Embodying Affect: Critical Interventions in Human-Computer Interaction via Embodied and Embedded Design in Extended Reality

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Abstract

Human computer interaction has been significantly advanced by the integration of biometric sensors and artificial intelligence, allowing more intuitive and engaging user experiences. However, there is a lack of critical engagement practices with artificial systems and their implementation in user design. The primary objective of this multimodal dissertation (composed of the virtual reality prototype *Us Xtended* and the online platform *Miro*) is to close this gap by proposing a methodology of critical embedded and embodied design via biofeedback in extended reality. It aims to do so by creating a design pathway that fosters embodiment, user agency and responsible consumption of emerging technologies. Moreover, the project sheds light on the issue of accessibility and different interaction and sentience opportunities in the digital realm.

The methodology involves affect recognition and self-quantification as a critical, analytical and storytelling device. This approach aims to redefine human-computer interaction by embedding criticality and agency within the process. This is applied in the prototype via the materialist and performative aspects of biometric data and affective analysis and represented on a three-dimensional affect scale. This quantification apparatus is integrated into the experience. Users' psychophysiological states are dynamically represented and evaluated through a 3D affect scale model and formed in the end into an audiovisual abstract representation of the user's journey within a virtual environment (embodied and embedded design). The critical evaluation lies within ways participants shape their experience through their biometric and behavioral inputs.

Via self-reflection and comparison between the systemic analysis and self-evaluation, the project critiques affect recognition practices and stresses ethical considerations in ways biometric data is interpreted by artificial systems, reflecting on the reproduction of systemic biases in affect recognition technologies. At the same time, it highlights the system's reliance on measurable bodily signals, emphasizing the importance of understanding its limitations. This educational aspect enhances users' ability to navigate new technologies, contributing to responsible consumption of emerging media.

In essence, this dissertation advocates for a critical, embodied approach to human-machine collaboration. By exploring the intersections of technology, art, and critical theory, it aims to foster deeper understanding and more responsible engagement with the technologies that increasingly shape our existence in the digital age.

Dedication

To all of you who always believed in me.

You know who you are.

Acknowledgements

First of all, I would like to thank all the funders and financiers without whose support I would never have been able to study for a doctoral degree in Canada. Namely, the Elia family and the Elia Scholars Program, Ontario Graduate Scholarship, The Susan Mann Dissertation Scholarship, and the CIBC Fine Arts Graduate Student Award.

I would like to thank my committee: my two co-supervisors Caitlin Fisher and John Greyson, who took me under their wings and from whom I have learned invaluable lessons throughout my studies at York University and my third committee member, Mark-David Hosale, for his productive suggestions and practical support while developing the prototype.

Throughout the five years of my doctoral journey I honed my skills in the Unreal game engine thanks to the support and collaboration of the following colleagues: Rayta Nobaiha Zaman and Yaari Efrati who collaborated with me to develop some of the assets used in the prototype while working for the Public Visualizations Lab headed by Patricio Dávila; Anna Leschanowsky for her creative coding ideas and solutions; Jorge de Oliveira for being always ready to help; Anke Petersen and Lou-Janna Daniels from JYOTI Film for their feedback, support and belief in the project; Johanna Silvennoinen and Jose Cañas Bajo from University of Jyväskylä for giving me priceless insights into quantified data research; Taien Ng-Chan and William Michael Irwin (BetaSpace) and the Immersive Storytelling Lab for always finding solutions when I was in dire straits. And finally, the YouTube and GitHub community for sharing their workflows and projects, without whom I would never be able to learn to code and design this work.

Last but not least, I would like to thank the Cinema and Media Arts Department faculty, especially Michael Zryd, the Graduate Program Director, for his invaluable help throughout the whole course of my studies and for always keeping his cool. I would like to thank Mary Bunch for her advice during my comprehensive exams. And big thanks to Kuowei Lee for always being two steps ahead for all administrative hurdles.

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Preface

Section 1: Introduction

Embodying Affect: Critical Interventions in Human-Computer Interaction via Embedded and Embodied Design in Extended Reality is a multimodal dissertation research-creation project which comprises a prototype[1] of an extended reality experience[2] *Us Xtended* (Pnacek(ova), 2024) and a UsXR project board on the interactive and collaborative platform *Miro* (Khusid, n.d.), an online whiteboard software. The former part of the dissertation serves to communicate the main research questions and to offer possible solutions through an immersive and interactive media tool in extended reality - an XR headset with biofeedback[3] - and embedded (De Micheli et al., 2002; Micheli et al., 2023; C. Wolf et al., 2018; M. Wolf, 2014) and embodied design (Baber, 2022; Parisi, 2013; Turkle, 2009).

Embedded and embodied design has primarily two functions in this specific application: embodied interaction and embedded systems design. It explores how users' physical interactions with the XR environment (through embedded design) enhance the immersive experience and affective engagement. Moreover, it discusses how technology can be integrated into immersive environments, enhancing the ubiquity and utility of biometric data tracking and sensing. The objective here is to embed design principles directly into the user's embodied experience in XR to measure and respond to affective states dynamically and build the main narrative around it. The implementation unfolds via the integration of sensors and input devices that capture real-time biometric and behavioral data from users, such as heart rate, gaze, voice and cognitive load. Moreover, it includes the design of interactive and narrative elements within the XR

[1] A prototype can serve different functions and thus have different meanings such as "a vertical slice" depicting one of the user journeys and experience mechanics, "proof of concept" used in science and technology, "visual prototype" serving rather as a teaser summarizing the narrative and depicting the visual style. *Us Xtended* is a proof of concept and a visual prototype as well.

[2] I understand extended reality as an umbrella term for media that augment humans, i.e. virtual, mixed and augmented reality).

[3] In this specific case the tool being used is the XR headset HP Omnicept Reverb 2, released in 2021 (Fieldman, 2021).

environment that adapt based on the user's affective states (e.g. changes in visual, sonic and haptic elements) ensuring a deeply personalized user experience.

In *Us Xtended*, the user partakes upon a personalized exploratory journey through a series of surreal environments that respond to their biometric data. Each world offers unique challenges to influence the environment using heart rate, voice, mouth, gaze, and cognitive load tracked by the headset's sensors. As users interact with these worlds, their experiences shape a dynamic environment that evolves with their emotional and physiological responses, culminating in a personalized reflection of their journey symbolized by a digital moving sculpture and evaluated by an artificial affect recognition system. The Miro board[4] archives different phases of the development of the prototype divided chronologically into frames; from its ideation in 2021 to prototyping in 2023 and 2024. In the center of the board resides the literature review and the methodology tying the different development stages together. By scrolling the reader can minimize or maximize the website and go through each frame in miniature detail.

In the extended reality (XR) prototype of *Us Xtended*, an artificial system assesses the user's bodily responses reflecting its results through dynamic surroundings. This prompts self-reflection, allowing users to ponder if their inner states align with their bodily signals. The experience encourages playful and creative exploration of affective design in VR (Liao et al., 2020), fostering mental health by establishing a deeper emotional connection and awareness. Not only does it provide a space for emotional engagement but it also aims to prompt critical examination of artificial systems. Users are confronted with an affect recognition tool (a 3D-affect scale designed as a primary example of embedded and embodied design) attempting to track, classify and assign their psychophysiological states (Russell, 1980). At the same time, it highlights the system's reliance on measurable bodily signals, emphasizing the importance of understanding its limitations. This educational aspect enhances users' ability to navigate algorithmic thinking, contributing to responsible AI consumption and agency in the digital realm.

