Neural Correlates of Social Cognition: Replicating the Heider and Simmel Paradigm in Virtual Reality

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July 2, 2025

Word count: 7398

Abstract

Understanding how visual representation shapes social cognition is essential to our understanding of social perception. This study used functional near-infrared spectroscopy (fNIRS) to examine neural responses to social animations in virtual reality (VR), comparing geometric shapes and humanoid avatars adapted from the classic Heider and Simmel (1944) paradigm. In a within-subjects lab design, participants ($N = 30$) viewed both animation types while fNIRS recorded activation in Theory of Mind (ToM) regions: medial Pre-Frontal Cortex, Anterior Temporal Lobe, Superior Temporal Sulcus, and Temporoparietal Junction. Participants also provided narrative interpretations and confidence ratings. Both conditions elicited significant ToM-related activations compared to baseline, with the strongest effects in the Superior Temporal Sulcus (geometric: $p < .001$, $d = 0.83$; humanoid: $p = .002$, $d = 0.77$). Humanoid avatars produced 50% more coded narrative content than geometric shapes ($p < .001$), yet no significant neural activation differences between animation types were found across any ToM region (all $p > .38$), nor in confidence ratings ($p = .79$). Thematic analysis revealed similar interpretive patterns across conditions, suggesting motion cues alone suffice to trigger social cognitive processes. These findings clarify the neural basis of social perception in VR and highlight the narrative-enhancing, but not functionally essential, role of anthropomorphic features.

Neural Correlates of Social Cognition: Replicating the Heider and Simmel Paradigm in Virtual Reality

Humans have evolved to be social creatures reliant on cooperation, communication, and collective action to survive (Henrich & Henrich, 2007). Unlike solitary creatures, human evolutionary success has been stimulated by our ability to cope with intricate social contexts, cohabit in cohesive units, and interpret others' behaviours and intentions. The social brain theory argues that increasingly complex societies drove brain development to accommodate *Theory of Mind* (ToM), pro-sociality, collective intentionality, and social reasoning (Tomasello et al., 2012; Gowlett, Gamble, & Dunbar, 2012). This reliance on collective living, as suggested by Tomasello's (2012) interdependence theory, developed neural systems that process social cues and reinforce social reasoning and "mind reading" in human behaviour. Thus, just as Dobzhansky (1973) argued, evolution provides the framework through which all biological phenomena must be understood including the social nature of humans, which is both the product of and driver for our sophisticated social and cognitive abilities.

Human's prosocial tendencies translate into a bias for detecting social events, and the ability of humans to detect social meaning in minimal or artificial stimuli is a key area of investigation. Classic and established paradigms such as Heider and Simmel's (1944) animation (Appendix A) demonstrate that individuals even tend to attribute agency and intention to simple geometric shapes. However, what remains under explored is how these attribution processes occur in immersive environments, where realism and embodiment, compounded by anthropomorphism, may amplify social engagement. This would allow us to investigate social attribution in a more controlled, ecologically valid and immersive way. To explore this, the current study combines immersive *Virtual Reality* (VR) and *functional Near-Infrared*

Spectroscopy (fNIRS) to examine how the form of an agent (humanoid vs. geometric) and the immersive quality of a task influence narrative interpretations, confidence ratings, and neural activation in core ToM regions.

Understanding these processes requires a critical assessment of the broader framework of social cognition and ToM, which provide the conceptual and neural foundation for interpreting social meaning from observed behaviour.

Social Cognition and Theory of Mind

Social cognition is an umbrella term for the mental processes that are involved in perceiving, interpreting, and acting upon the intentions and actions of other people (Frith, 2008). It underlies basic human capacities such as communication, empathy, cooperation, and social cohesion. Although social cognition only gained widespread academic attention during the cognitive revolution of the 1960s–70s (Ratner, 2020), it traces all the way back to Holt and Brown's (1933) work on imitation in humans, which anticipated future neurocognitive concepts only formulated decades later.

Modern more nuanced approaches, for instance, the Interactionist View (Vlasceanu et al., 2018), emphasize a wider conceptual definition. From the perspective of this view, social cognition has its roots in both innate mechanisms, like infant imitative behaviours, and life-long social learning based on culture. One of the central elements is ToM, which Premack and Woodruff (1978) characterise as having the capacity to attribute mental states (e.g., beliefs, desires, intentions) to others and to acknowledge that these may diverge from one's own. It is a crucial axis on which to coordinate social life and predict others' behaviour (Bohl &

Gangopadhyay, 2013). Understanding not only what mental states we attribute to others, but how certain we are of these attributions, is equally important.

Closely related to ToM is metacognition, our capacity to reflect on and evaluate our own thought processes. In social contexts, this includes metacognitive confidence, or how certain we are about the mental state attributions we make. While this confidence can inform adaptive social decisions, it does not always reflect accuracy. Neuroimaging evidence shows that higher metacognitive confidence is associated with stronger activation in self-referential and social processing networks, suggesting a link between reflective certainty and underlying neural engagement (Frith, 2012).

ToM has philosophical roots in Descartes' meditations (1641/1996) and Dennett's (1987) intentional stance, which describes the human tendency to assume that other agents act with purpose and intention. Developmental research shows that precursors to ToM, such as joint attention and imitation, emerge in infancy (Charman et al., 2000), with more advanced mental-state reasoning developing through social experiences and peer interactions, as emphasized by Piaget and Inhelder (1972). Although some non-human primates show rudimentary ToM-like behaviours like gaze-following and goal inference (Heyes, 1998), fully developed ToM is believed to be uniquely human (Brüne & Brüne-Cohrs, 2005).

Research shows animals do exhibit certain traits which hint towards ToM. For example, chimpanzees can understand goal-directed behaviour (Warneken & Tomasello, 2006), and corvids can deceive others about hidden food (Clayton et al., 2007). Yet most animals cannot tell when another agent believes something untrue (Krupenye & Call, 2019). Moreover, a recent study by Schafroth et al. (2021) supports this finding, showing that monkeys were able to track visual motion in a Heider and Simmel (1944) animation, yet were not able to interpret complex social behaviours.

The uniquely human tendency to see social behaviour in abstract shapes was first shown by Heider and Simmel (1944). In their classic study, people watched a silent animation of triangles and a circle moving around a rectangle and almost everyone created detailed social stories, describing the shapes as chasing, fighting, or protecting each other. Research by Weiß et al. (2025) suggests that social framing and attributed agency may be as critical as visual fidelity, as they found a wooden puppet with social framing could induce physiological social responses while a point cloud could not. These findings show that humans can activate ToM from movement alone, which is now seen as central to social perception.

Recent work has extended Heider and Simmel's (1944) work to immersive environments. For instance, Torabian & Grossman (2023) and Marañes et al. (2024) found that presenting Heider–Simmel animations in a VR environment, even as a simple 2D plane, not only increases intentionality ratings but enhances the emotional and social resonance of the stimuli. These studies suggest that the human capacity to attribute mental states, even to abstract, artificial agents, is robust and may be further amplified by more immersive, ecologically valid presentation formats.

Heider & Simmel Paradigm

The original 1944 Heider and Simmel experiment demonstrated that participants automatically attributed agency, animacy and meaning to abstract moving geometric shapes. This was an early and influential finding that revealed human's tendency to project intentionality onto abstract stimuli and integrate this attribution in social narratives, reflecting underlying ToM processes. In their experiment, they first showed participants a short animation which depicted two triangles and a circle moving around a rectangle, and then asked them to freely describe what they saw, paying attention to the shapes' actions and intentions. Interestingly, the vast majority of participants gave anthropomorphic meaning to the movements they saw. They attributed personalities, emotions and intentions to the shapes. They described scenarios like "chasing," "fighting," or a "bully" pursuing a "victim" (Torabian & Grossman, 2023). The general narrative among most participants was clear; one bigger triangle as aggressive or dominant and the smaller triangle and circle as fearful or seeking protection. Some even attributed gender to the shapes, reporting a love story or familial dynamics. This study proved that humans possess an automatic tendency to perceive social meaning from motion patterns alone, even in the complete absence of human-like features or explicit social cues.

Recently, Marañes et al. (2024) demonstrated that by simply changing the medium of presentation of the animation to a more immersive one in VR, led to increased intentionality attribution and enhanced social processing. Their findings could argue that elements such as depth perception and immersion amplify social attributions, as they are more effectively engaging perceptual, cognitive and neural mechanisms. This provides strong justification for further expanding the 3D dimension when presenting the Heider and Simmel animation, and in social cognition research as a whole.

However, while VR environments are able to enhance social attribution, an important question remains unresolved which is that of how does the level of anthropomorphism affect these processes. Some research suggests that anthropomorphic features are able to increase social engagement and empathy (Ma et al., 2025), while other studies indicate that abstract stimuli may provide purer measures of social attribution without confounding factors such as visual biases or uncanny valley effects (Mathur et al., 2019). These two differences become particularly relevant in immersive environments where enhanced realism might either amplify or interfere with social cognitive processes.

The current research thus embraces full VR immersion to explore its effects on social interpretation, ToM and neural processing. Additionally, this research addresses the unclear effect of anthropomorphisation of the characters, abstract vs. humanlike, on ToM and social cognition in immersive VR environments.

What is the Case for Virtual Reality?

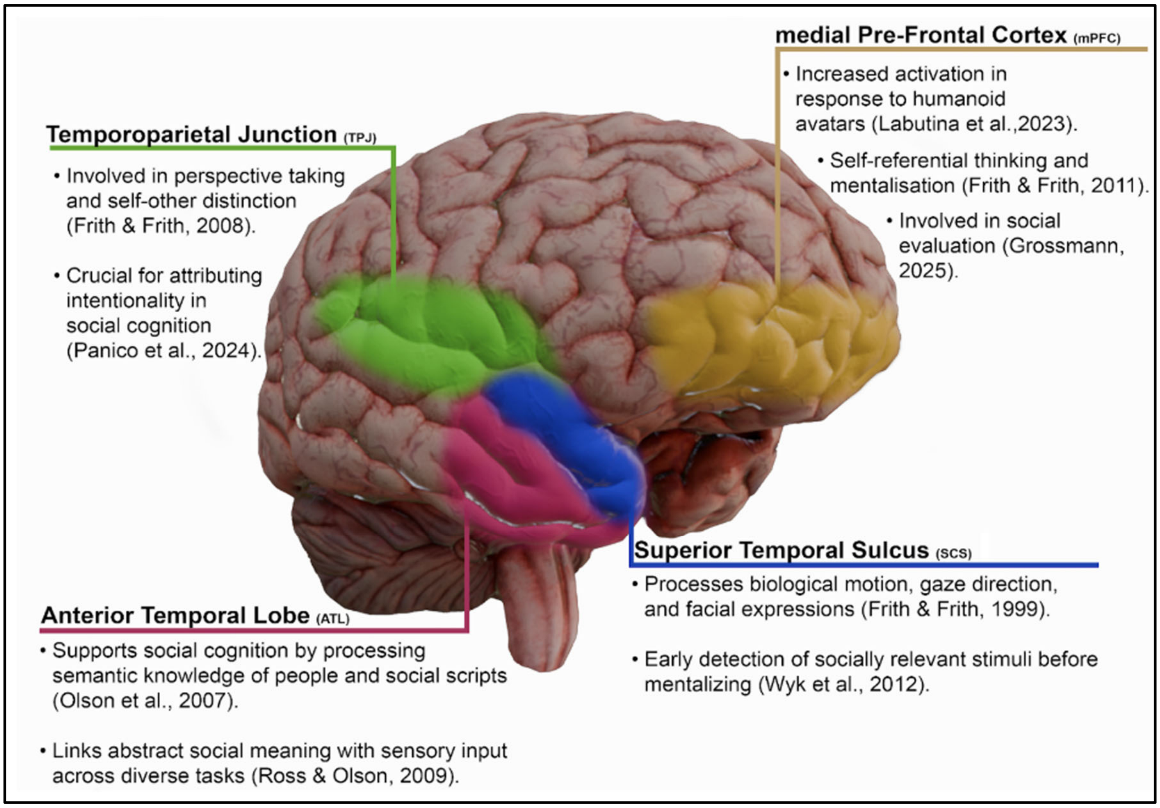
The case for virtual reality in further studying the neural mechanisms of social attribution and ToM is supported by the positive results of Marañes et al. (2024). They demonstrated that VR is an appropriate medium for the continuation of social cognition research, especially when considering the Heider and Simmel task. It is known that VR is a good vehicle for immersion enhancement since it provides the possibility for creating realistic and ecologically valid environments that can be well controlled (Kourtesis et al., 2020). In addition to improving immersion, theories such as the proteus effect (Yee et al., 2009; Ratan et al., 2024), argue that the avatar embodiment that VR can achieve also has an impact on self-perception and social interaction through theories such as the Proteus Effect where humans adapt their responses to the appearance of an avatar (Yee et al., 2009).

How Social Cognition shapes the brain

Social cognition and ToM rely on a vast network of areas in the brain. Of particular interest in this study are the medial prefrontal cortex (mPFC), temporoparietal junction (TPJ), anterior temporal lobe (ATL), and superior temporal sulcus (STS), which have been well-established to play dedicated roles in processing social interactions and attributing intentionality to agents (Figure 1). If the VR manipulation of immersion and appearance has an effect on ToM, we would expect to observe differences in the activation of the ToM network in the brain.

Figure 1

Regions of interest in the brain in relation to the ToM network



Note. Brain regions of interest (ROIs) implicated in social cognition are highlighted: the temporoparietal junction (TPJ), anterior temporal lobe (ATL), superior temporal sulcus (STS), and medial prefrontal cortex (mPFC), all on the right hemisphere.

