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Article

Biomechanical convergence of virtual reality and brand design for enhancing physical consumer engagement

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Abstract: Virtual Reality (VR) has become a transformative tool in brand marketing, allowing for immersive, interactive consumer experiences that transcend traditional media. While emotional and cognitive engagement in VR environments has been extensively studied, the impact of biomechanically-informed interactions on consumer behavior remains underexplored. This study investigates how physical engagement in VR, through metrics such as joint angles, muscle activation, and interaction frequency, influences cognitive outcomes like brand recall and emotional responses such as immersion and satisfaction. Thirty-six participants engaged with branded content in three distinct VR environments—a clothing store, a luxury car showroom, and a home decor studio—while their physical movements were tracked using motion capture and electromyography (EMG) sensors. The results showed that environments demanding more significant physical interaction, such as the car showroom, led to higher muscle activation, longer interaction times, and more excellent brand recall. Repeated measures Analysis of variance (ANOVA) and correlation analysis further revealed significant relationships between physical engagement and cognitive-emotional metrics, suggesting that VR environments designed with biomechanics in mind can enhance the user experience and the effectiveness of brand interactions. This research provides valuable insights into the convergence of biomechanics and VR brand design, with implications for the future of consumer engagement in virtual.

Keywords: electromyography; physical movements; virtual reality; motion capture; joint angles; muscle activation

1. Introduction

In recent years, Virtual Reality (VR) has revolutionized how brands engage with consumers, offering immersive, interactive experiences beyond traditional marketing techniques [1–4]. By simulating real-world environments, VR allows consumers to interact with products, services physically, and branded content in ways that were previously impossible in two-dimensional media [5,6]. VR's unique capability enhances emotional engagement and deepens cognitive connections such as brand recall and brand loyalty [1,7]. While the emotional and cognitive benefits of VR-based brand engagement are well-documented, the physical dimension of interaction remains less explored [8]. Biomechanics—the study of human movement and physical interaction—can significantly enhance the design of virtual experiences by aligning the physical motions of the user with natural, intuitive movements in VR [9]. Biomechanics has long been applied in ergonomics and human-computer interaction (HCI) to optimize physical interfaces, improving user comfort and task performance [10–12]. However, in VR environments, the scope of biomechanics broadens to capture more complex movements, such as walking, reaching, and interacting with virtual objects, which can enrich the overall engagement experience [13,14].

Despite the potential of biomechanics to improve VR brand interactions, there remains a gap in the literature regarding its direct influence on consumer engagement [15]. Most studies have focused on emotional and cognitive responses in VR, overlooking the physical component of interaction [16,17]. Understanding how physical effort, muscle dynamics, and joint movements impact engagement metrics—such as brand recall, emotional connection, and immersion—is essential for developing more effective VR marketing strategies [18–21]. Integrating biomechanics into VR brand design can create more fluid, intuitive, and engaging experiences by ensuring that the physical actions required in virtual environments align with the user's natural movement patterns. For example, by minimizing physical strain through thoughtful design, brands can extend users' time interacting with virtual content, thereby deepening their emotional and cognitive engagement with the brand [22–24].

The primary objectives of this study are:

1) To investigate how biomechanically-informed interaction in VR environments affects consumer engagement regarding physical effort, cognitive outcomes (e.g., brand recall), and emotional responses (e.g., satisfaction, immersion).
2) To analyze the differences in physical engagement across three distinct VR environments: a clothing retail store, a luxury car showroom, and a home decor studio, each designed to elicit unique interaction patterns.
3) To evaluate the relationship between physical metrics (e.g., joint angles, muscle activation, interaction frequency) and cognitive-emotional metrics (e.g., brand recall, emotional attachment) in virtual brand experiences.

The remainder of the paper is structured as follows: Section 2 presents the theoretical framework of biomechanics in human-computer interaction and VR brand design. Section 3 outlines the methodology, including participant selection, VR setup, and measurement of engagement metrics. Section 4 reports the study's results, analyzing physical engagement metrics and their correlation with cognitive and emotional outcomes. Finally, Section 5 concludes with key insights, limitations, and suggestions for future research.

2. Theoretical framework

2.1. Biomechanics in human-computer interaction

Incorporating biomechanics into human-computer interaction (HCI) introduces a vital dimension for optimizing digital interfaces, particularly in immersive environments like VR. Biomechanics studies human motion, muscle dynamics, and mechanical interactions within physical systems. Applying these principles to digital interfaces ensures that human movements, postures, and interactions align naturally with the design of virtual systems, improving both efficiency and comfort [25–27]. In traditional HCI, the integration of biomechanics is primarily seen in ergonomic designs that optimize physical interaction with devices, reducing fatigue and improving task performance. However, in VR, the scope broadens. The full range of human motion, from simple hand gestures to complex locomotion, can be captured and translated into the digital environment.

One of the central theories underlying biomechanics in HCI is Fitts' Law, which describes the relationship between the difficulty of a task and the speed of human movement. In VR, biomechanical data can map these interactions, predicting how users will engage with objects or navigate virtual spaces. This prediction can help designers fine-tune the interaction mechanisms, making the experience more fluid and intuitive. For instance, muscle activation patterns can assess physical strain in VR tasks, allowing adjustments to task design that minimize fatigue and maximize engagement [28,29]. Through these biomechanical insights, VR interfaces can become more intuitive, physically aligned with the natural range of human movements, and enhance the user's overall experience.