The critical evaluation of technology lies within agency and interactivity. It focuses on the ways users actively shape and control their experience within the VR environment through their

[4] https://miro.com/app/board/uXjVOaYyamQ=/?share_link_id=894467096034

biometric and behavioral inputs based on self-quantification practices (Ajana, 2017; Han, 2017; Schull, 2018). It also critiques affect recognition practices and analyzes potential biases and ethical considerations in how affective data is interpreted and used within technological systems, reflecting on the reproduction of systemic biases in affect recognition technologies and the consequences in other systems, such as health care (Botin, 2015).

The prototype serves as an example for responsible product design. By incorporating ethical and value-sensitive design principles, such as transparency, explainability, data privacy, reliability, accountability, autonomy, and accessibility (to data) (Friedman & Hendry, 2019), the project advocates for ethical development of new technologies including VR and AI, encouraging a more conscious and responsible production of these products. As different forms of new technologies continue to evolve, and are being applied in other social systems (health care, legal system, financing), fostering a deeper understanding of these ethical perspectives will be crucial for creating more inclusive, responsive, and value sensitive technologies (Watkins et al., 2013; J. Zhang & Yu, 2022; Z. Zhang et al., 2021).

Last but not least, throughout the research, I have maintained a high standard of ethical consideration, especially concerning privacy, consent, and the psychological impact of immersive technologies on users.

Section 2: Literature Review

Figure 1: Literature review in the UsXR Miro board (an illustrative example - use the Miro board to explore further).

Introduction to Extended Reality and Human-Computer Interaction

Extended reality (XR) encompasses virtual reality (VR), augmented reality (AR), and mixed reality (MR) (Vasarainen et al., 2021) offering immersive environments that blend digital and physical elements. Human-computer interaction (HCI) in XR has been significantly advanced by the integration of biometric sensors and AI technologies, allowing more intuitive and engaging user experiences. However, throughout, when I'm talking about my contributions to HCI I am talking about the space where interaction and co-creation of experience are happening and not to the field in computer science.

Critical Data Studies and Algorithmic Biases

Critical data studies have emerged as a crucial field to address concerns around data privacy, ethics, and transparency, especially relevant in XR contexts where personal and biometric data are extensively used. Researchers have highlighted how algorithmic processes can reproduce biases, thus affecting user interactions and experiences within digital environments (Cheney-Lippold, 2017; Gitelman, 2013). These studies argue for a more responsible approach to data handling and algorithm design, promoting fairness and equity (Crawford & Paglen, 2019; D'Ignazio & Klein, 2020; Hall & Dávila, 2022)

Phenomenology and Embodied Interaction

In this context, phenomenology and human-computer interaction stem from the first-person experience and the subjective perception of digital environments. Merleau-Ponty's notions of embodiment are particularly pertinent, emphasizing the body as the primary site of interacting with the world (Baldwin, 2004; Hezekiah, 2010). In XR, this perspective helps designers create more engaging and meaningful experiences by aligning digital interactions with natural human movements and senses (Fuchs & Koch, 2014).

Artificial Intelligence and Affect Recognition

The role of artificial intelligence (AI) in recognizing and responding to user emotions has been transformative in XR. Affect theory, particularly as explored by scholars like Sara Ahmed, and Brian Massumi (Ahmed, 2014; Deleuze, 1988; Massumi, 2002; Sedgwick, 2003) informs the development of affective computing systems that adapt to users' emotional states (Bösel & Wiemer, 2020; Liao et al., 2020; Picard, 1997). These systems use various data points, including facial expressions and heart rates, to dynamically alter user experiences based on real-time emotional feedback.

Assemblages of Co-Creation

Co-creation (Cizek & Uricchio, 2022; Sancho Querol & Carvalho, 2018) is here understood in the context of an assemblage (Gilles Deleuze & Guattari, 1987), where users, their bodies, interaction and data actively participate in the development and refinement of XR environments.

Co-creation arises within the processes between different actors engaged in them. In an assemblage objects are seen “not as a priori but rather as foundationally entangled and then emerging from their entanglements through processes of naming and differentiating” (Gilles Deleuze & Guattari, 1987, p. 67). Moreover, the actor-network-theory (ANT) (Latour, 2005) highlights the principles of varying constellations among different types of actors (bodies, environment, biosensors, artificial systems). It is within these entanglements of the ‘assemblage’ and ‘folding’ (Deleuze & Guattari, 1987) that co-creation arises as “coming together of bodies, subjectivities and audiences, and non-human actors like objects, technologies, space, and place” (Latour, 1993, p. 30). Its results are thus never constant and always everchanging. These notions are best visible in the final moving data artifact in the XR piece “Us Xtended”.

Future Directions

This review underscores the importance of integrating critical data studies, phenomenology, and AI in the development of XR systems. It highlights the need for further research on how these interdisciplinary approaches can enhance user autonomy and reduce biases in digital environments. As XR continues to evolve, fostering a deeper understanding of these theoretical perspectives will be crucial for creating more inclusive, responsive, and ethically aware technologies.