Previous studies with the classic Heider-Simmel animation demonstrate that individuals automatically assign intentions, emotions, and social roles to moving geometric shapes, which were further heighted when these animations were presented in a VR setting. Therefore, by combining fNIRS brain imaging and VR technology, the present research examines the influence of immersion and stimulus type on neural processing and intentionality attribution to different agents.

Why Use fNIRS?

fNIRS is a proven neuroimaging method for measuring brain activity through changes in blood oxygenation, offering a non-invasive and motion-tolerant way to monitor cortical responses in real time. While fNIRS is limited to cortical regions and lacks the depth penetration of fMRI, it offers more spatial resolution than EEG and is particularly suited to VR research due to its high motion artifact tolerance. Unlike EEG, which measures electrical activity and is extremely vulnerable to movement-induced noise as well as electromagnetic interference, fNIRS measures blood oxygen level changes that are less likely to be corrupted by participant movement (Naseer & Hong, 2015).

This motion stability is crucial for VR studies where head movement, gestures, and natural interaction are essential for ecological validity. The ability to capture real-time neural activity in active, immersive conditions without the contamination of motion artifact makes fNIRS the optimal neuroimaging technique with which to investigate social cognition within naturalistic VR scenarios (Minagawa et al., 2018).

Research Questions and Hypotheses

Previous neuroimaging studies have compared human faces to computer-generated avatars, showing differential processing in regions like the amygdala, the fusiform gyrus and STS (Moser et al., 2006; Kegel et al., 2020). However direct comparisons of geometric versus humanoid forms within VR social cognitive tasks remain unexplored. Understanding the way in which the brain processes social interactions can inform the development of more effective VR-based treatments for social-cognitive deficit disorders. It can also advance our theoretical understanding of the influence of embodiment and immersion context on social interpretation and intentionality attribution. Therefore, this study investigates whether the visual form of agents, anthropomorphised versus abstract geometric, modulates activation in social brain regions during a 3D adaptation of the classic Heider and Simmel animation, presented in VR. Both versions depict the same social interaction scenario, allowing us to examine how enriched social cues in humanoid figures influence the attribution of agency and intentionality. In addition, the study examines whether viewing the animations in VR enhances social interpretation compared to traditional 2D presentations, by analyzing participants' neural responses alongside their narrative descriptions and confidence ratings.

Methods

Design

This study employed a within-subject, block design. It was conducted in a controlled laboratory at the University of Twente (Appendix A2) between April and May 2025. The independent variable was animation type (geometric shapes vs. humanoid avatars), and the dependent variables included fNIRS activation in predefined ToM ROIs, open-ended narrative responses, and confidence ratings on a 7-point likert scale. Participants viewed both animation types in counterbalanced order. The study received ethical approval from the BMS Ethics Committee (Application Number: 250081, February 2025) (Appendix G1) and followed best-practice guidelines for fNIRS reporting (Yücel et al., 2021), data preprocessing (Artinis guide, appendix H1) and analysis (MNE guide appendix H2 and H3).

Participants

Participants were recruited via convenience sampling and were entered into a gift card lottery. All gave written informed consent; procedures were approved by the institutional review board and designed to preserve anonymity.

Inclusion criteria were: (1) no self-reported neurological or psychiatric disorders, (2) no history of epilepsy or sensitivity to flashing lights, (3) normal or corrected-to-normal vision sufficient for VR perception, (4) no diagnoses of autism spectrum disorder, and (5) no diagnoses of other neurodevelopmental conditions such as cerebral palsy or tourettes.

Sample Size Calculation

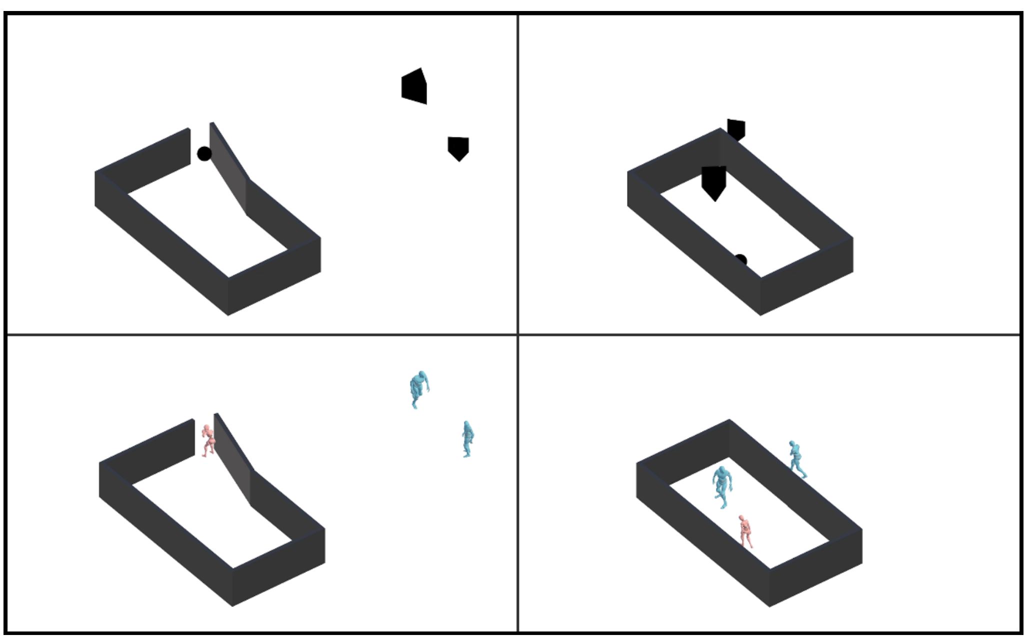
A G*Power analysis (Faul et al., 2009) ($f = 0.25$, $\alpha = .05$, $1–\beta = .90$, $r = .70$, 1 group and 2 measurements) indicated that 28 participants would suffice for a within-participant study. The medium effect size of $f = 0.25$ follows standard conventions and is considered a realistic and conservative estimate in exploratory neuroimaging research where prior data is lacking (Cohen, 1988; Lakens, 2013). The usage of high statistical power ($1–\beta = .90$) allows to prevent type II error and is especially relevant in fNIRS due to its issue of low signal-to-noise ratio (SNR) (Yücel et al., 2021), especially in VR environments. A two tailed alpha level of $\alpha = .05$ is a standard value which compromises between false-positive risk and discovery sensitivity. Finally, the correlation among repeated measures ($r = .70$) reflects a realistic test–retest reliability estimate for hemodynamic responses in cognitive tasks, consistent with psychometric benchmarks for behavioural measures in neuropsychological research (Nguyen et al., 2018).

Experimental Design

Participants completed the experiment in immersive VR, beginning with a Stroop task (Stroop, J. R., 1935a) which acted as a non-ToM-related cognitive control. They then viewed two animated scenarios: one featuring geometric shapes and one with humanoid avatars, both depicting the same social interaction based on the Heider and Simmel paradigm. The order of presentation was counterbalanced across participants. After each animation, participants provided open-ended verbal responses and rated their confidence on a 7-point Likert scale. These confidence ratings served as proxy measures of perceived metacognitive certainty. A second Stroop task followed the animations to assess potential cognitive fatigue. Finally, participants were given a set of questions comparing both animations, now having seen and reflected on both.

Figure 2

Stimuli Examples: Geometric and Humanoid Animation Conditions

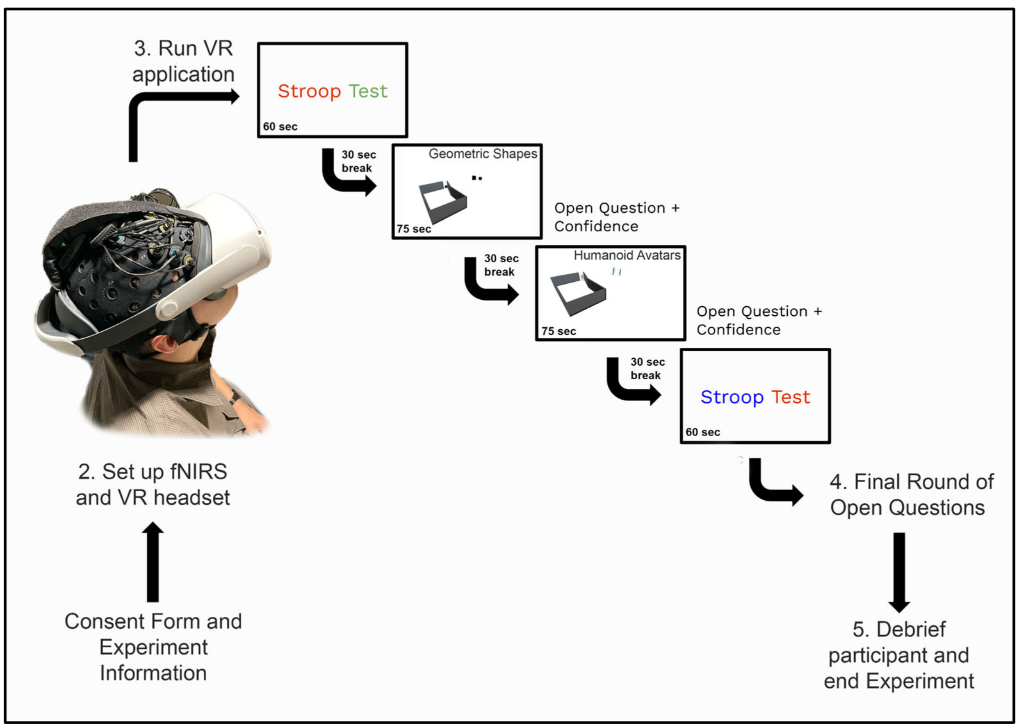


Note. Sample frames from geometric (top) and humanoid (bottom) animations.

The stimuli (Figure 2) were presented in 3D using a custom-built Unity VR environment (Unity 6.0.0), which also handled stimulus timing and internal logging. Characters were either modelled and animated in-house or sourced and rigged through Mixamo. Animations were implemented using Unity's Timeline and Animator systems to ensure consistent motion and timing across conditions. fNIRS data were recorded continuously throughout key phases, including animation viewing and Stroop tasks. The timeline and procedure are illustrated in Figure 3. Detailed descriptions of the stimuli, Unity implementation, and 3D setup are provided in Appendix A.

Figure 3

Experimental Procedure



Note. Participants completed a Stroop task, viewed two animated scenarios (geometric and humanoid), and answered open questions with confidence ratings. fNIRS was recorded during all key phases.

Session duration was determined using fNIRS logs, audio timestamps, and Unity application data. The average experiment session length was 17 minutes and 12 seconds (SD = 4.12), with setup time (from pre-questionnaire to session start) averaging 10 minutes and 55 seconds (SD = 4.97).

Participant instructions, training, and interactions

Participants received in-VR text instructions outlining each phase of the experiment, including the Stroop tasks, animation viewing, verbal interpretation, and confidence ratings (1–7 Likert scale). A researcher was present throughout to assist with clarification and provide support if needed. Instructions emphasized natural, spontaneous descriptions of action, interaction, and intent. A one-minute speaking guideline was suggested to help participants pace their verbal responses, though this was not enforced. Participants remained seated throughout the entire session. The fNIRS headset was worn continuously for the full duration of the experiment. The VR headset was also worn throughout, but participants were permitted to temporarily remove it during the question-answering phases if they experienced discomfort. Full participant instructions and setup procedures are provided in Appendix A.

fNIRS Data Acquisition device and parameters

The Brite MKIII CW system (21 channels; 760/850 nm; 25 Hz) was used with source-detector spacing at ~30 mm. The system uses <1 mW diodes and meets safety standards (Barolet et al., 2015). Individual hair characteristics were managed through optode adjustment; one participant withdrew due to poor signal quality. Setup procedures details are in Appendix A and B. Data acquisition and initial visualization were performed using OxySoft, Artinis' proprietary software.

All the procedures were in line with institutional ethical guidelines and manufacturer safety protocols (Appendix G2). Irradiance levels were not measured exactly, but the system is not invasive and non-ionizing and hence safe for subjects during the experiment.

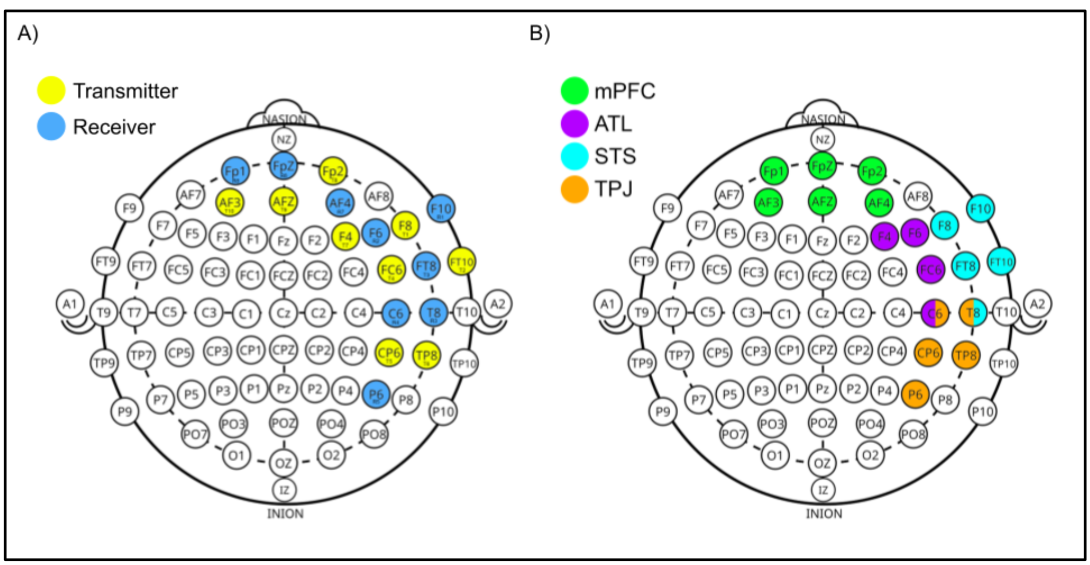
Optode Placement and Montage

Optode layout was guided by three primary sources: (1) the predefined optode channel configurations available in the Artinis OxySoft software, (2) the fNIRS Optodes' Location Decider (fOLD) toolbox (Morais et al., 2018), which supports region-specific placement using the 10–10 EEG coordinate system, and (3) relevant literature (Figure 1) on fNIRS targeting of brain areas involved in social cognition (Figure 4). These guided the selection and placement of transmitters and receivers to cover the aforementioned ROIs, resulting in each ROI being covered by four to six optodes (Figure 4).