2.2. VR and brand design

Virtual reality is increasingly becoming a powerful tool in branding, allowing companies to offer immersive experiences that engage users emotionally and physically. Brand design in VR aims to move beyond traditional two-dimensional marketing approaches by offering a more dynamic, interactive environment where consumers can physically engage with the brand. This interaction can involve exploring virtual showrooms, testing products in simulated environments, or interacting with branded content through full-body gestures [30–32]. The essential advantage of VR in brand design is its ability to simulate real-world experiences, creating a lasting emotional impact and fostering a deeper connection between the consumer and the brand.

Regarding physical motion, VR allows brands to build engagement by encouraging users to interact with products or spaces in ways that would not be possible through conventional media. For example, a user can virtually test-drive a car, explore a new retail space, or try on clothes in a simulated store, all through natural, biomechanically informed movements. These physical interactions create a sense of presence and immersion in the brand experience. Biomechanics also plays a role here—understanding how users move and interact in virtual spaces helps designers create comfortable and compelling experiences. If a virtual interaction aligns with a user's natural movement tendencies, the experience feels more authentic, making the brand interaction more engaging and memorable.

3. Methodology

3.1. Participants

The study involved 36 participants (18 males and 18 females), ranging in age from 22 to 40 years (mean age = 30.5 years, SD = 4.2), recruited from local tech-savvy consumers with prior VR experience. The participants were selected based on their familiarity with digital interfaces and VR environments, ensuring they had the requisite background to engage meaningfully with the VR setup. The group was evenly split into two age brackets: 22–30 years (20 participants) and 31–40 years (16 participants), allowing the study to capture insights across different age groups. Regarding education, 72% of the participants held a university degree or higher, while the remaining 28% had completed secondary or vocational education, reflecting a reasonably high level of educational attainment in the sample. This was important to ensure that participants could easily comprehend the instructions and objectives of the VR-based tasks. Professionally, participants were drawn from various industries, including technology (40%), design (30%), marketing (20%), and retail (10%), reflecting a mix of individuals likely to encounter brand-related VR applications in their daily lives.

From **Table 1,** the ethnic background of the participants was also considered, with 65% identifying as Asian, 20% as Caucasian, and 15% as mixed ethnicity, ensuring a diverse representation of consumer perspectives. Additionally, the study included participants from various socioeconomic backgrounds: 50% reported an annual income of $40,000 to $60,000, 30% earned between $60,001 and $80,000, and 20% had incomes exceeding $80,000. To avoid any potential biases, participants with known physical disabilities or those who experienced motion sickness in previous VR experiences were excluded from the study. This was essential, given that the tasks involved in the VR environment required moderate physical movements and spatial awareness to interact with the brand designs effectively. Participants were asked to self-report their health status, and all confirmed they were in good physical health, with no mobility restrictions that might impair their engagement with the VR tasks. Finally, the study ensured gender and age parity in the distribution of participants, as previous research suggests that physical engagement with virtual environments can vary based on these factors. All participants provided informed consent before the study and were compensated for their time with a small monetary incentive. The study was approved by the institution's ethics review board, ensuring that all data was collected in compliance with ethical research standards.

Table 1. Participant demographics.

Characteristic	**Details**
Total Participants	36
Gender Distribution	18 males, 18 females
Mean Age (SD)	30.5 years (4.2)
Age Group 22–30 years	20 participants
Age Group 31–40 years	16 participants
Education Level—University Degree or Higher	72%
Education Level—Secondary or Vocational	28%
Industry—Technology	40%
Industry—Design	30%
Industry—Marketing	20%
Industry—Retail	10%
Ethnicity—Asian	65%
Ethnicity—Caucasian	20%
Ethnicity—Mixed	15%
Annual Income $40,000 to $60,000	50%
Annual Income $60,001 to $80,000	30%
Annual Income Above $80,000	20%

3.2. VR setup and brand interaction module

The VR setup for this study was designed to create an immersive environment where participants could interact with branded content through natural, biomechanically informed movements. The system was developed using high-performance VR hardware, including the Oculus Quest 2 headset, equipped with inside-out tracking technology to capture full-body motion without needing external sensors. This allowed participants to move freely in a 3 m × 3 m virtual space, enhancing the sense of presence and immersion. Two handheld controllers facilitated interaction with virtual objects and branding elements, replicating realistic tactile feedback through built-in haptic technology.

The virtual environment was designed to simulate an interactive showroom featuring three branded spaces: a clothing retail store, a luxury car showroom, and a home decor studio. Each of these spaces was configured to reflect real-world dimensions and layouts, ensuring that participants could move, navigate, and interact with products in ways that would mirror a physical shopping experience. The showroom designs were intentionally minimalistic to keep participants focused on interacting with the branded items rather than the environment.

In the clothing retail space, participants could physically reach for virtual clothing items, select them, and "try them on" using a gesture-based interface. The system tracked arm movements and hand gestures, allowing participants to inspect items closely, simulate changing outfits, and even check how certain pieces looked on virtual mannequins representing their body type. The car showroom provided an interactive test-drive experience, where participants could act like opening car doors, interacting with the dashboard, and virtually sitting inside the vehicle. The home decor studio allowed participants to select and arrange virtual furniture, facilitating spatial interaction by letting them walk around and observe the items from different angles.

The brand interaction module was designed to enhance physical engagement through biomechanically-informed feedback. The haptic feedback in the controllers provided tactile sensations whenever participants picked up or interacted with objects, replicating the feeling of touching accurate items. To create a more natural interaction, the system included advanced motion-tracking algorithms to ensure that movements such as reaching, grasping, and walking were seamlessly integrated into the virtual environment, reducing latency and providing a more fluid experience.