Section 3: Theoretical Framework

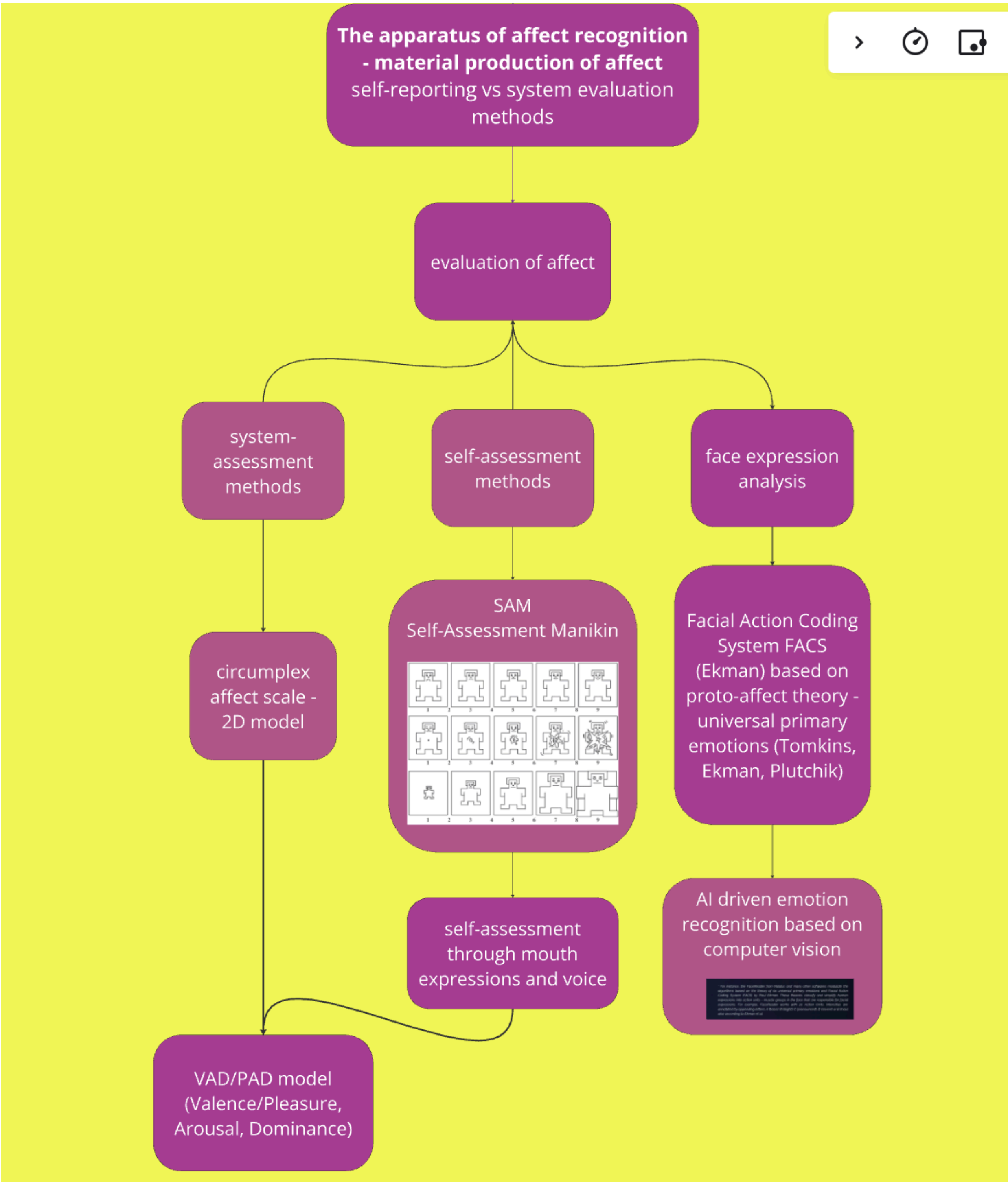

Figure 2: Part of the theoretical framework in the Miro board.

Based on the structure and content of the diagram (fig.2), the theoretical framework encompasses several interrelated components that link affective computing, biometric analysis, and the visualization of affective data in a multidimensional (Valence-Arousal-Dominance, VAD) model. The framework also includes critical considerations of materiality and agency within the system.

The foundations of affective XR design stem from Rosalind Picard's concept that affective computing involves giving computers the ability “to recognize, understand, and respond to human emotions” (Picard, 1997). One of the main questions this framework structure attempts to answer is: How are these principles applied in XR environments to create immersive, emotionally responsive systems?

The second crucial theoretical concept is the materiality of biometric data. For instance, data collection utilizes various biometric sensors to gather data reflective of users' emotional states, such as heart rate, facial expressions, and voice tone. These material data engagements convert physical properties and interactions (like touching or moving) into digital signals that inform system responses (Barad, 2007; Haraway, 2016; Massumi, 2002; Munster, 2006; Pasquinelli, 2023; Pasquinelli & Joler, 2020).

It is Karen Barad’s agential realism (Barad, 2007; Sehgal, 2014) and quantum theory that structures the materialization processes of affect, data and our bodies. Agential realism provides a critical framework for understanding how these artificial systems operate not just as neutral tools but as active users in defining what is materially significant. According to Barad, these apparatuses enact what matters and what is excluded from mattering, intertwining discursive practices with material conditions. This posthumanist perspective forms the basis for rethinking the relationships between humans and computers in the creation process. By treating these AI systems as active users in the formation of reality, this approach underscores the material-discursive nature of technology, where what is considered significant (or insignificant) is constantly being enacted.

Third, the Valence/Pleasure, Arousal, Dominance (VAD) 3D Model (Chin & Zhang, 2021; Liao et al., 2020; Russell, 1980) is re-conceptualized for affect analysis as an embedded embodied design method largely influenced by value sensitive design (Watkins et al., 2013; Friedman & Hendry, 2019; J. Zhang & Zhang, 2023). The VAD model is used to quantify emotions along three axes—valence, arousal, and dominance—providing a comprehensive measure of emotional states. It serves the role of an artificial system and simulates AI processes used in emotion recognition. The embedded and embodied implementation of this system in XR discusses how these dimensions can be visualized and manipulated within an XR environment to dynamically respond to user inputs. In analogue qualitative research, self-assessment manikin served the main self-reporting tool (Bradley & Lang, 1994; Handayani et al., 2015; Iturregui-Gallardo & Méndez-Ulrich, 2020; Stevens et al., 2016; Xie et al., 2020). With bio-sensing technology self-quantification practice became the norm even though questions of ethics and well-being are being answered only now (primarily in the health care sector) (Haddadi & Brown, 2014; Sharon, 2017).

This framework integrates concepts from computer science, psychology, design, actor-network-theory and critical theory to examine the complex interactions between humans and computer systems in environments where emotional engagement plays a critical role. It thus facilitates answering the following crucial points of this dissertation:

- To understand how emotional responses can be accurately captured and influenced using technology.
- To develop systems that respond more adaptively to human emotional states leading to more responsible design of new technologies.
- To critique the socio-technical implications of deploying such systems, particularly focusing on issues of privacy, consent, and the authenticity of emotional interactions.

The framework provides a comprehensive basis for examining and developing affective XR systems, with a strong emphasis on both the technical development and the critical evaluation of these technologies. Next, the methodological approaches explain how these data are collected, processed, and analyzed.