Placement was aligned with the 10–10 EEG system and digitized within OxySoft, then validated for spatial consistency using MNE-Python (Figure 5).

Figure 4

fNIRS Optode Placement showing receivers, transmitters and ROIs



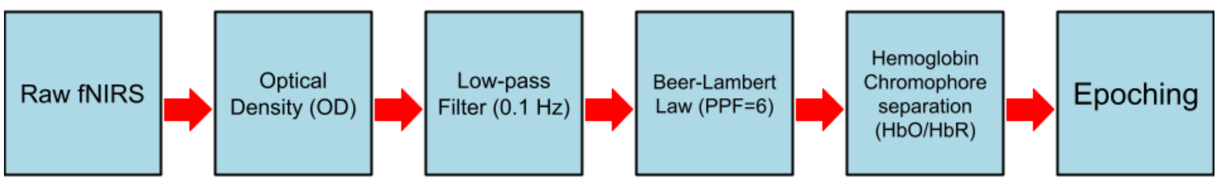
Note. Panel A shows transmitter (yellow) and receiver (blue) optode placement using the 10–10 EEG system. Panel B shows ROIs: mPFC (green), ATL (magenta), STS (cyan), and TPJ (orange), selected to target ToM regions in the right hemisphere.

fNIRS Data Processing

Preprocessing was done according to standard fNIRS procedures (Yücel et al., 2021) with MNE-Python and MNE-NIRS toolboxes. Raw intensity data were converted to optical density, filtered (0.01Hz), and converted to hemoglobin concentration changes (HbO/HbR) using the Modified Beer-Lambert Law (Baker et al., 2014). Channel quality estimation resulted in rejection of 39 channels in 23 participants (4.5% of all channels) due to low signal quality or optode coupling issues. Figure 5 shows the complete preprocessing pipeline. Sample timeline examples from the annotated fNIRS data are provided in Appendix C.

Figure 5

Data Preprocessing pipeline.

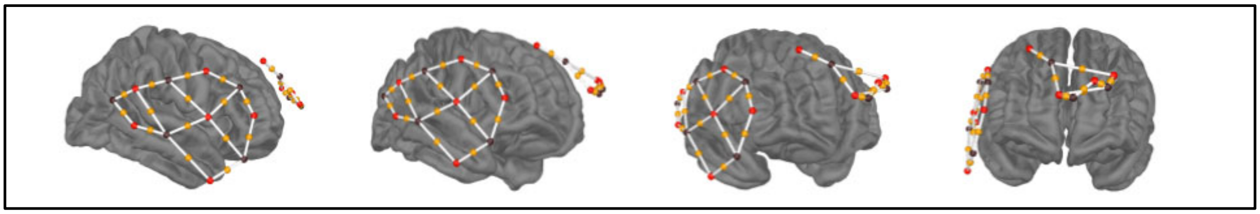


Note. OD = optical density; PPF = partial pathlength factor; HbO/HbR = oxygenated/deoxygenated hemoglobin. A 0.1 Hz low-pass filter was applied prior to chromophore separation and epoching.

Following quality assessment, optode positions were projected onto a standard cortical surface model to verify anatomical coverage of target brain regions. Figure 6 shows the four-view visualization of optode coverage across ToM networks. Channels were grouped into four anatomically-defined ROIs (see Figure 4 for abbreviations and locations): mPFC (5 channels), ATL (3 channels), STS (8 channels), and TPJ (6 channels), with responses averaged within each ROI separately for HbO and HbR chromophores to create robust regional estimates. Detailed channel assignments for each ROI are provided in Appendix Table A1.

Figure 6

fNIRS Optode Coverage projected onto Cortical Surface



Note. Optode pairs are projected onto a standard cortical surface to illustrate spatial coverage. Lines represent measurement channels between transmitter–receiver pairs targeting frontal and right temporal regions.

fNIRS Statistical Analysis

In order to compare differences in brain activation between conditions, subject-level data for the Geometric and Humanoid Animation trials were first extracted and aggregated at a group ROI level. They were contrasted against a baseline defined as the first 75 seconds of the experiment, during which participants received minimal instructions to avoid cognitively engaging them. Data were downsampled to 0.5 Hz, and mean signals for each brain region of interest, and for both chromophores (HbO and HbR) were calculated following standard Artinis and MNE preprocessing conventions.

Model-Based Approach. To fully address the research questions and account for participant variability, a Generalised Linear Model (GLM) was used to test key comparisons across all brain regions and chromophores. A GLM is a flexible statistical framework that models the relationship between one or more predictors and a continuous or categorical outcome variable. In this context, it allowed us to estimate brain activation differences between conditions while accounting for within-subject correlations. The model included animation type (geometric/humanoid) as a within-subjects factor and participant as a random effect to account for repeated measures. Multiple comparison correction was applied using the False Discovery

Rate (FDR) method of Benjamini-Hochberg (Benjamini & Hochberg, 1995) to control for Type I error across the statistical tests.

Audio Transcription and Verbal Data Analysis

To complement the neuroimaging data, qualitative analysis was conducted on participants' spoken interpretations of the animations. These verbal responses were collected immediately after each animation viewing during the in-VR interpretation phase (see Figure 2 for procedural timeline). This phase aimed to capture participants' spontaneous descriptions and interpretations of the social dynamics they perceived, offering insight into how different visual agent types may influence narrative construction and attribution processes.

Participant responses were transcribed with the AmberScript software and manually cleaned to remove filler speech and irrelevant segments, retaining only content related to the experimental prompts. In total 8 hours and 59 minutes of spoken language was transcribed. Cleaned transcripts were imported into ATLAS.ti for thematic analysis. Coding was conducted using an AI-assisted approach using the built-in OpenAI pipeline in ATLAS.ti, with oversight from the researcher to ensure accuracy and interpretive validity (Information about the LLM version can be found in the AI statement). The two prompts which were fed to the AI-assisted approach can be found in Appendix E5.

Two rounds of deductive thematic analysis were performed. In the first, transcripts were coded holistically to achieve a general overview of all participants' transcripts. These were used to create a general narrative understanding.

In the second round, codes were created explicitly around descriptions of the two animation types, and compared across the two conditions to identify condition-specific themes.

A list of key task-related terms was created to further clean the transcripts by removing filler speech and irrelevant content (full list available in Appendix E). After, word frequency analyses were generated for each condition and used to produce word clouds illustrating salient concepts (Appendix E).

This qualitative analysis complements the fNIRS findings by revealing participant's real-time interpretations of social meaning. Differences in thematic content across conditions align with neural activation patterns, while individual variation in responses offers insight into variability in brain data.

Results

Participant Characteristics

A sample of 30 participants was recruited for the study. An overview of the participant's demographic characteristics is presented in Table 1.

Table 1

Participant demographics

Variable	Value
Mean Age (SD)	22.6 (SD = 2.3)
Gender Distribution	16 males to 14 females
Number of Nationalities Represented	15
Participants with VR experience	93% of participants (n = 28)
Regular Gamers (≥ 1x/week)	37% of participants (n = 11)

Note. Participant demographic information including age, gender, nationality, and familiarity with VR and gaming.

Neural Differences Between Geometric vs Humanoid Agents (RQ1)

Direct Comparison: Humanoid vs Geometric Animations

Contrary to the initial hypothesis, GLM analysis revealed no statistically significant differences between the humanoid and geometric animations in any of the four ToM brain regions, nor across either chromophore (all p-values > .38; see Table 2). Effect sizes were consistently small (Cohen's d < 0.25), suggesting only minimal differences in activation strength. While the humanoid condition showed slightly higher average activation in mPFC HbO, this difference was not statistically meaningful. Overall, these results suggest that both animation types elicited comparable levels of activation within the social brain network.

Table 2

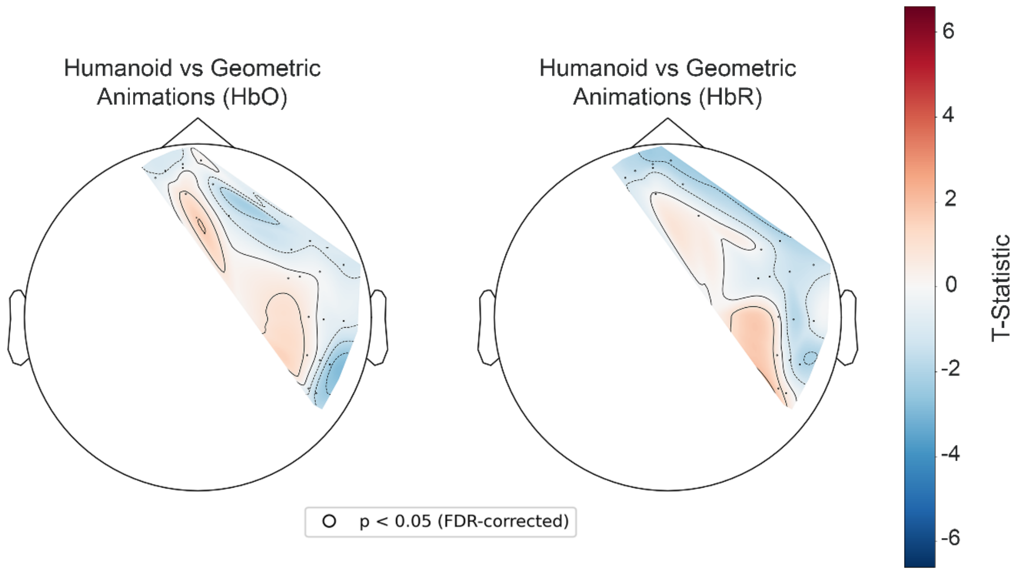
Direct Comparison of Humanoid vs Geometric Animations (FDR-Corrected)

ROI	Chromophore	Effect (μM)	T-value	Cohens-D	FDR corrected P-value
mPFC	HbO	0.04	0.33	0.07	.88
	HbR	-0.15	-1.25	-0.25	.38
ATL	HbO	-0.09	-0.75	-0.15	.65
	HbR	-0.06	-0.5	-0.10	.78
STS	HbO	-0.06	-0.5	-0.10	.76
	HbR	-0.09	-0.75	-0.15	.64
TPJ	HbO	-0.08	-0.67	-0.13	.68
	HbR	-0.01	-0.08	-0.02	.93

Note. Group-level GLM results comparing activation between humanoid and geometric animations across ROIs. No significant differences emerged. Effect sizes (Cohen's d) were calculated, indicating uniformly small effects. HbO = oxyhemoglobin; HbR = deoxyhemoglobin. All ROI abbreviations can be found in Figure 1.

Figure 7

fNIRS Cortical Projection of Contrast: Humanoid vs Geometric Animations



Note. T-statistics for the contrast between humanoid and geometric animations (HbO left, HbR right). Black dots show optode positions. White circles would indicate significant channels ($p < .05$, FDR-corrected), but none were found.

Animation Engagement: Both Conditions vs Baseline

Both animation types significantly activated core ToM regions, with the strongest effects in the STS (d = 0.83 geometric; 0.77 humanoid). Humanoid animations showed slightly larger effect sizes and lower p-values in some ROIs, suggesting a trend toward stronger engagement. Significant results are shown in Table 3; full results are available in Appendix D1.