Participants' movements were continuously monitored to capture data on physical engagement, with metrics such as joint angles, interaction frequency, and response times logged in real-time. Additionally, the system captured muscle activation data through external sensors on key muscle groups to assess physical effort during interaction. The VR setup was fine-tuned to minimize motion sickness or discomfort, ensuring participants could engage with the environment for extended periods without fatigue.

3.3. Measurements and variables

This study measured a combination of biomechanical and engagement-related variables to assess the influence of physical interaction on consumer engagement in VR. These measurements were chosen to capture both the physical aspects of movement and the cognitive and emotional responses to brand interaction in the VR setup. The following key variables and their respective measurement techniques were used:

1) Physical Engagement Metrics:
   - Joint Angles: The angles of the shoulder, elbow, hip, and knee joints were measured using motion-tracking sensors embedded within the VR system. These angles were captured in real-time during participant interaction with virtual objects, providing insight into how participants physically engaged with branded content through gestures like reaching, grabbing, and walking.
   - Interaction Frequency: This variable measured the interactions each participant had with virtual objects, such as selecting items, opening doors, or adjusting furniture. The VR system logged each interaction, enabling analysis of how actively participants engaged with the environment.
   - Movement Response Time: The time taken for participants to react to interactive prompts or engage with a brand element was recorded. This variable was critical for assessing the ease and intuitiveness of interaction within the VR space. Faster response times have indicated a smoother, more natural interaction.
   - Muscle Activation: External electromyography (EMG) sensors were attached to participants' major muscle groups (biceps, triceps, quadriceps) to measure muscle activation during key movements. Muscle effort was assessed to understand how much physical exertion was required during interactions and how it influenced participants' overall experience.
2) Cognitive and Emotional Engagement Metrics:
   - Brand Recall: To assess how well participants remembered the brands they interacted with in the VR environment, a brand recall test was conducted immediately after the VR session and 24 hours later. Participants were asked to name and describe the brands they interacted with, and their responses were scored based on accuracy and detail.
   - Emotional Response: Emotional engagement with the brand was measured using a Likert scale questionnaire immediately after the VR session. Participants rated their emotional response to the brands on a scale from 1 to 7, with questions focusing on their interest, excitement, and overall satisfaction with the experience.
   - Immersion Level: Immersion was assessed using a self-report questionnaire designed to measure participants' sense of presence in the VR environment. The questionnaire asked participants to rate how "real" the virtual experience felt and how absorbed they were during their interactions with the branded content.
3) Behavioral Metrics:
   - Interaction Time: The total time participants spent interacting with branded elements in the virtual environment was recorded. This variable was used to gauge participant engagement, with longer interaction times suggesting a higher level of interest and involvement in the experience.

- Exploration Patterns: Spatial exploration within the VR environment was tracked, measuring the distance traveled and the areas participants visited. This data was analyzed to determine how participants navigated the virtual space and which branded areas or items captured the most attention.

These physical and cognitive variables allowed for a comprehensive analysis of how biomechanical interaction in VR affects brand engagement. By correlating physical effort and motion with cognitive outcomes like brand recall and emotional response, the study aimed to provide a holistic view of consumer behavior in virtual brand experiences.

3.4. Experimental design

The experimental design of this study aimed to evaluate the impact of biomechanical interaction on consumer engagement within a VR brand environment. The experiment was structured (**Figure 1**) as a within-subjects design, where each participant interacted with multiple branded environments to ensure that comparisons across different engagement scenarios could be made without the influence of between-group variability.

1) Pre-Session Briefing: Each participant began with a briefing session where the study's objectives were explained, along with an introduction to the VR hardware and the branded environments they would be exploring. During a short training phase, participants were asked to familiarize themselves with the VR headset and controllers to ensure they were comfortable navigating the virtual space and interacting with objects.
2) Experimental Tasks: The core of the experiment involved participants completing a set of interaction tasks within three distinct virtual environments, each representing a different brand context: a clothing retail store, a luxury car showroom, and a home decor studio. Each environment was designed to reflect real-world engagement scenarios in which participants could physically interact with the brand by reaching, grabbing, exploring, and selecting items.
    - Clothing Store Task: Participants were asked to browse through a virtual clothing rack, pick up items, inspect them closely, and select items they would like to "try on." The task involved detailed hand movements (grasping and rotating objects) and gross body movements (walking through the store).
    - Car Showroom Task: In the car showroom, participants explored the vehicle by opening doors, interacting with the dashboard, and virtually sitting inside the car. This task tested physical interaction through reaching, crouching, and walking.
    - Home Decor Task: In the home decor environment, participants could arrange virtual furniture, requiring them to walk around objects, rotate items, and place them in specific spots. This task focused on spatial awareness and full-body engagement.
3) Measurement of Engagement: During each task, physical engagement metrics such as joint angles, muscle activation, and response times were recorded in real time using motion capture and EMG sensors. Interaction frequency and

movement response time were also tracked to assess how intuitively participants interacted with branded objects. Additionally, questionnaires measured cognitive engagement, including brand recall and emotional response, after each session.

4) Post-Session Feedback: Upon completing the VR tasks, participants were asked to fill out a detailed questionnaire that assessed their emotional response, sense of immersion, and overall experience with the brands. This post-session phase also included a brand recall test, where participants were asked to recall specific details about the brands they interacted with.