Section 4: Methodology

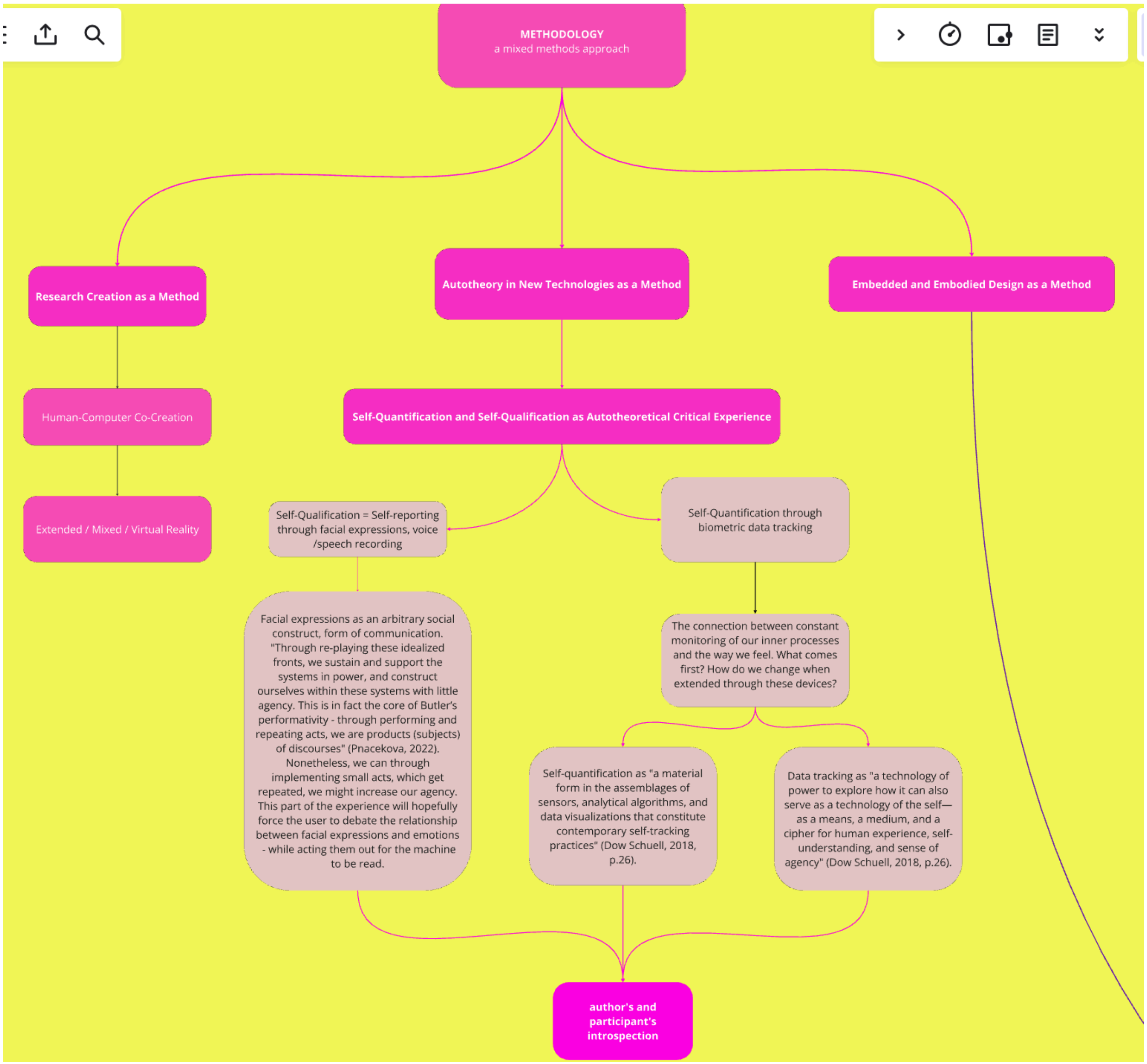

Figure 3: Methodology in the Miro board.

The methodology encapsulates a mixed-method approach combining Research Creation, Embedded and Embodied Design, and Self-Quantification as Autotheory in New Technologies. This comprehensive methodology is applied to the research project exploring new technologies, particularly in the context of XR. This tripartite methodological framework is designed to facilitate a deep exploration of human-computer interaction in virtual environments, focusing on the embodied and autotheoretical experiences of self-quantification and affect measurement.

Research Creation as a Method

Research-creation, a method combining artistic practice and empirical research (Chapman & Sawchuk, 2012), is increasingly used in VR to explore new forms of interaction and expression. This approach is complemented by co-creation practices (for more detail see Section 3). The main objective of research-creation in this context is to leverage creative practice as a form of inquiry to generate new knowledge within emerging media. The process is three-fold and encompasses:

- Extended reality environments that allow for dynamic interaction between humans and computer-generated elements.
- Human-computer co-creation aspects refine these environments based on participant feedback and interaction data.
- Documentation and analysis of the creation process and the interactions help us understand the nuances of human engagement with virtual components.

Embedded and Embodied Design as a Method

The concept of embodied design originated from cognitive studies and architecture studies (Parisi, 2013), and in this context stresses the embodiment as a crucial element of user design in XR (Baber, 2022). It doesn't separate mind from the body, on the contrary, it unites body and mind through presence, immersion and interaction. The objective here is to embed design principles directly into the user's embodied experience in XR to measure and respond to affective states dynamically and build the main narrative around it. Embedded design puts in forefront hardware/software co-design (AAAI et al., 2016; Battistuzzi et al., 2018; Borsci et al., 2022; C. Wolf et al., 2018) inadvertently making the systemic processes more transparent and user friendly. It's where the back-end becomes also the front-end. Therefore I relate it to responsible and value sensitive design. It makes ethics of new technologies more visible by implementing them as tools and by making them a crucial element of the story and the user journey.

The embedding of embodied design unfolds via:

- Integration of sensors and input devices that capture real-time biometric and behavioral data from users, such as heart rate, gaze, and cognitive load.
- Design of interactive and narrative elements within the XR environment that adapt based on the user's affective states (e.g., changes in environment color, sound, and texture based on user emotions).
- Utilization of the three dimensions of affect (Valence, Arousal, Dominance) as primary indicators for adapting the XR environment, and the unfolding of the biometric data artifact ensuring a deeply personalized user experience.

Self-quantification and Self-qualification as Autotheoretical Design in New Technologies

The aim is to utilize autotheoretical approaches for critical exploration of artificial systems and to reflect upon the intersection of technology and personal experience (Cavitch, 2022; Clare, 2020; Cvetkovich, 2012; Fournier, 2021; Wiegman, 2020). This approach encompasses self-quantification and self-qualification processes (Bradley & Lang, 1994; Haddadi & Brown, 2014; Iturregui-Gallardo & Méndez-Ulrich, 2020; Sharon, 2017; Stevens et al., 2016; Xie et al., 2020) through both metrics and self-reflection. It involves application of theoretical frameworks to interpret these data, linking personal narratives to broader socio-technical discourses. Last but not least, using self-quantification via the lens of autotheory facilitates the interrogation of agency, identity, and embodiment as users interact with and through data visualization and sonification practices as technological apparatuses.

I have applied this method via:

- Engaging the users in self-quantification and self-qualification processes, and documenting their experiences through both quantitative metrics and qualitative self-reflection.
- Application of theoretical frameworks to interpret these data, linking personal narratives to broader socio-technical discourses.

- Exploration of agency, identity, and embodiment as users interact with and through technological apparatuses.

This mixed methods approach provides a holistic understanding of the impacts of new technologies on individual perceptions and behaviors. It establishes iterative feedback loops where insights from autotheory inform the design of the XR environment, and data from the embedded design influences theoretical explorations. Moreover, it continuously documents both the technological development and participant experiences and uses mixed methods (e.g., thematic analysis for qualitative data and statistical analysis for quantitative data) to analyze the data. This approach not only advances academic knowledge but also informs practical applications in designing empathetic and adaptive technology systems.