Table 3

Animation Types vs Baseline (FDR-Corrected) GLM significant results

Animation Type	ROI	Chromophore	Effect (μM)	T-value	Cohens-D	FDR corrected P-value
Geometric	mPFC	HbO	0.61	2.90	0.57	.03
	ATL	HbO	0.70	3.33	0.65	.01
		HbR	-0.54	-2.57	-0.50	.05
	STS	HbO	0.89	4.24	0.83	<.001

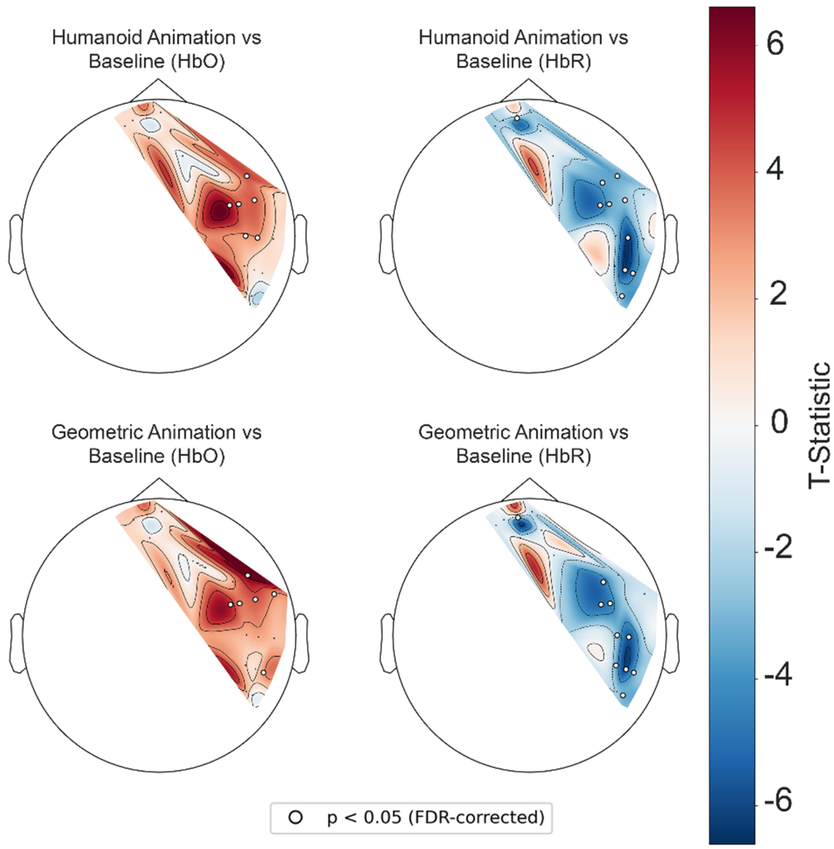
Humanoid	mPFC	HbO	0.65	3.1	0.61	.02
		HbR	-0.50	-2.38	-0.47	.07
	ATL	HbO	0.62	2.95	0.58	.03
		HbR	-0.60	-2.86	-0.56	.03
	STS	HbO	0.83	3.95	0.77	.002
		HbR	-0.55	-2.62	-0.51	.04

Note. Group-level GLM results comparing activation for humanoid and geometric animations to baseline across ROIs. Effect sizes (Cohen's d) are reported alongside FDR-corrected p-values. HbO = oxyhemoglobin; HbR = deoxyhemoglobin. Full table can be found in Appendix D1. All ROI abbreviations can be found in Figure 1.

The Superior Temporal Sulcus (STS) showed the strongest activation across both animation types (Cohen's d = 0.83 geometric; 0.77 humanoid, both $p < .01$). The mPFC and ATL were also significantly engaged, reflecting ToM network activation. In contrast, TPJ was not significantly activated, suggesting it was less responsive to the task demands.

Figure 8

Cortical Projection of fNIRS Activation: Animation vs. Baseline



Note. T-statistics for contrasts between humanoid and geometric animations versus baseline, shown separately for HbO (left column) and HbR (right column). Black dots represent optode positions. White circles indicate statistically significant channels ($p < .05$, FDR-corrected).

Stroop Task Effects: Cognitive Load Validation

To validate our experimental paradigm, we examined activation patterns during the pre- and post-animation Stroop tasks, which served as non-social cognitive control conditions.

Table 4

Pre and Post Stroop vs Baseline Comparison (FDR-Corrected) GLM significant results

Stroop condition	ROI	Chromophore	Effect (µM)	T-value	Cohens-D	FDR corrected P-value
Pre	mPFC	HbO	0.46	2.42	0.47	.03

	ATL	HbO	0.60	3.16	0.62	.01
		HbR	-0.47	-2.47	-0.48	.05
	STS	HbO	0.86	4.53	0.89	<.001
Post	ATL	HbR	-0.55	-2.89	-0.57	.03
	STS	HbO	0.71	3.74	0.73	.003
		HbR	-0.50	-2.63	-0.52	.04

Note. GLM results showing significant activation for pre- and post-Stroop conditions compared to baseline. Cohen's d and FDR-corrected p-values are reported. HbO = oxyhemoglobin; HbR = deoxyhemoglobin. All ROI abbreviations can be found in Figure 1.

The Stroop tasks successfully activated regions within our measurement array, with pre-Stroop showing stronger activation in mPFC, ATL, and STS. The reduced post-Stroop activation may reflect adaptation effects following animation viewing.

Table 5

Post vs Pre Stroop Comparison (FDR-Corrected) GLM significant results

ROI	Chromophore	Effect (μM)	T-value	Cohens-D	FDR corrected P-value
mPFC	HbO	-0.47	-4.70	-0.92	<.001
ATL	HbO	-0.30	-3.01	-0.59	.01

Note. GLM results comparing post- to pre-Stroop activation. Negative values reflect reduced activation. Cohen's d and FDR-corrected p-values are reported. HbO = oxyhemoglobin; HbR = deoxyhemoglobin. All ROI abbreviations can be found in Figure 1.

A comparison between pre- and post-Stroop tasks revealed statistically significant reductions in activation in mPFC and ATL (HbO), with large effect sizes (Cohen's d = –0.92 and –0.59 respectively; see Table 5). This decline may reflect the onset of executive fatigue or neural adaptation following the animation phase. Although the STS remained active post-Stroop, mPFC activity dropped to near-baseline levels (mean HbO = 0.01 μM), suggesting a region-specific decline in sustained cognitive control. The full table of results can be found in Appendix D5.

VR Enhancement Effects on social cognition evaluations (RQ2)

Neural Basis from RQ1

Both animation types significantly activated core social cognition regions compared to baseline, confirming that participants were engaged in social cognitive processing during the task. However, direct comparisons between geometric and humanoid animations revealed no significant differences (all $p > .38$), indicating equivalent neural engagement across conditions.

Thematic Comparison

The initial coding process generated 53 codes across five thematic groups (Appendix E6). When viewing the humanoid animations, many participants spontaneously used language related to power dynamics (e.g., "power complex," "control"), social relationships ("mother," "boyfriend," "child"), and gendered framing (e.g., "the woman was with a guy"). These interpretations were quicker and more consistent across participants, suggesting that human-like features help trigger familiar social ideas.

While both animation types included references to conflict and agency (e.g., "angry triangle," "chasing"), the geometric interpretations were generally more abstract and showed greater variability across individuals. Although participants frequently attributed intentionality and emotion to the geometric agents, the absence of human-like features may have led to more diverse or less role-specific narratives.

Participants' subjective preferences varied. Several indicated that they found the humanoid animations more expressive, particularly in terms of body language and facial cues (e.g., "the woman was crouching," "hands on her face"), which helped them interpret emotions and intentions. Others preferred the geometric animations, citing their simplicity and lower cognitive demand as advantages. These differing preferences suggest that while anthropomorphic agents may enrich narrative depth, minimal abstract forms may appeal to participants who prefer reduced visual complexity or interpretive ambiguity.

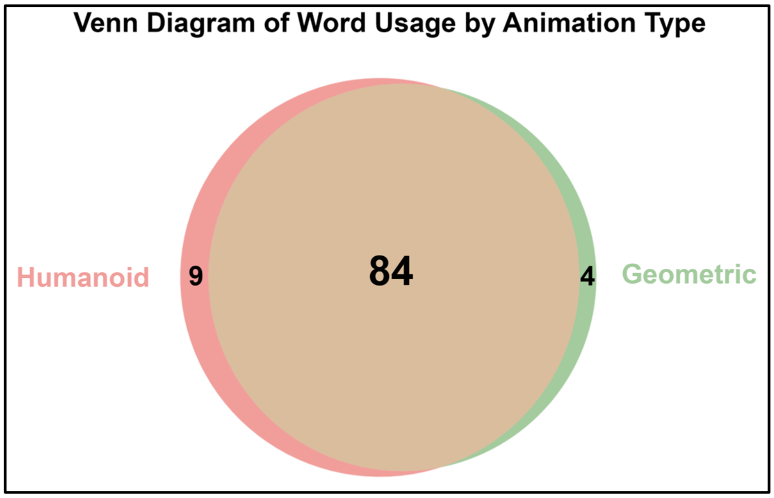
Representative quotes describing these differences and preferences are found in Appendix E.

Qualitative Word Use and Narrative Content

Word frequency analysis revealed extensive lexical similarity between conditions with 84 similar words and only 14 unique condition specific words (85.7% similarity) (Figure 8). A paired t-test on total word counts showed no significant difference between conditions ($t = 0.0008$, $p = .999$), indicating that participants spoke equally across both. This supports that differences in social codes reflect content, not speech quantity. However, significant differences were observed in overall word production, with humanoid animations generating 743 coded references compared to 493 for the geometric animations ($p < .001$), representing a 50% higher vocabulary density.

Figure 9

Venn Diagram of Unique and Shared Word Usage by Animation Type



Note. This figure illustrates the overlap in vocabulary used by participants when describing humanoid and geometric animations. A total of 80 words were common to both conditions, while 9 were unique to the humanoid condition and 4 were unique to the geometric condition, suggesting a high degree of lexical similarity despite the differing visual stimuli.

Statistical analysis of shared vocabulary revealed systematic preferences (t = -6.46, p <.001, *Cohen's d* = -0.71), with strongest humanoid-preferred terms including "abuse" (5:1 ratio) and "man" (19:4 ratio), while geometric-preferred terms included "bullying," "daughter," and "flee" (all 2:1 ratios). This pattern suggests humanoid animations elicited more intense usage of emotion and relationship terms. Effect size analysis (*Cohen's d* = -0.71) indicated a large practical difference in vocabulary richness, with humanoid animations generating 1.5× more coded content across both exclusive vocabulary (10 vs. 4 unique terms) and shared vocabulary preferences.

Confidence Ratings

Confidence scores did not significantly differ (p = .79) across conditions. The average change in confidence between rating the two different animations was ΔM = 0.07 (SD = 1.17), with minimal differences based on animation order (–0.07 if humanoid was shown first, 0.20 if geometric was first). Distribution plots are available in Appendix D.

Discussion

This research aimed at investigating the neural correlates of social cognition. In the first part, this study tested whether anthropomorphised versions of abstract geometric shapes from the classic Heider and Simmel animation activate social brain regions more strongly than the original geometric shapes. This was done during observation of social interactions in a 3D-VR environment. Additionally, this study attempted to assess if presenting the Heider and Simmel animation in a 3D-VR format, enhanced intentionality attribution, in comparison to the traditional 2D presentations of the Heider-Simmel animation.

Summary of main results. Neural activation was observed in the mPFC, ATL, and STS for both animation types in comparison to baseline, with STS showing the strongest overall response, especially during geometric animations. While both conditions showed similar patterns of activation compared to baseline, the humanoid condition produced a higher amount of statistically significant results across ROIs. However, direct comparisons between humanoid and geometric conditions revealed no significant differences across any ToM region or chromophore, indicating broadly similar levels of neural engagement.

Qualitative and cognitive performance data aligned closely with these neural findings. Increased error rates during the second Stroop task, together with decreased mPFC activation patterns (Appendix D3), point to emerging signs of executive fatigue, which is supported by prior research linking sustained cognitive load to diminished prefrontal engagement (Li et al., 2009). Although the total task duration was relatively short (~17 minutes), the combination of immersive VR and cognitively demanding content may have accelerated the onset of mental fatigue. This interpretation aligns with Zhang et al. (2022), who demonstrated that VR experiences lead to greater reductions in brain network efficiency and connectivity compared to traditional 2D displays. These findings suggest that neural efficiency can decline even during brief but intense cognitive experiences, particularly in immersive environments like VR.

Despite the different visual characteristics of the animations, participants demonstrated highly similar patterns of social attribution across conditions. Lexical analysis revealed substantial overlap in word usage, yet humanoid animations elicited significantly more total coded terms, and a greater frequency of socially loaded and relevant terms. However, this increase reflected narrative richness rather than a shift in social interpretation.

Confidence ratings showed no significant differences between conditions or presentation order, suggesting that the increased narrative elaboration observed for humanoid agents was not accompanied by increased metacognitive certainty. Together, these converging lines of evidence: neural, verbal, and self-reported, indicate that both animation types successfully trigger core social cognitive mechanisms. While humanoid agents may enrich narrative depth, geometric agents appear equally capable of eliciting fundamental social responses. These findings demonstrate that immersive 3D-VR environments preserve classical patterns of social attribution, replicating effects observed in the 2D literature while offering a viable medium for future social cognition research.

Does anthropomorphizing geometric shapes enhance social brain activation during VR-based observation of social interactions?

Research Gap and Core Findings. The findings of this study address a critical gap in VR social cognition research, as previous studies demonstrated differential neural processing between human and computer-generated faces (Moser et al., 2006; Kegel et al., 2020), yet direct comparisons of geometric versus humanoid forms during VR social tasks remained unexplored. Our findings reveal an important dissociation: while humanoid and geometric animations activated social brain regions equivalently, humanoid forms generated 50% more coded narrative content. This suggests that core neural mechanisms for social perception operate on motion patterns alone, while anthropomorphic features selectively enhance higher-order narrative elaboration without requiring additional neural resources from fundamental ToM networks. This dissociation offers new insights into the hierarchical nature of social cognition.

Motion Drives Social Attribution.These findings align with Heider & Simmel's (1944) original experiment, which demonstrated that motion patterns, rather than visual form, trigger social engagement. The current results provide additional evidence that motion patterns themselves, not specific anthropomorphic visual features, drive the fundamental neural mechanisms underlying social attribution in immersive environments. This supports Dennett's (1987) concept of the intentional stance, which posits that humans automatically adopt a framework for interpreting behaviour in terms of beliefs, desires, and intentions, even when applied to minimal abstract agents. From an evolutionary perspective, motion primacy is adaptive. Early humans had to quickly detect and interpret movement to spot threats, allies, or social cues, well before processing detailed visuals (Troje, 2008). Our findings suggest these ancient motion-detection systems still play a key role, even in modern immersive settings.

Differential Processing Levels. The qualitative narrative data revealed richer narratives told about the anthropomorphised humanoid avatars. This suggests that while core social brain networks respond in similar ways to movement-based social events, higher-order interpretive processes may be influenced by visual anthropomorphic features. These findings are supported by Torabian and Grossman (2023), who demonstrated that motion perception alone is sufficient to drive ToM, with visual anthropomorphic features serving to elaborate rather than initiate social cognitive processing. This highlights that anthropomorphic features enhance narrative depth without requiring additional neural resources from fundamental social cognition networks.