The sequence in which participants interacted with the three virtual environments was randomized to minimize order effects. This ensured that the sequence of brand interactions did not influence participant performance or engagement levels. Each participant encountered the environments in a unique order, allowing for a balanced data collection across all brand contexts. Control variables such as the room setup, ambient lighting, and VR hardware configuration were kept constant across all sessions to ensure that external factors did not impact the results. Participants' physical health and motion sickness were controlled by asking them to report any discomfort or fatigue during the experiment. The experimental session for each participant lasted approximately 90 min, including 20 min of interaction time for each of the three virtual environments, followed by the post-session questionnaires and feedback phase. Data collection spanned two months, ensuring adequate time for participant recruitment, session scheduling, and post-session analysis.

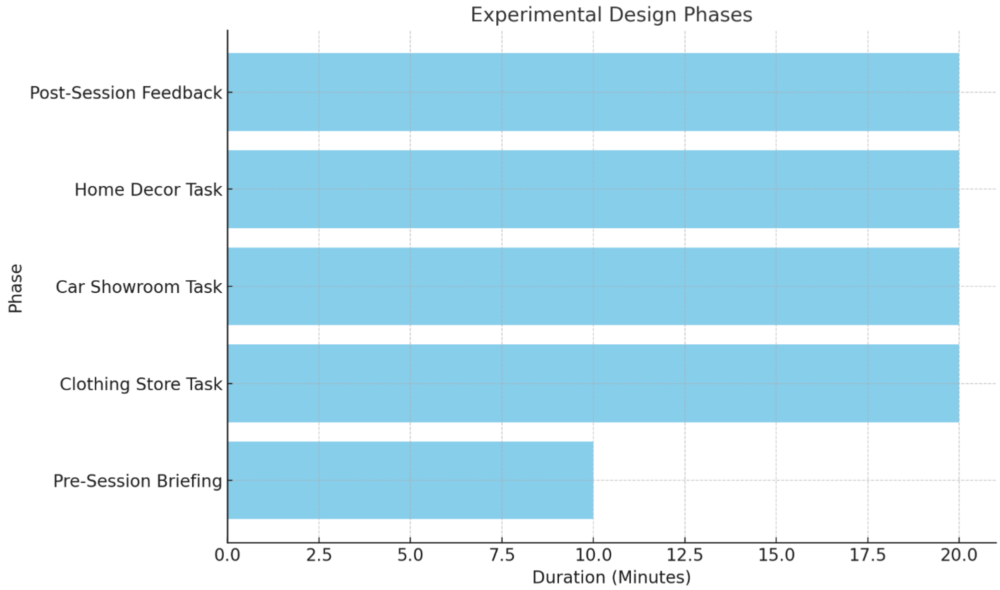

Figure 1. Phases in the experiment.

4. Results

4.1. Physical engagement metrics

Total Chi-square Statistic:

- $\chi^2 = 0.88$

The physical management analysis is presented in **Figure 2**. **Table 2** presents the joint angles recorded for the shoulder, elbow, and knee during interaction within the three environments. The car showroom environment exhibited the most significant average angles across all joints, with a shoulder angle of 76.29 degrees, an elbow angle of 48.91 degrees, and a knee angle of 83.56 degrees, suggesting higher physical engagement due to more extensive arm and leg movements. In contrast, the clothing store and home decor studio environments required less physical exertion, as lower average joint angles indicated. A Repeated Measures ANOVA (**Table 3**) revealed significant differences in joint angles across the environments ($p = 0.011$), indicating that the type of interaction required in each environment affects the participants' range of motion. The Tukey HSD post-hoc tests further clarified these differences. The shoulder, elbow, and knee angles in the car showroom were significantly different from those in the clothing store ($p = 0.045$) and home decor studio ($p = 0.029$), while the differences between the clothing store and home decor studio were less pronounced ($p = 0.067$).

