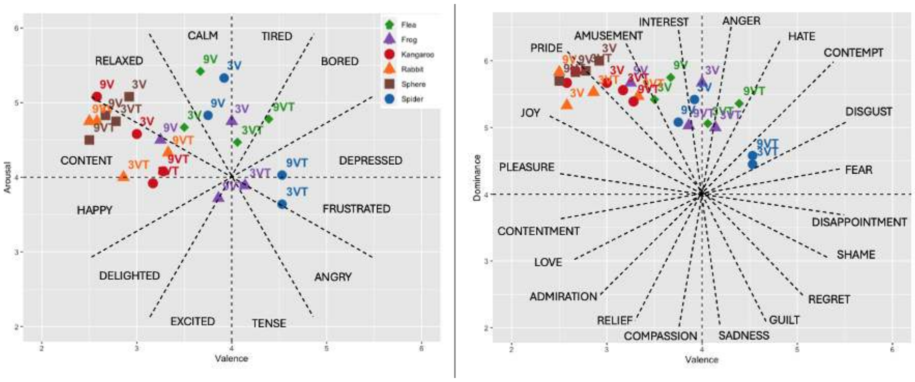

Fig. 7. Left: the circumplex model of emotion for valence and arousal. Right) the Genova Emotion Wheel plotting valence against dominance.

Valence-Arousal: Participants reported increased feelings of relaxation and contentment when exposed to images of a rabbit, kangaroo, or a sphere. While the sphere was intended as a neutral stimulus, its inherent bouncing effect, due to its shape, classified it as a more pleasant stimulus. This observation suggests that a more static object, like a cube or cone, could have been a more appropriate choice for a truly neutral stimulus. The introduction of tactile stimulation yielded several interesting findings. In the visual-only condition, both the flea and the spider were linked to feelings of calmness and relaxation. However, the addition of tactile feedback altered these emotions; participants felt tired or bored when exposed to the flea. For the spider, tactile stimuli induced feelings of depression and frustration, in the nine- and three-hop conditions, respectively. Moreover, the frog, when combined with tactile stimulation, led to a more neutral emotional response.

Valence-Dominance: The dynamics of valence and dominance exhibited similar results. More pleasant stimuli, such as the rabbit, kangaroo, and sphere, elicited feelings of pride and amusement in participants. In contrast, the flea and the spider, when presented visually, initially induced interest. However, when tactile feedback was introduced, this interest shifted to anger and hate in the 3-hop and 9-hop conditions, respectively, for the flea, and to disgust for the spider. Notably, these responses occurred despite none of the participants reporting any fear of insects or spiders.

5 Discussion and Conclusion

In this work, we further explored the emotional responses elicited by the visuo-tactile cutaneous rabbit effect (CRE) within a virtual reality context. Quantitative findings and participants' subjective feedback revealed a complex interplay among valence, arousal, dominance, and tactile experiences. The type of visual stimulus, particularly different animal representations, profoundly influenced these responses. For instance, spiders were consistently rated as more unpleasant than benign animals like rabbits and kangaroos. The number of hops also played a crucial role, particularly the three-hop condition, which affected ratings more significantly when comparing visually pleasant stimuli (like rabbits) with less pleasant ones (such as frogs or fleas), reflecting our earlier findings where the frequency and duration of visual stimuli affected emotional impact [28, 29].

The circumplex model and the Geneva Emotion Wheel have been instrumental in providing a holistic evaluation of the affective dimensions explored in this study. As participants described their evolving emotional states, the impact of tactile feedback was particularly notable, not only in enhancing the realism and emotional depth of the VR experience but also in altering the emotional landscape. Tactile stimulation associated with fleas and spiders induced negative emotions such as tiredness, boredom, or even depression and frustration. Conversely, tactile feedback related to rabbits, kangaroos, and spheres evoked feelings of relaxation and contentment, highlighting how tactile interactions can significantly alter the emotional context of a virtual encounter. Furthermore, the valence-dominance dynamics revealed that while pleasant stimuli like rabbits and kangaroos elicited feelings of pride and amusement, less favorable animals such as fleas and spiders provoked feelings of anger, hate, or disgust when paired with tactile stimulation, despite participants reporting no inherent fear of these animals.

Participants' subjective responses highlighted the critical role of tactile feedback in distinguishing between different animals. They reported that the absence of tactile cues diminished the distinction between animals and the realism of the scene. Conversely, tactile vibrations significantly contributed to perceived realism, with suggestions for varying the vibration intensity and pattern to match different animal characteristics. The portrayal of larger animals, like kangaroos, as being the same size as smaller ones sometimes led to reduced excitement and a sense of unreality, highlighting the importance of proportionate and contextually appropriate visual representations, as was the case in our previous findings [29]. Many participants reported feeling calmer and more in control as the experiment progressed, while some expressed a dislike for creatures like frogs and spiders, and a preference for others, such as rabbits. Conversely, more neutral or traditionally 'cute' animals, such as rabbits and kangaroos, elicited more positive responses.

Overall, our body of work reveals significant insights into the interplay between sensory modalities and emotional perception in VR. Animals typically associated with aversive reactions consistently invoked negative emotional responses, suggesting an evolutionary emotional coding that VR can leverage to enhance user engagement. Conversely, traditionally 'cute' animals elicited more positive responses. The differential impact underscores the potential for VR designers to tailor experiences based on desired emotional impacts, using animal types and sensory manipulations such as the number of hops to invoke specific feelings. Further exploration into optimizing these configurations for specific emotional outcomes is necessary. Additionally, integrating physiological measures such as electrodermal activity (EDA), heart rate, or pupillary responses in future studies could provide a more comprehensive understanding of the multimodal interactions underpinning emotional responses in virtual environments.

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