These findings enhance our understanding of how the human brain processes social information in naturalistic contexts, revealing that while visual anthropomorphic cues may enrich narrative interpretation, the fundamental ToM network recruitment is primarily driven by motion patterns rather than visual form in immersive presentation formats.

Evolutionary and Clinical Implications. From an evolutionary perspective, humans developed sophisticated neural systems to process social cues with remarkably low activation thresholds (Tomasello et al., 2012). Our findings are consistent with the literature (Jicol et al., 2023; Weiß et al. 2025), which demonstrated that perceived agency, not visual realism, is the primary driver of presence, a core proxy for social and emotional engagement in immersive environments. These findings provide crucial neural justification for VR therapy research using minimalist stimuli, particularly beneficial for individuals with social phobias or conditions where reduced cognitive load may be advantageous, such as Autism Spectrum Disorder. Therefore, abstract agents are sufficient for triggering core social brain regions and offer a cost-effective approach for VR social interventions, allowing more flexibility to create complex behavioural dynamics while sacrificing visual fidelity.

Does presenting the Heider and Simmel animation in 3D enhance social attribution, intentionality, animacy, and engagement?

This study hypothesized that presenting the Heider and Simmel animation in 3D-VR would enhance social attribution, intentionality judgments, and neural engagement compared to traditional 2D formats. The results showed that the VR animations successfully activated the ToM network, consistent with prior neuroimaging studies using 2D stimuli (Schurz et al., 2014). However, there was no evidence of significantly stronger neural activation in the VR condition. Qualitative analyses revealed that participants generated rich and intentional narratives, often matching or slightly exceeding the narrative quality found in 2D studies. These findings support the ecological validity of VR as a tool for studying social cognition, aligning with prior work by Marañes et al. (2024) and Kourtesis et al. (2020), which suggests that VR can enhance emotional engagement and perceived realism in experimental settings.

Limitations. Several limitations of the current study should be acknowledged. The first category of limitations is those of ***technical and methodological*** nature. While fNIRS technology is highly advantageous for VR social cognition studies due to low invasiveness, robustness and good spatial specificity, it is only able to indirectly measure cortical activity using a slow blood flow signal. While we targeted highly relevant social cognition and ToM-related ROIs were targeted, fNIRS is unable to measure deeper brain structures such as the amygdala, which is highly relevant for social interpretation and emotion formation.

The second category revolves around ***experimental design and stimulus limitations***. While our introduction emphasized humans as intrinsically social creatures reliant on cooperation, our study used passive observation rather than interactive social scenarios that would better leverage VR's collaborative potential. Assessing only the Heider-Simmel animation limits generalizability across different social situations. Furthermore, the decision to omit the original 2D animation from the experiment limited direct comparison between 2D and 3D conditions.

Another set of limitations relates to ***participants and sample characteristics,*** as the sample was homogeneous, consisting mainly of young, VR-familiar university students which limits the generalization of the results to the wider population

Finally, in terms of ***statistical analysis***, not having connectivity analysis limits our ability to examine functional networks and inter-regional communication patterns, such as the synchronization or directional influence between brain regions. This type of analysis is crucial for understanding how different areas of the brain interact during social cognitive processing, and its absence restricts deeper insight into the neural mechanisms underlying the observed behavioural effects.

Further Improvements & Future Directions. Future research should address various issues. On the ***technical side***, improvements should be aimed at creating a more holistic and multimodal understanding of social cognition. This would include collecting data from a wider range of physiological points, such as heart rate, eye tracking, and galvanic skin response, in addition to the already collected brain activity, narrative responses, and confidence ratings. Moreover, combining fNIRS with other brain imaging methods like EEG or fMRI could provide better temporal and spatial sensitivity. Moreover it will give access to deeper brain areas important for social understanding. For example understanding the relation between ToM regions and deep cortical areas such as the visual cortex, which could be involved in the visual aspects of ToM detection, as inferred by Torabian and Grossman’s (2023) findings, or the amygdala which is highly involved in emotion formation. This would achieve a more holistic and informed picture of how people process social information. Additionally, processing and analysing this wider dataset with advanced techniques such as machine learning, may reveal patterns that standard statistical models cannot.

The biggest methodological improvement would be directly comparing 2D and 3D conditions in the same participants to clearly show the specific benefits of VR. To increase ecological validity, and participant engagement, future research should also move away from passive viewing tasks, and towards interactive scenarios in which participants are actively making choices in VR. This approach would better reflect how humans naturally interact socially and make better use of VR's potential for creating dynamic social environments.

Testing clinical populations offers the most promising application of the approach presented here, especially people with autism, social anxiety, or other social difficulties. Including participants of different ages would show how VR driven social processing develops over time, while creating VR-based therapy programs could improve social skills training. Although this research further highlighted that low-fidelity animations are sufficient for social cognition, more research should go into how hyper realistic avatars and more nuanced social scenarios would make findings more applicable to real-world social situations.

These improvements would help establish VR as a valuable tool for both understanding and treating social cognition challenges, moving the field toward more practical and clinically relevant applications that could benefit diverse populations with varying social needs.

Conclusion

This research demonstrates that anthropomorphised avatars and abstract geometric shapes in VR elicit remarkably similar neural activation in social cognition and ToM brain regions, while humanoid characters generate significantly richer narrative content. These findings support a two-level model of social cognition in immersive environments: (1) fundamental neural activation driven by motion patterns regardless of visual form, and (2) narrative enrichment selectively enhanced by anthropomorphic features. This dissociation reveals that core brain regions involved in social cognition respond primarily to movement dynamics suggesting interactions or relationships (e.g., chasing, helping, avoiding), while higher-order narrative elaboration benefits from human-like visual features. In other words, it's not the complexity or realism of the visuals that drives neural social processing, but whether the stimuli convey social meaning through their dynamics. While the findings validate VR as an effective medium for social cognition research, they do not confirm that VR is inherently superior to other visualization formats.

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Yee, N., Bailenson, J. N., & Ducheneaut, N. (2009). The Proteus effect. *Communication Research, 36*(2), 285–312. https://doi.org/10.1177/0093650208330254

Yücel, M. A., Lühmann, A. V., Scholkmann, F., Gervain, J., Dan, I., Ayaz, H., Boas, D., Cooper, R. J., Culver, J., Elwell, C. E., Eggebrecht, A., Franceschini, M. A., Grova, C., Homae, F., Lesage, F., Obrig, H., Tachtsidis, I., Tak, S., Tong, Y., ... Wolf, M. (2021). Best practices for fNIRS publications. *Neurophotonics, 8*(01). https://doi.org/10.1117/1.nph.8.1.012101

AI statement

During the preparation of this work the author used the following AI tools for different phases of the thesis process. After using these tools, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.

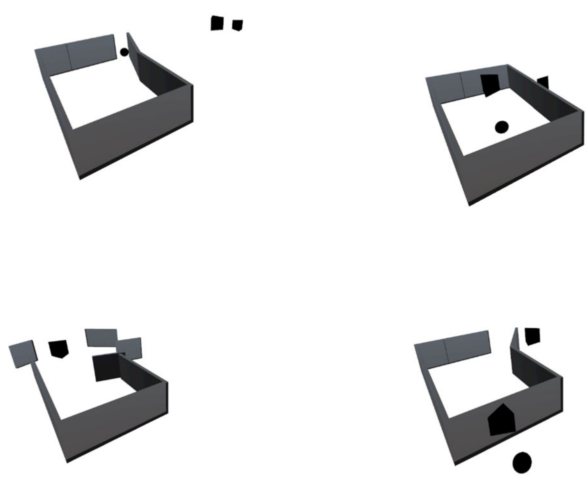
- ChatGPT-4o (OpenAI): Used for brainstorming, ideation, and decluttering complex ideas. It was also used in voice-based interaction as a conversational companion during the early writing stages.
- ChatGPT-4o, Grammarly AI, Claude Sonnet 3.7 & 4.0 (Anthropic): Employed for writing assistance, including editing, improving clarity, and formatting according to APA 7 guidelines.
- Claude Sonnet 3.7 & 4.0: Used to support programming tasks in Unity and for assistance with data analysis workflows (including Python-based fNIRS processing).
- Google Gemini 2.5 and NotebookLM: Used for literature review, synthesis of academic texts, and background research across topics in neuroscience, social cognition, and immersive technology.
- ATLAS.ti AI Coding (Beta): Used for initial rounds of qualitative data analysis and code generation. This feature is powered by OpenAI's GPT models; however, the specific version is not disclosed by the software. All AI-generated codes were manually reviewed, refined, and contextualized by the author.

All outputs from these tools were critically reviewed and revised by the author to ensure academic rigor and alignment with the project’s methodological framework.

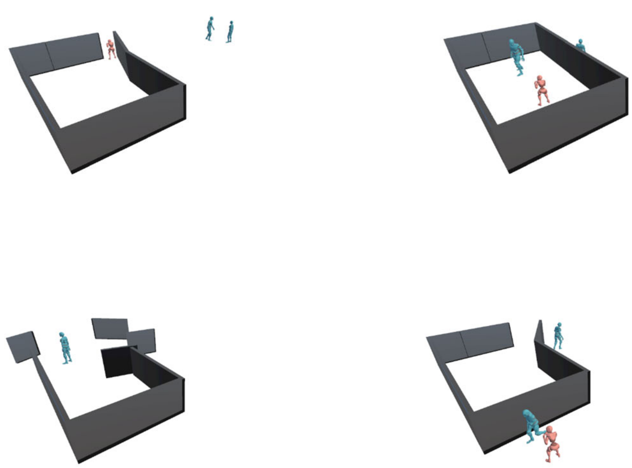
Appendix A: Stimuli and Experimental Materials

A1. Stimuli examples

Geometric shapes animation



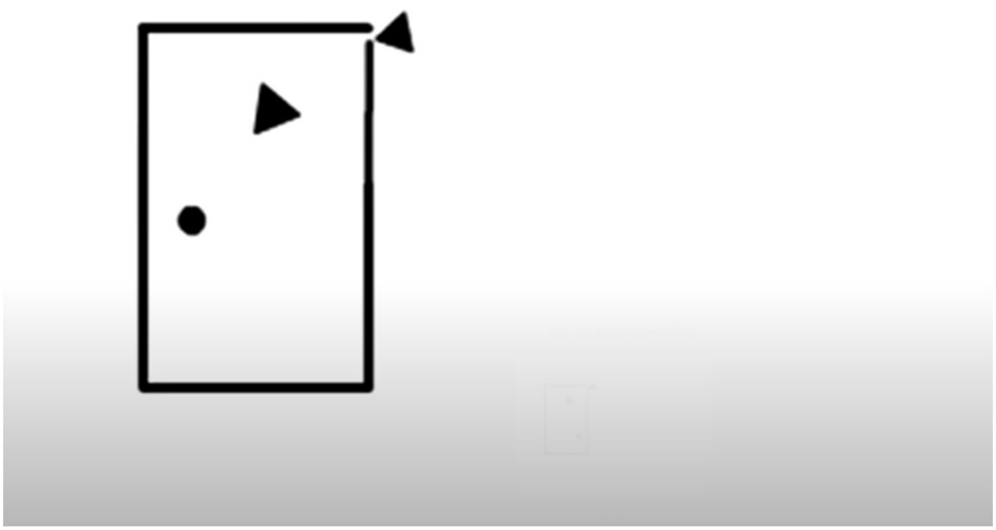
Humanoid avatars animation



A2. 3D model from Unity VR and fNIRS environment setup (special permission given by participant)

https://poly.cam/capture/C2312991-DDF4-453E-AED9-CE8F83A8CF0A

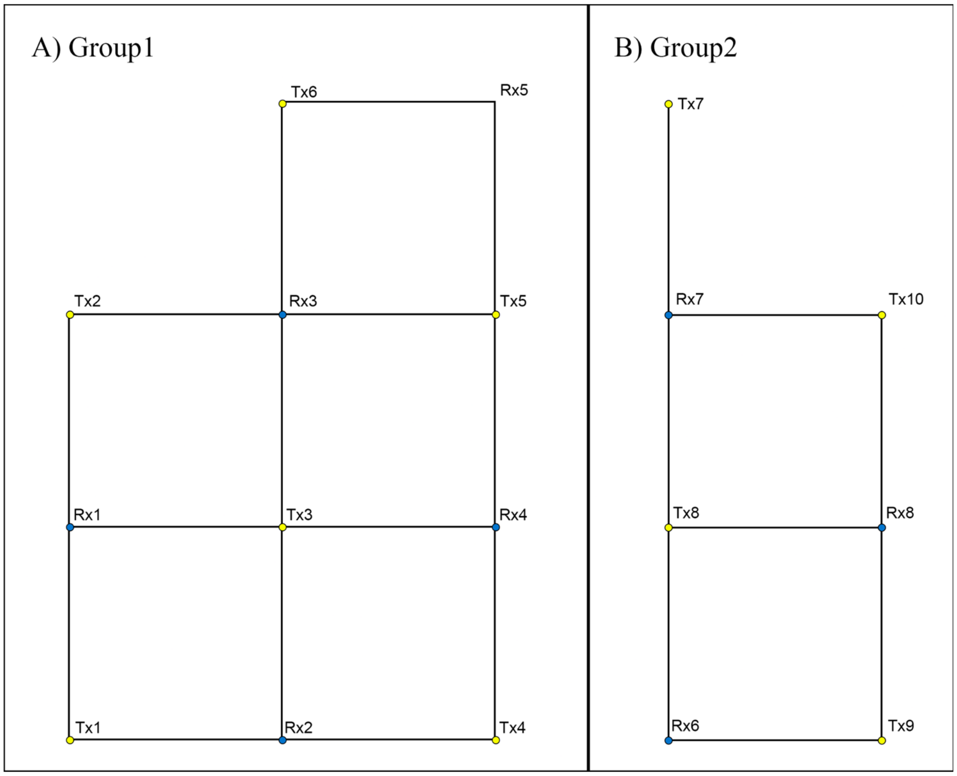
A3. Original Heider Simmel Image and youtube link