Section 5: Project Development, 2021

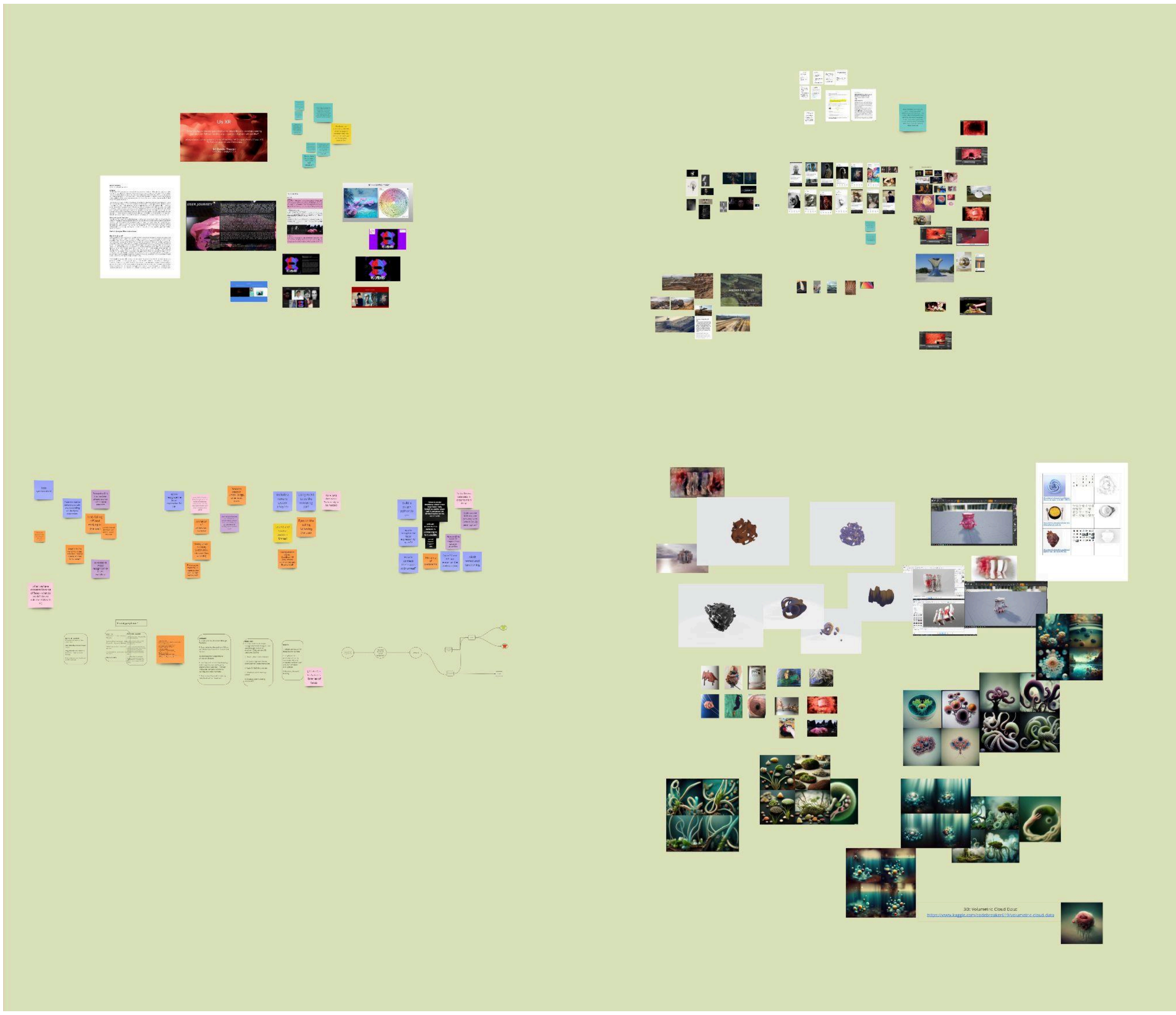

Figure 4: Miro board frame showing the dissertation development in 2021 (an illustrative example).

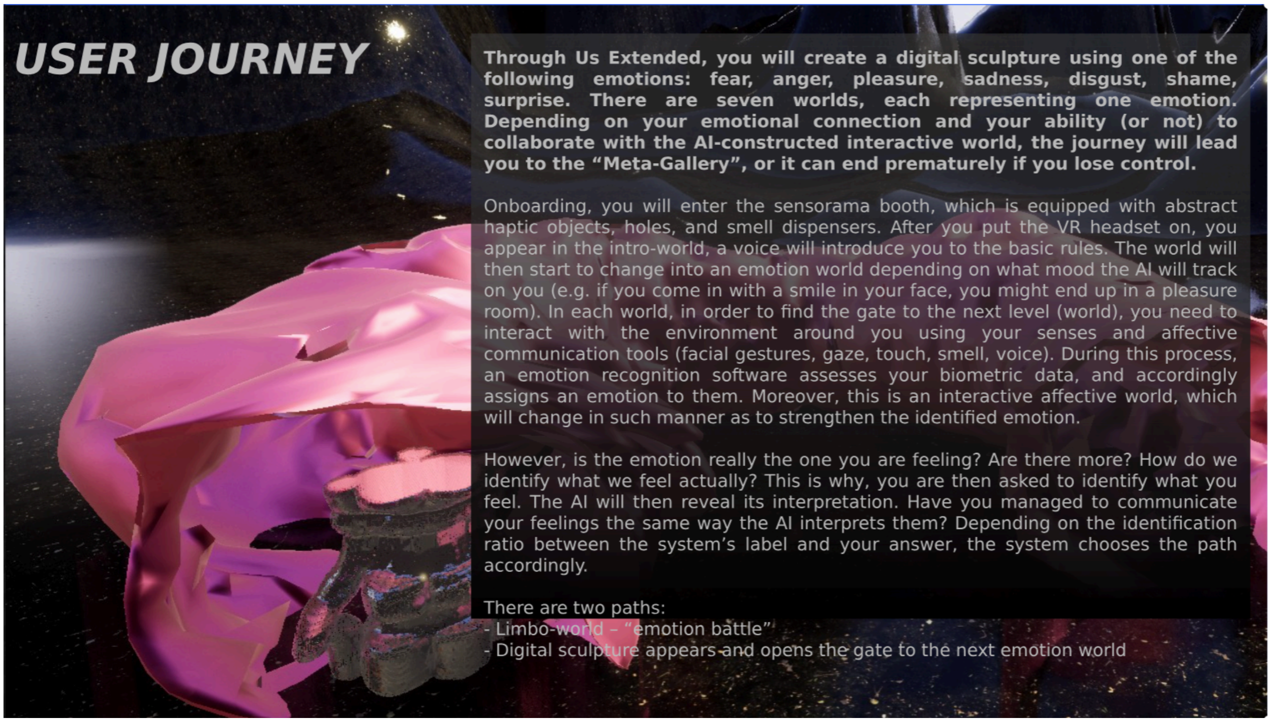

Figure 5: User journey description from the second pitch deck in 2022.

During my work at the Public Visualizations Lab (PVL) in 2021, together with two undergraduate students from the Engineering School at York University Nobaiha Rayta Zaman and Yaari Efrati, we created 3D assets with Generative Adversarial Networks (GANs). Some of these assets found their way into the final prototype, as well (see Miro board). The process was not easy, and although we had strong agency in co-creating the 3D objects, the effort invested into this process was larger than if they were designed from scratch by a human in a 3D modeling software without any help from AI. We did most of the work instead of the AI doing it for us (we used four pieces of software). This process was thus deemed useless, and we had decided not to proceed with it. The detailed workflow is explained in one of the documents in the 2021 frame of Miro board.