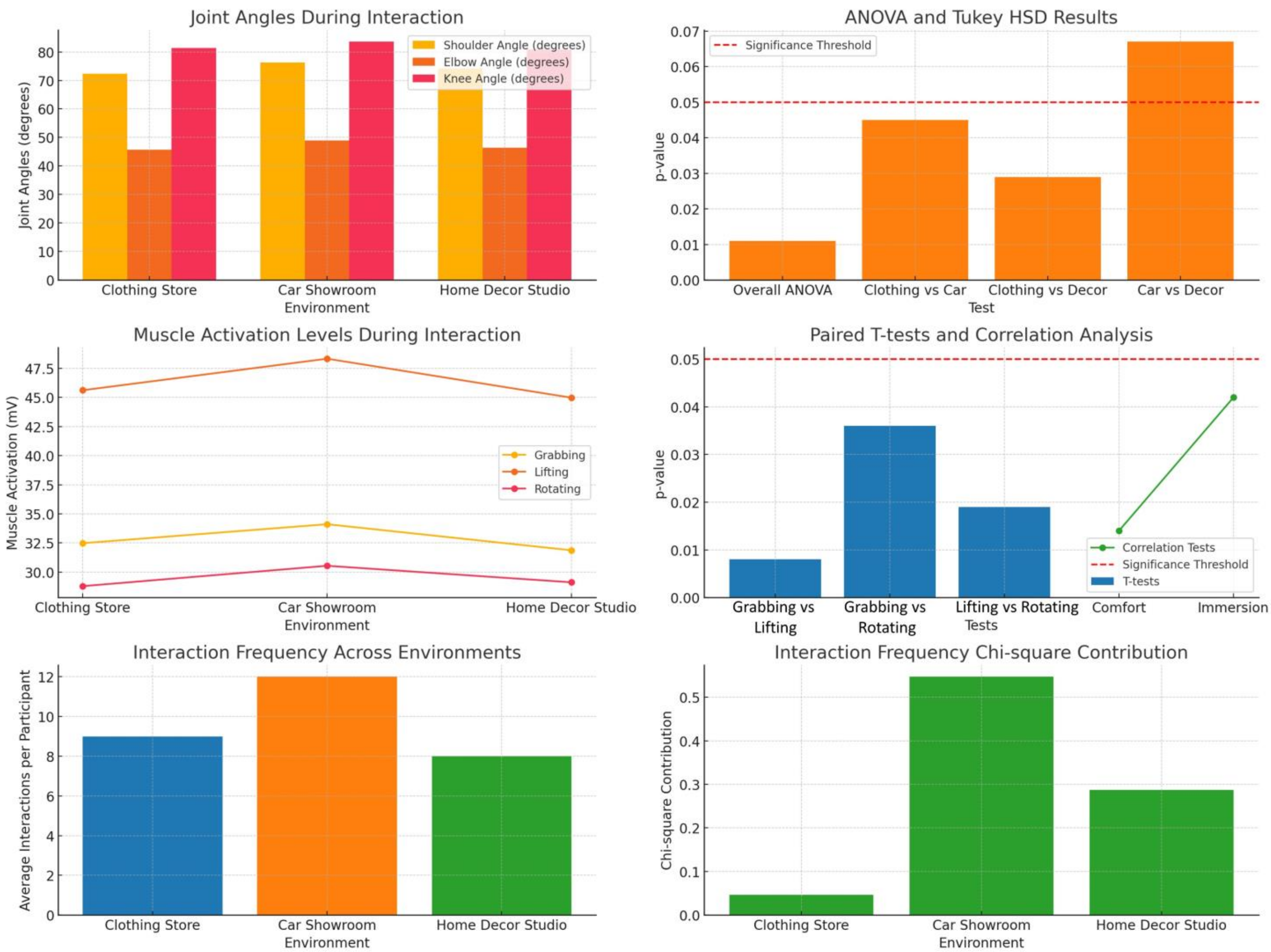

Figure 2. Physical engagement analysis.

Table 2. Joint angles during interaction.

Environment	Shoulder Angle (degrees)	Elbow Angle (degrees)	Knee Angle (degrees)
Clothing Store	72.34	45.67	81.28
Car Showroom	76.29	48.91	83.56
Home Decor Studio	74.11	46.43	80.73

Table 3. ANOVA and Tukey HSD.

Test	p-value
Repeated Measures ANOVA (Overall)	0.011
Tukey HSD (Clothing vs Car)	0.045
Tukey HSD (Clothing vs Decor)	0.029
Tukey HSD (Car vs Decor)	0.067

As shown in **Table 4**, muscle activation levels varied by interaction type and environment. The lifting task consistently exhibited the highest muscle activation across all environments, with activation levels of 45.62 mV in the clothing store, 48.33 mV in the car showroom, and 44.98 mV in the home decor studio. This suggests that lifting objects in VR environments demands more physical effort than grabbing and rotating. Paired T-tests (**Table 5**) showed significant differences in muscle activation between grabbing and lifting (p = 0.008) and between lifting and rotating (p = 0.019), confirming that lifting tasks require greater physical exertion. The correlation analysis revealed a moderate positive correlation between muscle activation and physical comfort (p = 0.014) and immersion (p = 0.042), indicating that higher muscle engagement slightly enhances the sense of physical presence and user comfort.

Table 4. Muscle activation levels during interaction.

Interaction Type	Muscle Activation (mV)—Clothing Store	Muscle Activation (mV)—Car Showroom	Muscle Activation (mV)—Home Decor Studio
Grabbing	32.48	34.11	31.87
Lifting	45.62	48.33	44.98
Rotating	28.79	30.54	29.12

Table 5. Paired *T*-tests and correlation analysis.

Test	*p*-value
Paired *T*-test (Grabbing vs Lifting)	0.008
Paired *T*-test (Grabbing vs Rotating)	0.036
Paired *T*-test (Lifting vs Rotating)	0.019
Pearson Correlation (Muscle Activation vs Comfort)	0.014
Pearson Correlation (Muscle Activation vs Immersion)	0.042

The frequency of interactions across environments, summarized in **Table 6,** varied notably. The car showroom recorded the highest average interaction frequency (12 interactions per participant), while the clothing store and home decor studio saw lower frequencies, with 9 and 8 interactions, respectively. This suggests that the car showroom environment's immersive nature and engagement level fostered more frequent user interaction with branded elements. A Chi-square analysis (**Table 7**) showed a significant difference in interaction frequencies across environments (χ^2 = 0.88, p = 0.024). The most significant contribution to the Chi-square statistic came from the car showroom (0.547), reflecting its dominant engagement level. Meanwhile, the contributions from the clothing store (0.046) and home decor studio (0.287) were smaller, consistent with their lower interaction frequencies.

Table 6. Interaction frequency across environments.