https://www.youtube.com/watch?v=sx7lBzHH7c8

Appendix B: Optode and fNIRS Technical Details

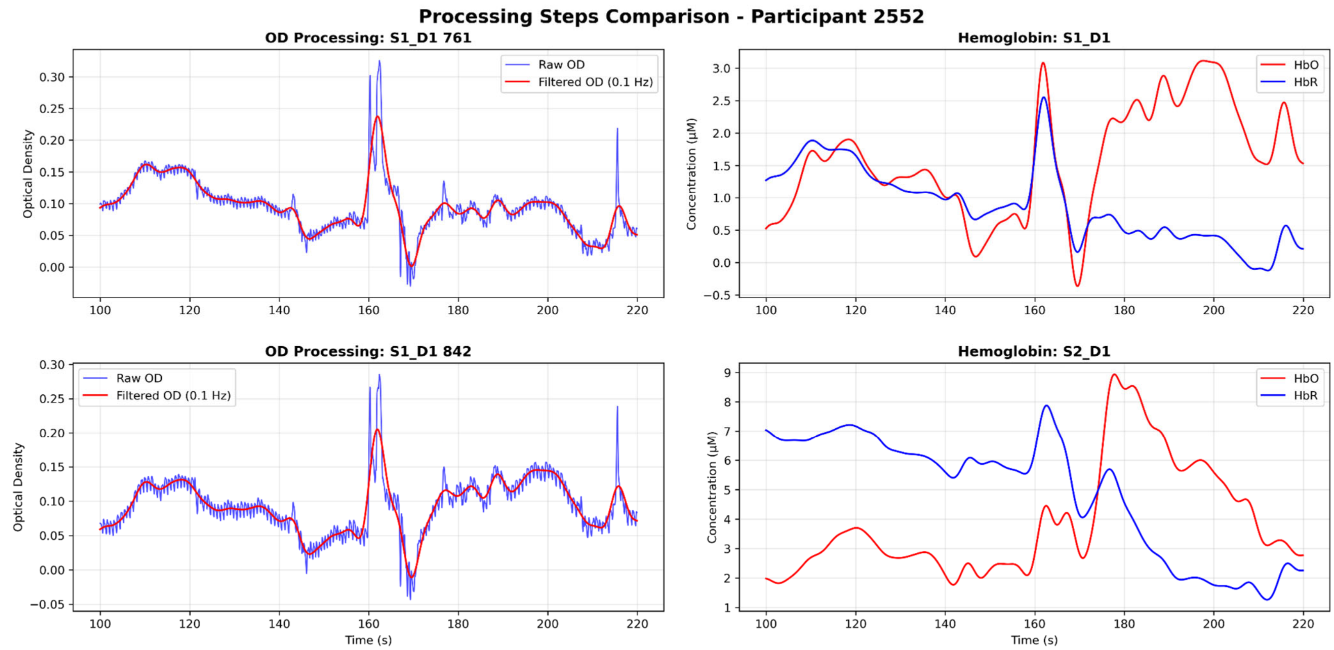
B1. fNIRS channel groups as seen on OxySoft



B2. fNIRS cap as seen on participant

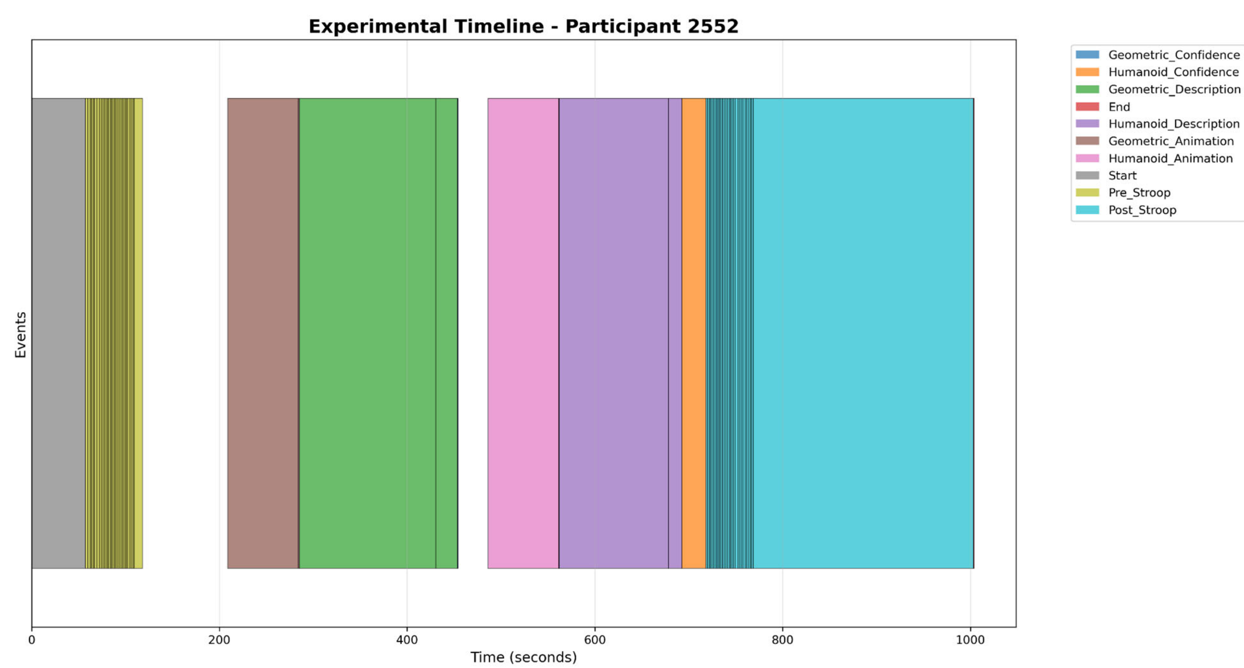
Appendix C: fNIRS Data Preprocessing and Quality Checks

C1. Sample plots of raw vs. filtered signals (HbO/HbR)

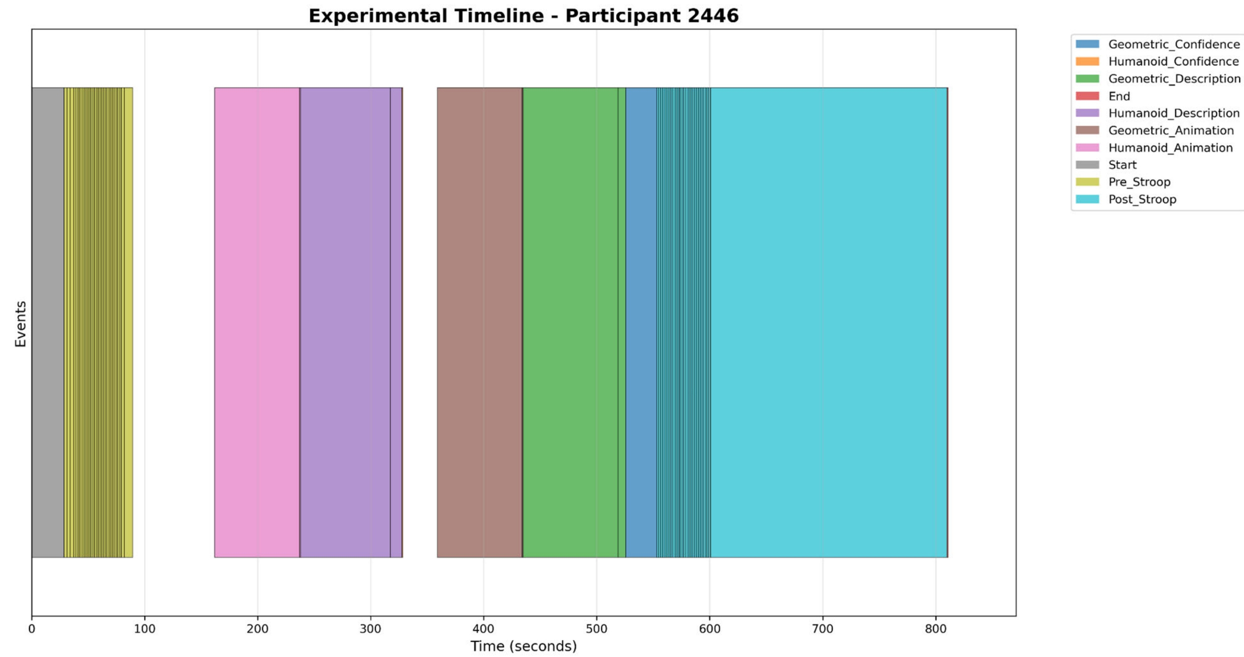


C2. Time-annotated fNIRS data structure examples

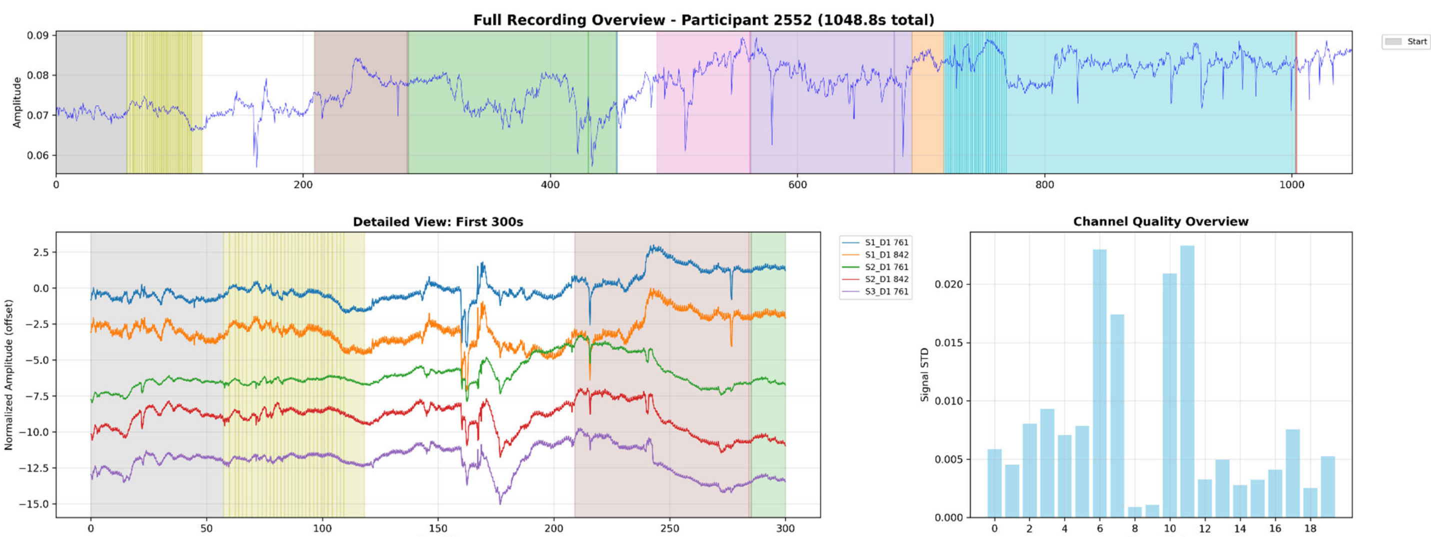
Humanoid first



Geometric first



Full recording with superimposed signal



Appendix D: Additional Statistical Analysis Outputs

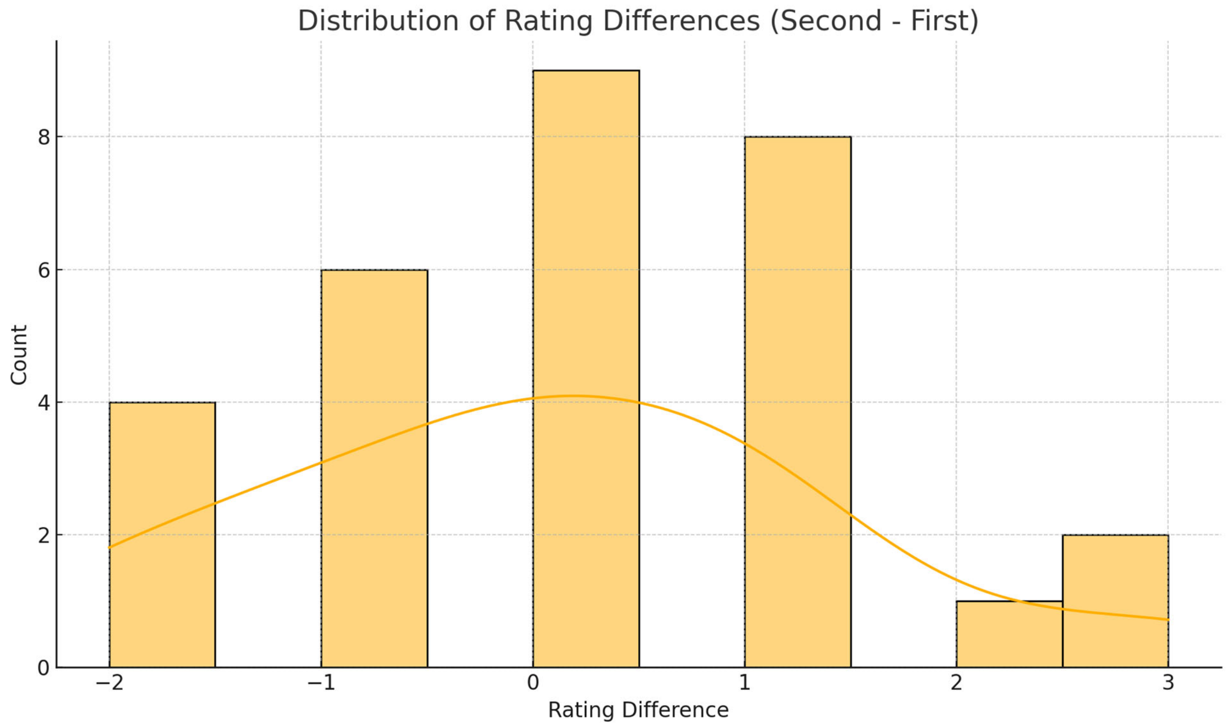
D1. Full output tables for all Animation Types vs Baseline (FDR-Corrected)