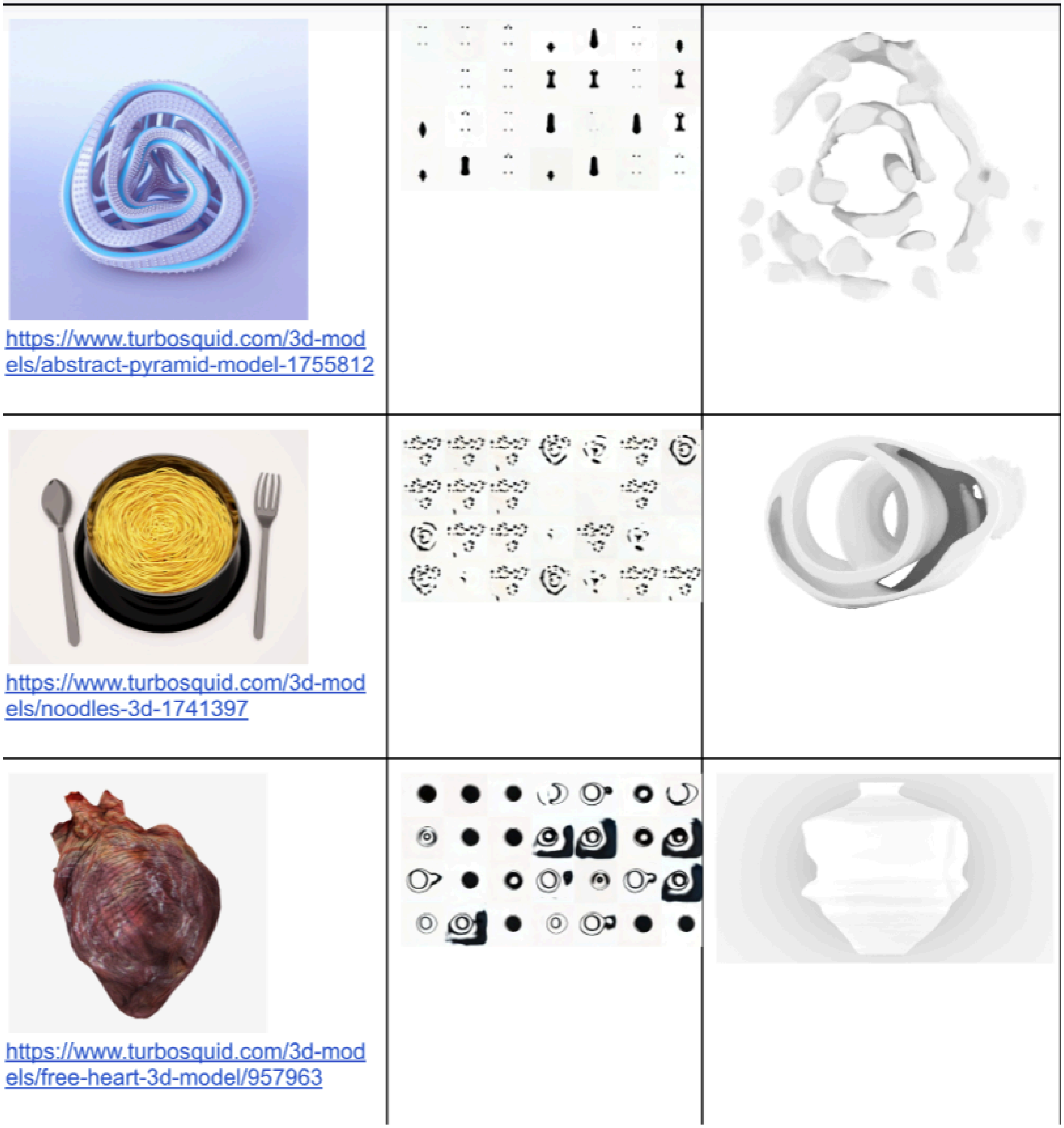

Figure 6: My first co-creation learning process with AI - 3D objects generated with styleGAN in 2021

Section 6: Project Development, 2022

In this phase, the project acts as a digital artwork of one's emotions focusing on the exploration and critique of the proto-affect theory (Scherer & Ekman, 2014; Tomkins, 2008) and facial recognition via using rigged theatre masks copying the user's facial expressions. The experience aims to establish a relationship between our minds, bodies and the AI itself through art. The goal is to explore our control of emotion recognition and its biases. Is there really a specific number of emotions which are universal, or are they culturally constructed? What role does affective communication through gestures, eyes, and tone of the voice play? And lastly, is the human extension an emotional symbiosis between us and the AI? The specific interaction design resulted in a biofeedback based experience.