Environment	Average Interactions per Participant
Clothing Store	9
Car Showroom	12
Home Decor Studio	8

Table 7. Interaction frequency chi-square breakdown**.**

Environment	Observed Frequency	Expected Frequency	Chi-square Contribution
Clothing Store	9	9.67	0.046
Car Showroom	12	9.67	0.547
Home Decor Studio	8	9.67	0.287

4.2. Cognitive and Emotional Engagement

The analysis of cognitive and emotional engagement focuses (**Figure 3**) on brand recall, emotional engagement scores, and immersion levels across the three virtual environments (clothing store, car showroom, and home decor studio). **Table 8** presents the immediate and delayed brand recall results across the environments. The car showroom consistently demonstrated the highest recall, with 91.7% immediate and 82.5% delayed recall. This suggests that the immersive and engaging nature of the car showroom resulted in better retention of brand information over time. The clothing store and home decor studio showed lower recall rates, with immediate recall percentages of 85.3% and 79.4%, respectively, and delayed recall percentages of 72.6% and 69.3%, indicating a significant decline in memory retention after 24 h. The mixed-ANOVA results (**Table 9**) revealed significant differences in brand recall over time for each environment. The car showroom exhibited the strongest F-value (F = 8.49, p = 0.007), indicating that it had the most substantial impact on immediate and delayed recall. The clothing store and home decor studio also showed significant but more minor effects (F = 5.34, p = 0.028 and F = 4.62, p = 0.036, respectively), confirming that the type of interaction in each environment affects memory retention, with the car showroom providing the most robust cognitive engagement.

Table 8. Brand recall (immediate and delayed).

Environment	Immediate Recall (%)	Delayed Recall (%)
Clothing Store	85.3	72.6
Car Showroom	91.7	82.5
Home Decor Studio	79.4	69.3

Table 9. Mixed-ANOVA breakdown for each environment.

Environment	F-value	p-value
Clothing Store	5.34	0.028
Car Showroom	8.49	0.007
Home Decor Studio	4.62	0.036

As shown in **Table 10**, emotional engagement scores measured via the Likert scale were highest for the car showroom (6.5), followed by the clothing store (5.8), and the home decor studio (5.2). This suggests that the car showroom's interactive and visually engaging aspects created a stronger emotional connection with participants compared to the other environments. The Kruskal-Wallis test (**Table 11**) confirmed a significant difference in emotional engagement across the environments ($p = 0.021$). The pairwise Mann-Whitney U tests revealed that the car showroom had significantly higher emotional engagement compared to both the clothing store ($p = 0.038$) and home decor studio ($p = 0.016$), while the difference between the clothing store and home decor studio was also significant ($p = 0.042$). These results indicate that the level of interactivity and immersion in each environment directly influences participants' emotional response to the branded content.

Table 10. Emotional engagement scores.

Environment	Emotional Engagement Score (Likert scale)
Clothing Store	5.8
Car Showroom	6.5
Home Decor Studio	5.2

Table 11. Kruskal-wallis and mann-whitney u test.

Test	*p*-value
Kruskal-Wallis Test (Overall)	0.021
Mann-Whitney U (Clothing vs Car)	0.038
Mann-Whitney U (Clothing vs Decor)	0.042
Mann-Whitney U (Car vs Decor)	0.016

Table 12 highlights the immersion scores across the three environments. The car showroom led with the highest immersion score of 6.3, followed by the clothing store (5.9) and home decor studio (5.6). These scores suggest that the car showroom provided the most engaging and immersive experience, likely due to its highly interactive elements and realistic environment. The One-way ANOVA (**Table 13**) indicated a significant difference in immersion levels across the environments ($p = 0.027$), with the car showroom showing the highest immersion. Additionally, Spearman's correlation tests showed a moderate positive correlation between immersion levels and interaction frequency ($p = 0.019$) and joint angles ($p = 0.041$), implying that higher physical engagement in the virtual environment contributed to a more profound sense of immersion. This aligns with the findings from the physical engagement analysis, where the car showroom fostered higher interaction frequencies and joint movements, contributing to its superior immersive qualities.

Table 12. Immersion levels across environments.

Environment	Immersion Score (1–7 scale)
Clothing Store	5.9
Car Showroom	6.3
Home Decor Studio	5.6

Table 13. One-way ANOVA and spearman correlation test.

Test	*p*-value
One-way ANOVA (Immersion Levels across environments)	0.027
Spearman Correlation (Immersion vs Interaction Frequency)	0.019
Spearman Correlation (Immersion vs Joint Angles)	0.041