Animation Type	ROI	Chromophore	Effect (µM)	T-value	Cohens-D	FDR corrected P-value

Geometric	mPFC	HbO	0.61	2.9	0.57	.03
		HbR	-0.34	-1.62	-0.32	.26
	ATL	HbO	0.70	3.33	0.65	.01
		HbR	-0.54	-2.57	-0.50	.05
	STS	HbO	0.89	4.24	0.83	<.001
		HbR	-0.45	-2.14	-0.42	.10
	TPJ	HbO	0.29	-1.38	-0.27	.35
		HbR	-0.40	-1.9	-0.37	.18
Humanoid	mPFC	HbO	0.65	3.1	0.61	.02
		HbR	-0.50	-2.38	-0.47	.07
	ATL	HbO	0.62	2.95	0.58	.03
		HbR	-0.60	-2.86	-0.56	.03
	STS	HbO	0.83	3.95	0.77	.002
		HbR	-0.55	-2.62	-0.51	.04
	TPJ	HbO	0.21	1.0	0.20	.60
		HbR	-0.41	-1.95	-0.38	.16

Note. Group-level GLM results comparing activation for humanoid and geometric animations to baseline across ROIs. Effect sizes (Cohen's d) are reported alongside FDR-corrected p-values. HbO = oxyhemoglobin; HbR = deoxyhemoglobin.

D2. Confidence rating differences distribution plot



D3. Reaction time and error rate data for pre and post animation viewing Stroop tasks

Condition	Mean Congruent RT	Mean Incongruent RT	Average Error rate
Pre-stroop	0.68	0.76	5.49
Post-stroop	0.69	0.74	10.09

D4. Pre and Post Stroop vs Baseline Comparison (FDR-Corrected) GLM results

Stroop condition	ROI	Chromophore	Effect (µM)	T-value	Cohens-D	FDR corrected P-value
Pre	mPFC	HbO	0.46	2.42	0.47	.03
		HbR	-0.22	-1.16	-0.23	.26
	ATL	HbO	0.60	3.16	0.62	.01
		HbR	-0.47	-2.47	-0.48	.05
	STS	HbO	0.86	4.53	0.89	<.001

		HbR	-0.41	-2.16	-0.42	.10
	TPJ	HbO	0.24	1.26	0.25	.35
		HbR	-0.28	-1.47	-0.29	.18
Post	mPFC	HbO	0.01	0.05	0.01	.99
		HbR	-0.34	-1.79	-0.35	.21
	ATL	HbO	0.30	1.58	0.31	.28
		HbR	-0.55	-2.89	-0.57	.03
	STS	HbO	0.71	3.74	0.73	.003
		HbR	-0.50	-2.63	-0.52	.04
	TPJ	HbO	0.05	0.26	0.05	.89
		HbR	-0.31	-1.63	-0.32	.26

Note. Group-level GLM results comparing activation for humanoid and geometric animations to baseline across ROIs. Effect sizes (Cohen's d) are reported alongside FDR-corrected p-values. HbO = oxyhemoglobin; HbR = deoxyhemoglobin.

D5. Pre Vs Post Stroop Comparison (FDR-Corrected) GLM results

ROI	Chromophore	Effect (µM)	T-value	Cohens-D	FDR corrected P-value
mPFC	HbO	-0.47	-4.7	-0.92	<.001
	HbR	-0.11	-1.1	-0.22	.47
ATL	HbO	-0.3	-3.0	-0.59	.02
	HbR	-0.08	-0.8	-0.16	.64
STS	HbO	-0.15	-1.5	-0.29	.30
	HbR	-0.09	-0.9	-0.18	.59
TPJ	HbO	-0.19	-1.9	-0.37	.18

HbR	-0.03	-0.3	-0.06	.86

Appendix E: Audio Transcription and Thematic Coding

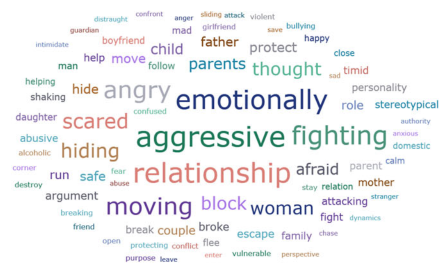
E1. Example cleaned transcript excerpts based on 5 coding subgroups

- **Character Dynamics**
  - *"The small triangle arrived with the ball while the big one was inside. The big triangle went out and seemed to confront the smaller one. The movements were quite aggressive… the ball seemed to hide away and be quite shy."* (Participant, *5_2552-Cleaned_Transcript*)
- **Emotional States**
  - *"The orange character… was looking afraid by like having the hands in front of the face, like covering a little bit down… the others were rigid, aggressive."* (Participant, *27_2135-Cleaned_Transcript*)
- **Intent Interpretation**
  - *"One was really kind of aggressive and was chasing the other two… The pink one looked like it was seeking help or trying to hide. The blue one… like it had a plan to distract the aggressor."* (Participant, *2_4071-Cleaned_Transcript*)
- **Relationship Dynamics**
  - *"I can see the bigger triangle being like the absentee alcoholic father… the smaller one like a guardian more in touch with the child. The ball was a weak child who was afraid."* (Participant, *15_5535-Cleaned_Transcript*)
- **Visual Cues**

- ○ *"Now the same characters were avatars… the aggressive triangle was now a big avatar with animations like wiggling arms… emotions were visible and they looked afraid."* (Participant, *24_8332-Cleaned_Transcript*)

E2. Word clouds for each condition

Word Clouds by Animation Type (Left = Humanoid, Right = Geometric)



E3. Frequency of Conflict-Related Terms by Animation Type

Term	Humanoid (n)	Geometric(N)
aggressive	12	9
scared	10	8
fight/fighting	8	6
afraid	7	5
conflict	5	6
abuse	4	3

E4. Unique word frequency tables

Unique Words by Animation Type

Geometric Animations	Humanoid Animations
block	bystander
destroy	control
dynamics	defend
perspective	partner
	power
	rescue
	sibling
	sneaky
	walk

E5. Prompts given to Open-AI ATLAS.ti

Whole text analysis prompt:

> *"I'm analyzing short texts where people describe what they saw in animated videos showing characters interacting. Please help me code these texts into five categories:*

1. ***Character Dynamics** – What roles or actions do the characters take? (e.g., chasing, escaping, helping, leading).*
2. ***Emotional States** – What emotions do the characters seem to feel or express? (e.g., fear, anger, happiness, sadness).*
3. ***Intent Interpretation** – What are the characters trying to do? What are their goals or intentions? (e.g., being aggressive, helping someone, avoiding danger).*
4. ***Relationship Dynamics** – How do the characters relate to each other? (e.g., fighting, bonding, ignoring each other).*
5. ***Visual Cues** – What things in the animation help the viewer understand what's happening? (e.g., how the characters move, how close they are, what they look like)."*

Whole text analysis led to these questions:

Question: *What roles or actions do the characters take?*
Code Category: *Character Dynamics*

Question: *What emotions do the characters seem to feel or express?*
Code Category: *Emotional States*

Question: *What are the characters trying to do? What are their goals or intentions?*
Code Category: *Intent Interpretation*

Question: *How do the characters relate to each other?*
Code Category: *Relationship Dynamics*

Question: *What things in the animation help the viewer understand what's happening?*
Code Category: *Visual Cues*

Geometric vs Humanoid analysis prompt:

Prompt:

This study explores how people interpret two different types of animations: one using **humanoid avatars** and the other using **geometric shapes**. Both types depict similar social scenes, but we want to understand how the form of the agents influences interpretation.

Please analyze the following response and identify whether the participant is describing a **Humanoid animation** or a **Geometric animation** (based on cues in the text or known assignment). Then, code the content according to the appropriate category:

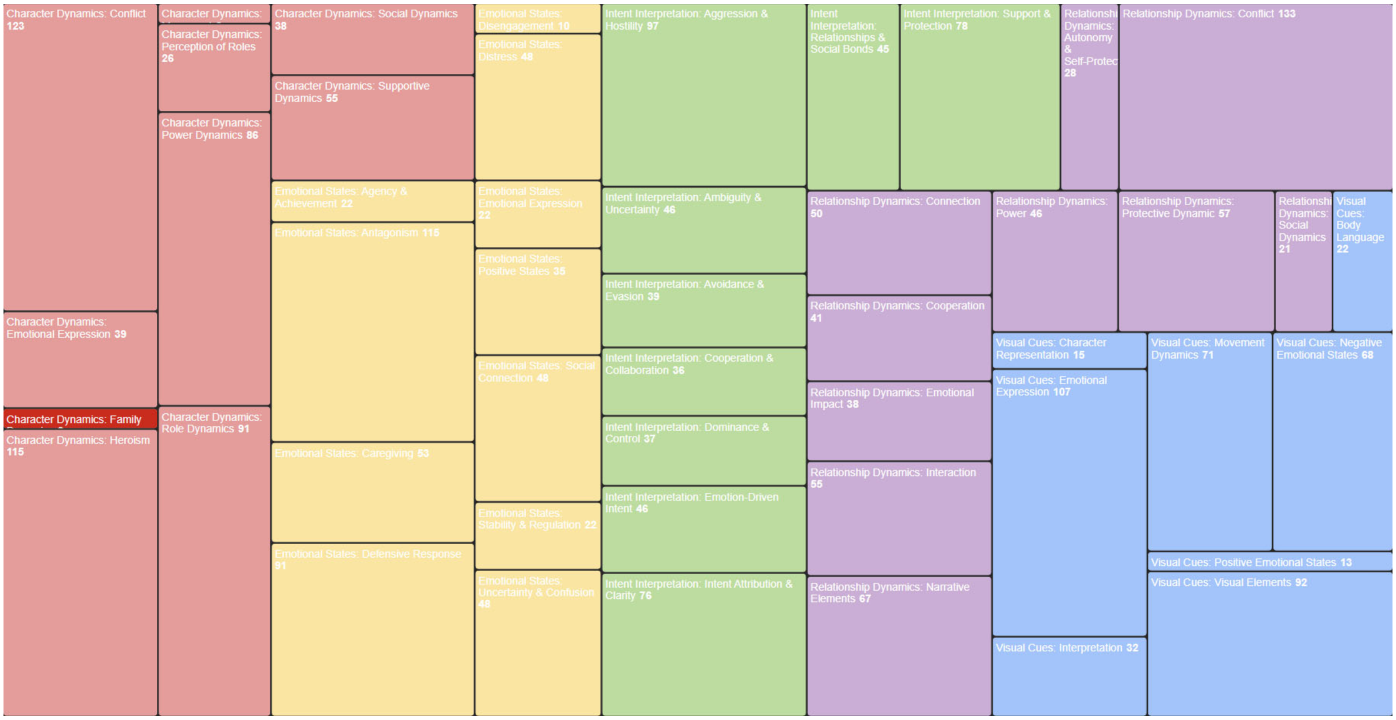
- **Humanoid Themes** – Use this code if the text reflects interpretations, reactions, or descriptions specifically about the humanoid animation. Focus on humanlike traits, emotions, motivations, or interactions attributed to the avatars.

- **Geometric Themes** – Use this code if the text is about the geometric animation. Focus on mechanical or abstract interpretations, and how social meaning is inferred despite the lack of human features.