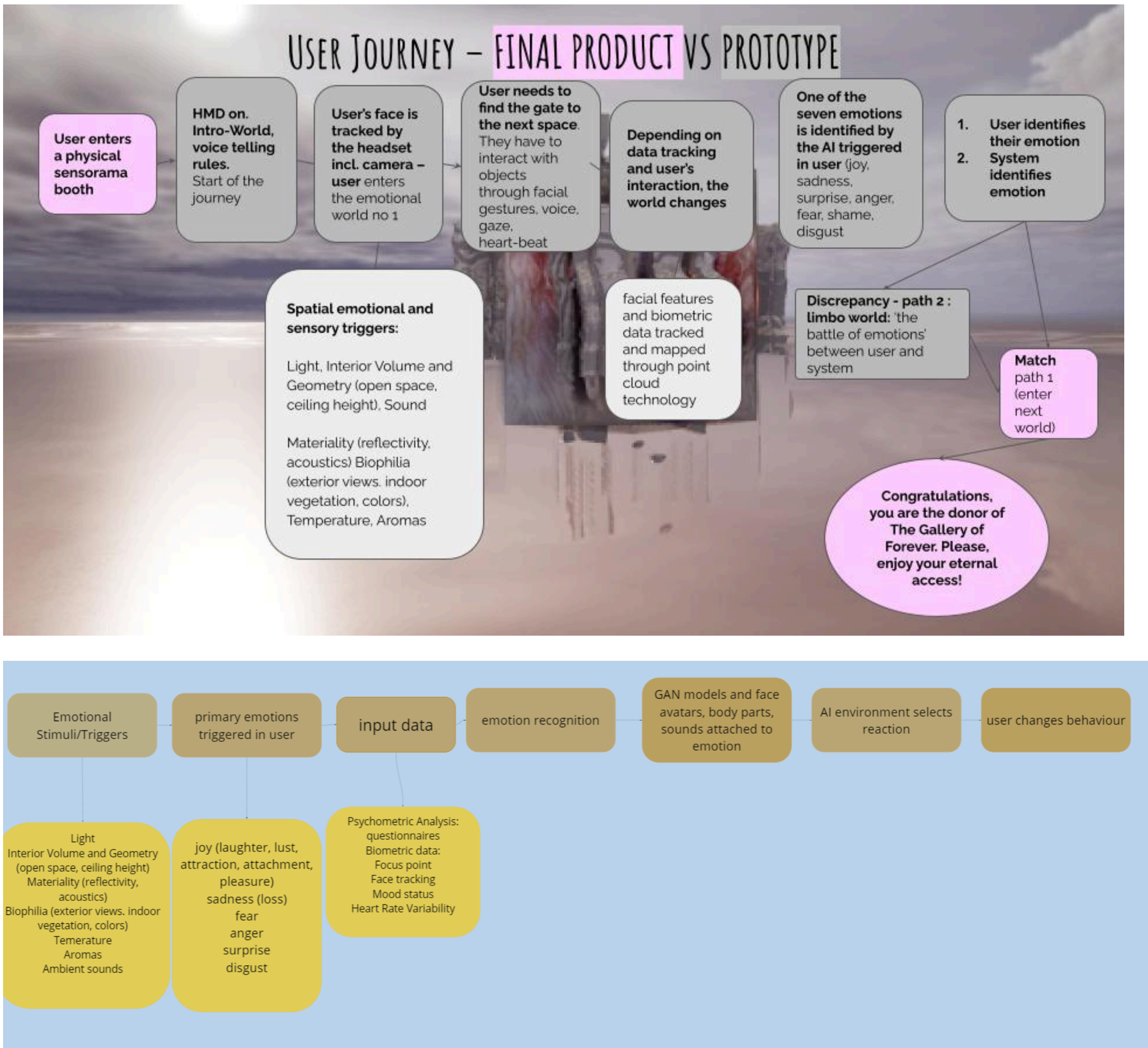

Figure 7: Diagram of the user journey and interaction design in 2022 (the first concept of embedded and embodied design).

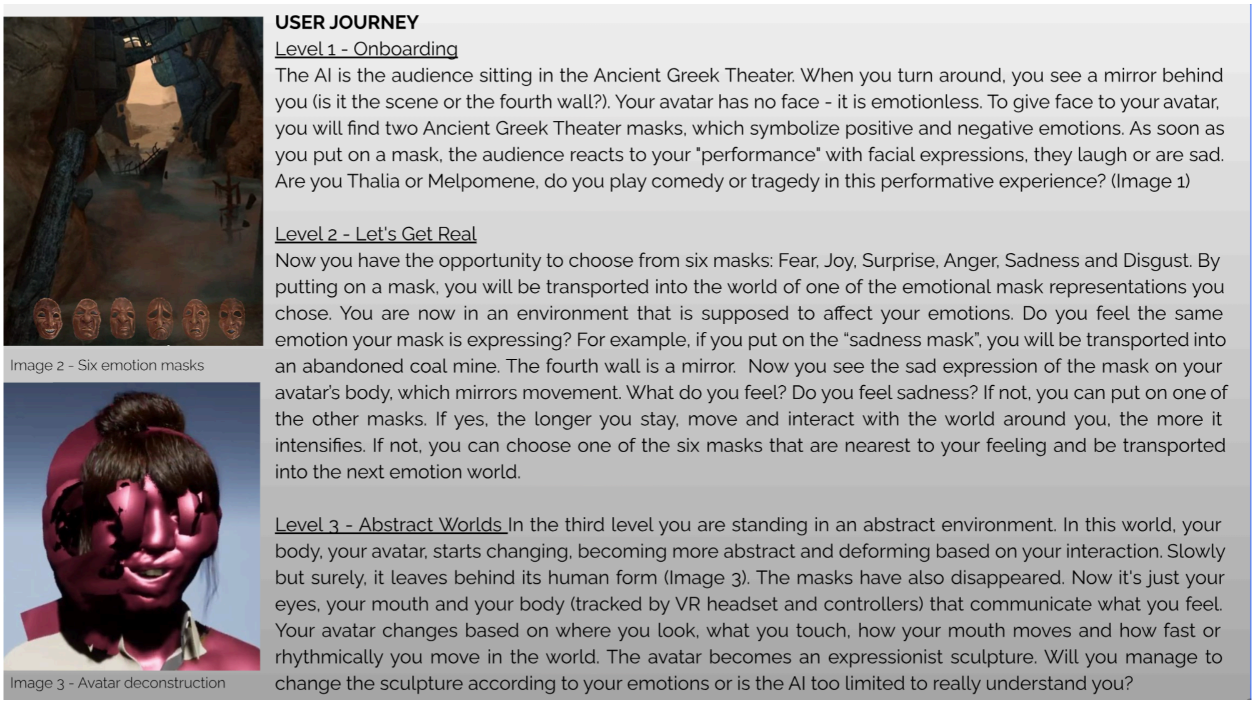

Figure 8: User journey description and prototyping in UE4 using Metahumans and LiveLink iOS app.

I composed a design approach which connects the new materialism (Barad, 2007; Gilles Deleuze & Guattari, 1987; Haraway, 2016; Massumi, 1995, 2002) and performative aspects of affect (Ahmed, 2014; Sedgwick, 2003) with the concept of 'face work' and 'fronts' (Goffman, 1956). "FACS represents Goffman's system of fronts - an arbitrary FEA system implemented within ER. Gates describes the attempts of coders to find agreement in facial expression analysis in order to standardize it. This attempt results in the same accountability fallacy, in terms of the system's internal agreement—that is, whether the classification system consistently agrees with itself (Gates, 2011, p. 171). The system chooses from a certain number of FACS fronts, silencing anything that does not fit, and thus eliminating unidentified emotions and facial expressions. In order for agents to interact with these technologies, they have to speak "their language" so to say, and have to perform emotions according to this arbitrary system. Moreover, this system is only accountable to itself, and it forms the material expression of emotion, which might mold our own understanding and 'feeling' of emotions. "Facial expressions are made to fit the technology and the decontextualized, mathematical theory of information that informs its design" (Gates, 2011, p. 171). Our facial expressions and emotions are thus misidentified, misrecognized, and then distributed through tools of “mimetic communication” (Gibbs, 2010), such as emojis, facial recognition applications and many more. “The apparatuses of affective AI produce a topography of face and emotion. Our faces and our emotions are analyzed, recognized, predicted and produced by the apparatuses of ML and CV as dynamic agents, and then performed and transmitted by (sometimes the same but not same) agents" (Pnacek(ova), 2022).

The plot of this version of the experience would revolve around the processes of ‘emotional AI’ such as facial expression analysis using theatre masks as a metaphor of the limited databases the emotion recognition uses. During the whole experience the user would have the possibility to observe the change of their face avatar in a mirror co-creating a sort of “emotional selfie”. As the experience progresses, they’ll learn that the only way to communicate with the AI is through emotional expressions starting from the use of theatre masks, through movement and to their facial vocal interaction interpreted by an affective AI system. The more they can influence the environment, the more their avatar changes into an emotional work of art. During the research of the back-end architecture, I stumbled upon a challenge concerning face tracking in VR. For an actual avatar rigging system and facial expression analysis, more sensors are needed than just mouth- and gaze-tracking sensors. There are face parts covered by the VR headset (i.e. eyebrows, cheeks, nose) that are crucial for a face recognition software to work. Although not making it part of this dissertation, I would like to collaborate on the application of face recognition and develop a new technology for embedded and embodied affective design in XR (see Section 9).