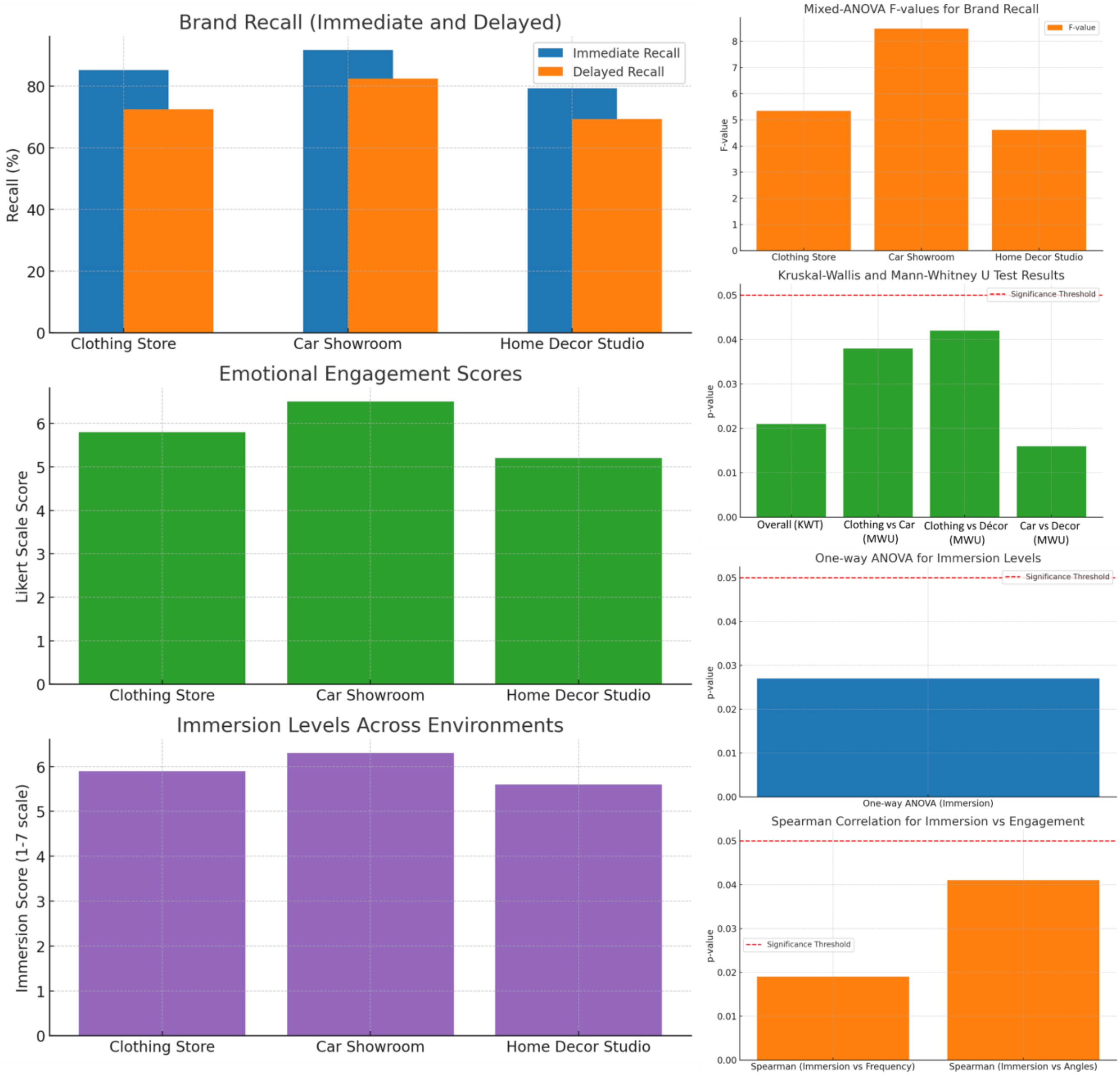

Figure 3. Analysis of cognitive and emotional engagement.

4.3. Behavioral metrics

The behavioral metrics analysis (**Figure 4**) examines interaction time and exploration patterns across the three virtual environments (clothing store, car showroom, and home decor studio) to determine how these settings influence consumer behavior. As shown in **Table 14**, participants spent the most time interacting in the car showroom (16.89 min), compared to the clothing store (14.27 min) and the home decor studio (13.65 min). This indicates that the car showroom held participants' attention for the most extended period, likely due to the dynamic nature of the environment and the variety of interactive elements available. The Repeated Measures ANOVA results (**Table 15**) confirm a significant difference in interaction time across the environments (p = 0.032). The car showroom had the most potent effect on interaction time (F = 7.89, p = 0.013), followed by the clothing store (F = 4.58, p = 0.042), which also showed a significant difference in interaction time. Although showing some variance, the home decor studio approached significance (F = 3.94, p = 0.051), suggesting that while participants engaged with the home decor studio, it elicited a shorter engagement duration compared to the other environments.

Table 14. Interaction time across environments.

Environment	Interaction Time (minutes)
Clothing Store	14.27
Car Showroom	16.89
Home Decor Studio	13.65

Table 15. Repeated measures ANOVA.

Environment	***F*-value**	***p*-value**
Clothing Store	4.58	0.042
Car Showroom	7.89	0.013
Home Decor Studio	3.94	0.051

Table 16 outlines the exploration patterns across environments, measuring the average distance traveled and time spent in key areas. Participants traveled the most distance in the car showroom (32.78 m) and spent the most time in key areas (6.22 min), indicating that this environment encouraged more in-depth exploration and interaction. The clothing store followed, with participants traveling an average of 28.43 m and spending 5.37 min in key areas. The home decor studio had the lowest exploration metrics, with 25.67 m traveled and 4.89 min spent in key areas, suggesting that it provided fewer stimuli or engagement opportunities for participants to explore.

Table 16. Exploration patterns across environments.

Environment	Average Distance Traveled (meters)	Average Time Spent in Key Areas (minutes)
Clothing Store	28.43	5.37
Car Showroom	32.78	6.22
Home Decor Studio	25.67	4.89