Geometric vs Humanoid analysis led to these questions:

-
    - *How do participants interpret humanoid animations?*
    - *How do participants interpret geometric animations?*

E6. Code group distribution for whole text analysis



Appendix F: Guideline following

F1. fNIRS best practice Yucel et al 2020

(Y= Yes, P=Partially, N=No)

Table of Contents	***Completed***	***Reasoning***
1 Motivation	***Y***	The introduction provides a clear rationale for using VR and fNIRS to study social cognition, grounded in evolutionary, philosophical, and neuroscientific perspectives.
2 Title, Abstract, and Introduction	***Y***	The title accurately reflects the study scope; the abstract

		is structured and comprehensive, and the introduction provides theoretical background.
2.1 A Good Title and Abstract Structure	***Y***	Title is concise and descriptive. Abstract includes background, methods, results, and conclusions.
2.1.1 Choosing a good title	***Y***	"Neural Correlates of Social Cognition: Replicating the Heider and Simmel Paradigm in Virtual Reality" accurately describes study content and scope.
2.1.2 Structured abstract: Clarity and consistency	***Y***	Abstract clearly outlines the research questions, methods, results, and interpretation.
2.2 Introduction Sections in Functional Near-Infrared Spectroscopy (fNIRS) Papers: Structure and Content	***Y***	The introduction covers historical background, theoretical context, the gap in the literature, and the study aim.
2.2.1 Scope, context, significance, and aim of the work	***Y***	Scope (VR social cognition), context (Heider & Simmel), and significance (neural evidence in VR) are clearly defined.
3 Methods: Making a Study Reproducible	***Y***	Methodological details are comprehensive, including equipment, preprocessing, statistical models, and participant info.
3.1 Participants	***Y***	Inclusion/exclusion criteria, recruitment, compensation,

		and ethical approval are clearly described.
3.1.1 Human participants	***Y***	Ethics approval and informed consent mentioned in both text and Appendix G.
3.1.2 Sample size and statistical power analysis	***Y***	G*Power analysis described using proper parameters and justification.
3.2 Experimental Paradigm and Instructions	***Y***	Experimental design and stimuli are clearly outlined and visualized (Figures 2, Appendix A).
3.2.1 Experimental design (or "study design")	***Y***	Within-subject design, counterbalancing, and dependent variables are specified.
3.2.2 Participant instructions, training, and interactions	***Y***	Instructions and interaction flow in VR are clearly documented and referenced in Appendix A.
3.3 System and Acquisition	***Y***	fNIRS system and acquisition parameters described in full.
3.3.1 fNIRS device and acquisition parameters description	***Y***	Brite MKIII specs, optode distances, frequencies, and safety guidelines included.
3.3.2 Optode array design, cap, and targeted brain regions	***Y***	Described with visual diagrams (Figures 3 and 5) and validated spatially.
3.3.3 For publications on instrumentation/hardware development	***N***	The study does not involve new hardware development.
3.4 Preprocessing Steps	***Y***	Data cleaning, filtering, HbO/HbR conversion, and channel rejection are described in detail.

3.4.1 fNIRS signal quality metrics and channel rejection	***Y***	Rejection of 39 channels across 23 participants documented.
3.4.2 Motion artifacts	***Y***	Justified choice of fNIRS for its motion tolerance and addressed artifact rejection in preprocessing.
3.4.3 Modified Beer–Lambert law, parameters and correction	***Y***	Described and cited appropriately.
3.4.4 Impact of confounding systemic signals on fNIRS	***Y***	General filtering and averaging strategies minimize systemic noise; low-pass filtering mentioned.
3.4.5 Strategy for statistical tests and removal of confounding signals	***Y***	T-Tests for preliminary comparisons and GLM used to model subject variability and compare conditions.
3.4.6 Filtering and drift regression	***Y***	0.1 Hz low-pass filter applied
3.5 Physiological Confounds in the fNIRS Signal: Strategies	***P***	Motion and filtering addressed, but no measurement of systemic physiology (e.g., heart rate) included.
3.5.1 Strategies for enhancing the reliability of brain activity measurements	***Y***	Included spatial validation, channel rejection, and GLM modeling.
3.5.2 Strategy 1: Enhance depth sensitivity through instrumentation and signal processing	***P***	Mentioned limitations of cortical-only data, but didn't apply specific depth-enhancing strategies.
3.5.3 Strategy 2: Signal processing without intrinsic depth sensitive measurements	***Y***	Standard filtering and HbO/HbR signal separation used.

3.5.4 Strategy 3: Incorporating measurements of changes in systemic physiology in the NIRS signal processing	***N***	No concurrent physiological recordings (e.g., pulse, respiration). But mentioned for further improvements.
3.6 Analysis and Statistical Methods	***Y***	Both exploratory and model-based statistical tests described with appropriate citations.
3.6.1 Hemodynamic response function estimation: Block averaging versus general linear model	***Y***	GLM clearly defined and preferred over simple block averaging.
3.6.2 HRF estimation: Selection of the HRF regressor in GLM approaches	***Y***	GLM parameters (e.g., ROI, chromophores) matched to HRF estimation goals.
3.6.3 Statistical analysis: General remarks	***Y***	Included t-tests, GLMs, confidence ratings, and qualitative coding.
3.6.4 Statistical analysis of GLM results	***Y***	Reported GLM outcomes per ROI, aligned with APA style.
3.6.5 Statistical analysis: Multiple comparisons problem	***Y***	False Discovery Rate (FDR) method of Benjamini-Hochberg. This was used to control for Type I error across the statistical tests, and the results tables are explicitly labeled as "FDR-Corrected".
3.6.6 Specific guidelines for data processing in clinical populations	***N***	No clinical population.
3.6.7 Specific guidelines for data processing in neurodevelopmental studies	***N***	Adult neurotypical participants only.

3.6.8 Connectivity analysis	***N***	Not performed but mentioned as a limitation.
3.6.9 Image reconstruction	***N***	Not part of the current analysis pipeline.
3.6.10 Single trial analysis and machine learning	***N***	Not included, mentioned as a future direction.
3.6.11 Multimodal fNIRS integration	***N***	Not implemented, discussed as future improvement.
4 Results: How and What to Report	***Y***	Results reported clearly with figures, tables, APA formatting, and alignment to hypotheses.
4.1 Figures and Visualization	***Y***	Figures were appropriate, labeled, and supplemented with notes (Figures 1–7).
4.2 Concise Text and Rigor	***Y***	Text is concise, with interpretations linked to results and consistent terminology.
5 Discussion and Conclusion: The Implications of the Work for the Bigger Picture	***Y***	Discussion interprets results in light of literature and broader implications.
5.1 Discussion of the Results in Light of Existing Studies: Strengths, Limitations, and Future Work	***Y***	Limitations, replication, and VR implications discussed thoroughly.
5.2 Conclusion	***Y***	Summarizes findings and future applications effectively.
6 Bibliography	***Y***	References comprehensive and in APA 7 format.

6.1 Proper Citations	***Y***	In-text citations and references formatted correctly.
7 Supplementary Data: Reinforcing Reproducibility	***Y***	Appendices contain fNIRS data procedures, transcripts, coding, and visualizations.
7.1 Preregistration, Data, and Code Sharing	***P***	No preregistration or data/code shared but can be requested to researchers.
8 Appendix	***Y***	Appendices A–I included all supplementary methods, figures, and transcripts.
Acknowledgments	***N***	No dedicated section; may be added if desired.
References	***Y***	Included, complete, and APA 7 compliant.

Appendix G: Ethics and Documentation

G1. Ethics Committee BMS / Domain Humanities & Social Sciences ethical approval data and Informed consent form template

UNIVERSITY OF TWENTE.

Humanities & Social Sciences (HSS)

250081 APPLICATION FOR ETHICAL REVIEW

Application nr:	250081	**Intro form:**	8 - Introduction
Researcher:	Verschure, L.J.M. (M-PSY)	**Middle form:**	7 - Humanities & Social Sciences (HSS)
Supervisor:	Piano Simoes, J. (BMS-PGT)	**Outro form:**	5 - Submission
Reviewer:	ten Klooster, P.M. (BMS-PHT)		
Status:	Positive advice by reviewer		
Date of application:	24-01-2025 16:57		
Application version:	1		

0. GENERAL

0.1. Personal details

Student/employee number: s2420856
Initials: L.J.M.
First name: Luca
Last name: Verschure
Email : l.j.m.verschure@student.utwente.nl
Education/department: n/a
Faculty: n/a
Study field: M-PSY
Study level: MSC
Faculty/service department: BMS (Selected for this application)

0.2. Project title

Neural correlates of Social Cognition and perspective taking using VR and the Heider and Simmel paradigm

G2. Informed consent form

Informed consent form for Neural correlates of Social Cognition and perspective taking using VR and the Heider and Simmel paradigm.

Author: Luca Verschure using a Template made by the University of Twente

1. Purpose of the Research
This study examines how individuals perceive and attribute agency to moving objects and human-like avatars in a VR adaptation of the classic Heider-Simmel experiment. Brain activity will be measured using fNIRS to assess responses related to social perception and Theory of Mind.

2. Procedures
If you agree to participate:

- You will first read an information sheet and provide informed consent.
- You will complete a brief demographic questionnaire.
- You will be fitted with an fNIRS headset, which measures brain activity, and a Virtual Reality Head Mounted Display.
- You will experience five short VR scenarios, each lasting 1 minute 20 seconds, with 1-minute breaks in between.
- After each scenario, you will describe your perception of the events.
- The study will last approximately 35-40 minutes, including setup and debriefing.

3. Potential Risks & Benefits
- There are minimal risks associated with this study. You may experience mild discomfort from wearing the fNIRS headset or from VR exposure.
- There are no direct benefits, but your participation will contribute to understanding social cognition in immersive environments. Additionally, you will have the opportunity to enter a raffle for one of three €10 gift cards as a token of appreciation for your time. This information will be collected in a separate form and therefore will not be connected in any way to your data in order to ensure full anonymity.

4. Voluntary Participation & Withdrawal
- Your participation is completely voluntary.
- If you experience discomfort, you may request a break or withdraw at any time.
- You may refuse to answer questions or withdraw at any time without providing a reason.
- If you withdraw, any data collected up to that point will be deleted upon request.

5. Data Protection & Confidentiality
- All collected data will be anonymized and stored securely.
- No personal identifying information will be shared beyond the research team.
- Anonymized data may be used for academic publications, presentations, and future research.

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Consent Form for Neural correlates of Social Cognition and perspective taking using VR and the Heider and Simmel paradigm
YOU WILL BE GIVEN A COPY OF THIS INFORMED CONSENT FORM

Please tick the appropriate boxes	Yes	No
Taking part in the study		
I have read and understood the study information dated 24/01/2025, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
I understand that taking part in the study involves answering a demographics questionnaire, wearing an fNIRS headset while experiencing short VR scenarios, and providing verbal descriptions of what I perceive.	☐	☐
I consent to giving my contact information to be notified if I won one of the three €10 gift cards.	☐	☐
Risks associated with participating in the study		
I understand that taking part in the study involves the minimal risk, but I may experience mild discomfort from wearing the fNIRS headset or from VR exposure.	☐	☐
Use of the information in the study		
I understand that information I provide will be used for a master thesis and potentially for research publications and presentations.	☐	☐
I understand that personal information collected about me that can identify me, such as [e.g. my name or where I live], will not be shared beyond the study team.	☐	☐
I agree that my information can be quoted in research outputs	☐	☐
Consent to be Audio Recorded		
I agree to be audio recorded.	☐	☐

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Future use and reuse of the information by others		
I give permission for anonymized data to be archived for future research.	☐	☐
I agree that my anonymized data may be shared with other researchers for future studies related to social cognition.	☐	☐

Signatures

Name of participant ______ Signature ______ Date ______

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Researcher name ______ Signature ______ Date ______

Study contact details for further information:
Luca Verschure
l.j.m.verschure@student.utwente.nl

Contact Information for Questions about Your Rights as a Research Participant
If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee/domain Humanities & Social Sciences of the Faculty of Behavioural, Management and Social Sciences at the University of Twente by ethicscommittee-hss@utwente.nl

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Appendix H: Guidelines used

H1. Artinis MNE-nirs guide:

https://www.artinis.com/blogpost-all/2021/fnirs-analysis-toolbox-series-mne-python

H2. MNE-nirs Utilising Anatomical Information example:

https://mne.tools/mne-nirs/stable/auto_examples/general/plot_70_visualise_brain.html#sphx-glr-auto-examples-general-plot-70-visualise-brain-py

H3. MNE-nirs Group level GLM.

https://mne.tools/mne-nirs/stable/auto_examples/general/plot_12_group_glm.html

Appendix I: Acronym and terms glossary

Term / Abbreviation	Definition

VR	Virtual Reality – A simulated environment experienced through devices such as head-mounted displays, enabling immersive interaction with 3D environments.
fNIRS	Functional Near-Infrared Spectroscopy – A non-invasive optical imaging technique that measures brain activity by detecting changes in oxygenated and deoxygenated hemoglobin.
ToM	Theory of Mind – The cognitive ability to attribute mental states (e.g., beliefs, desires, intentions) to oneself and others.
mPFC	Medial Prefrontal Cortex – A brain region involved in social cognition, self-referential processing, and understanding others' intentions.
TPJ	Temporoparietal Junction – A region at the boundary of the temporal and parietal lobes involved in perspective-taking and belief attribution.
ATL	Anterior Temporal Lobe – A brain area that processes social knowledge, such as personal traits and social scripts.
STS	Superior Temporal Sulcus – A region involved in perceiving biological motion, gaze direction, and goal-directed actions.
ROI	Region of Interest – Specific brain areas selected a priori for focused neuroimaging analysis.
HbO	Oxygenated Hemoglobin – The form of hemoglobin bound to oxygen; used as a marker of increased neural activity in fNIRS.
HbR	Deoxygenated Hemoglobin – Hemoglobin that has released its oxygen; often decreases in regions with increased neural activity.
CW	Continuous Wave – A type of fNIRS system that emits a constant stream of near-infrared light for measuring hemodynamic responses.
EC	European Credit – A standardized unit for measuring academic workload in the European Credit Transfer and Accumulation System (ECTS); 1.25 EC roughly equals 35 hours of study.
Stroop Task	A cognitive task used to measure executive function and interference control, involving color-word naming with conflicting stimuli.
Heider-Simmel Paradigm	A classic animation-based experiment where participants spontaneously attribute social meaning to moving geometric shapes.

Intentional Stance	A philosophical concept by Dennett (1987) referring to the human tendency to interpret behaviour in terms of beliefs, desires, and goals.
Proteus Effect	A phenomenon where an individual’s behaviour conforms to the characteristics of their digital avatar in virtual environments.
fOLD Toolbox	fNIRS Optodes’ Location Decider – A software tool used to guide optode placement over specific cortical regions based on standardized EEG coordinates.
MNE-Python / MNE-NIRS	Open-source Python toolkits used for processing MEG, EEG, and fNIRS data, including signal preprocessing, ROI mapping, and statistical analysis.