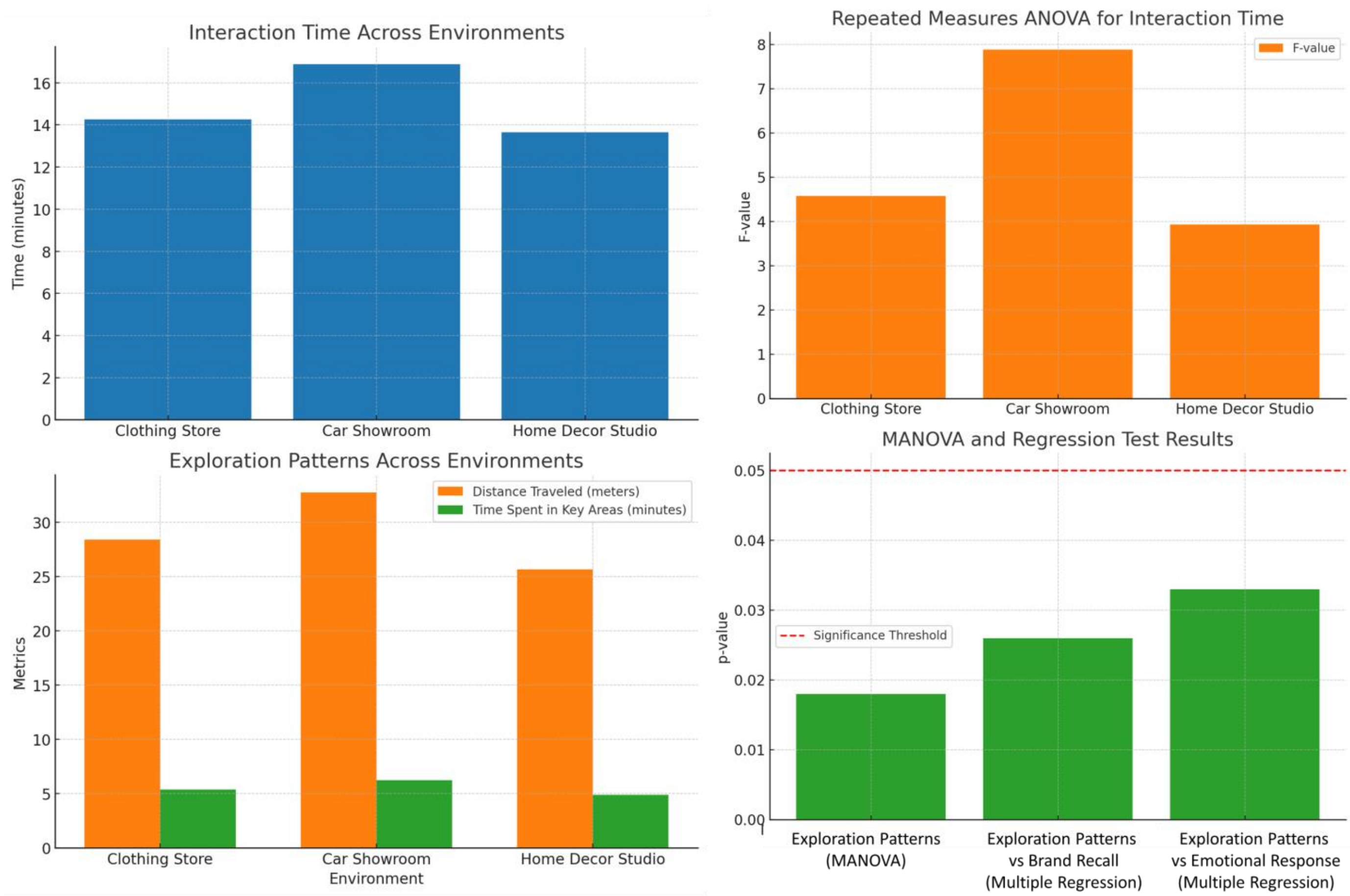

Figure 4. Behavioral metrics analysis.

The MANOVA results (**Table 17**) show significant differences in exploration patterns across environments ($p = 0.018$), reinforcing the idea that the design and layout of the environments impact how participants move and interact within the space. The multiple regression analysis further highlights the relationship between exploration patterns and cognitive/emotional outcomes. Exploration patterns were significantly correlated with brand recall ($p = 0.026$) and emotional response ($p = 0.033$), suggesting that the more participants explored an environment, the stronger their cognitive and emotional engagement with the brand. In conclusion, the analysis of behavioral metrics indicates that environments that offer a more immersive and interactive experience, like the car showroom, lead to longer interaction times, more extensive exploration, and more robust cognitive and emotional engagement. The design and interactivity of the environment play a crucial role in shaping consumer behavior and their connection with branded content in virtual reality.

Table 17. MANOVA and regression test.

Test	*p*-value
MANOVA (Exploration Patterns across environments)	0.018
Multiple Regression (Exploration Patterns vs. Brand Recall)	0.026
Multiple Regression (Exploration Patterns vs. Emotional Response)	0.033

5. Conclusion and future work

This study highlights the critical role of biomechanically informed design in enhancing consumer engagement within VR brand environments. By analyzing the relationship between physical interaction metrics (joint angles, muscle activation, interaction frequency) and cognitive-emotional outcomes (brand recall, immersion, emotional response), we found that VR environments that demand greater physical engagement can significantly enhance consumer experiences. The luxury car showroom, which elicited higher muscle activation and interaction frequency levels, demonstrated the most substantial effects on brand recall and immersion, reinforcing that VR environments that align with users' natural movements promote deeper engagement. The findings suggest that designing VR brand experiences with biomechanics in mind can lead to more intuitive and memorable interactions. Moreover, this research underscores the potential of VR as a medium for experiential marketing, where physical interaction becomes a key factor in influencing consumer behavior. By incorporating motion tracking and muscle activation data, brands can optimize VR environments to enhance comfort, minimize fatigue, and drive stronger consumer emotional connections.

Future research should continue to explore the intersection of biomechanics and consumer behavior in VR, particularly in more diverse and complex branded environments. Additionally, investigating the long-term impact of physically engaging VR experiences on brand loyalty and purchase behavior will be crucial for understanding the broader implications of this convergence. This study sets the foundation for a more comprehensive exploration of how physical engagement in virtual environments can redefine the digital marketing landscape and consumer-brand interaction in the coming years.

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