Section 7: Project Development, 2023

This phase was mostly devoted to building a narrative and a visual style. I am a big Andrey Tarkovsky fan, and so the film and the book *Solaris* (Lem, 2002; Tarkovsky, 1972) became a strong visual inspiration. The concept of a bio-artificial mass reading and reacting to human emotions was introduced.

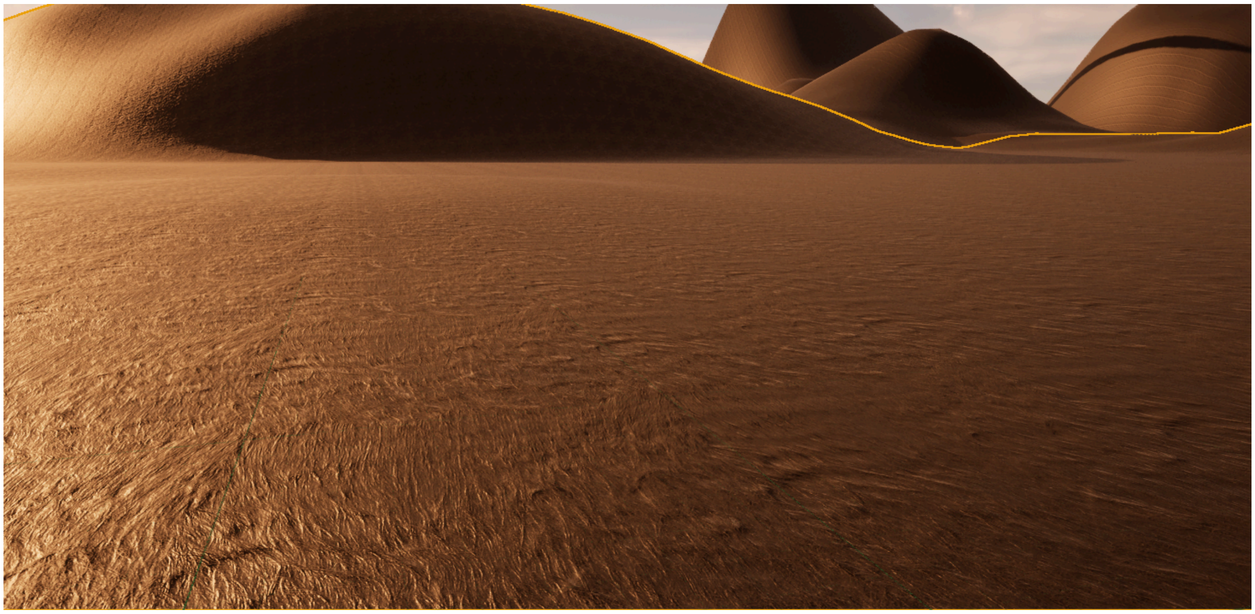

Figure 9: Solaris-inspired texture in Unreal Game Engine 5 (UE5).

Figure 10: Onboarding in the ancient theatre with a faceless avatar choosing the tragic or comic mask.

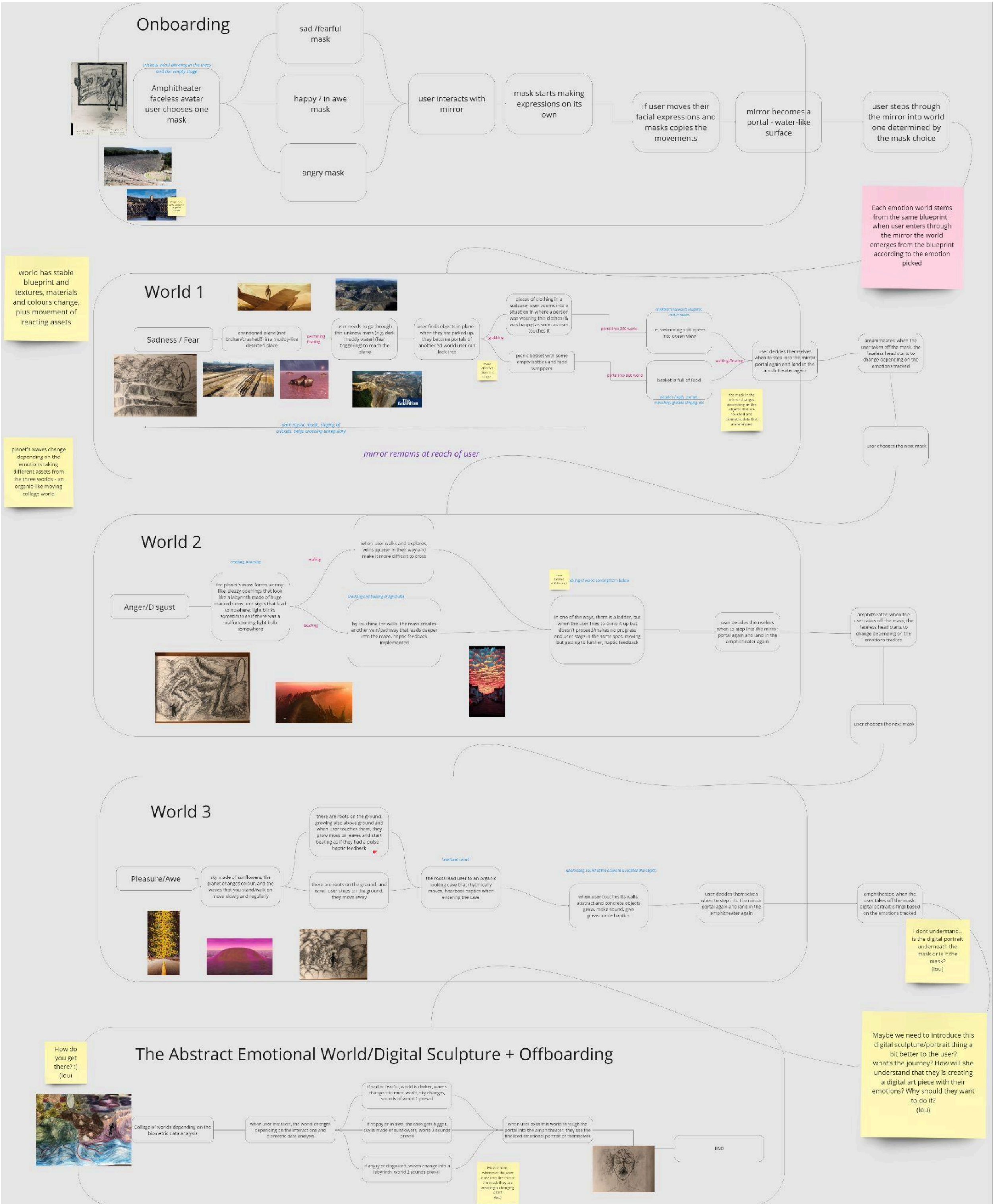

Figure 11: User journey with the Solaris-concept (an illustrative example - use Miro board to explore).

Section 8: The Final Prototype in Unreal Engine 4 (UE4), 2024

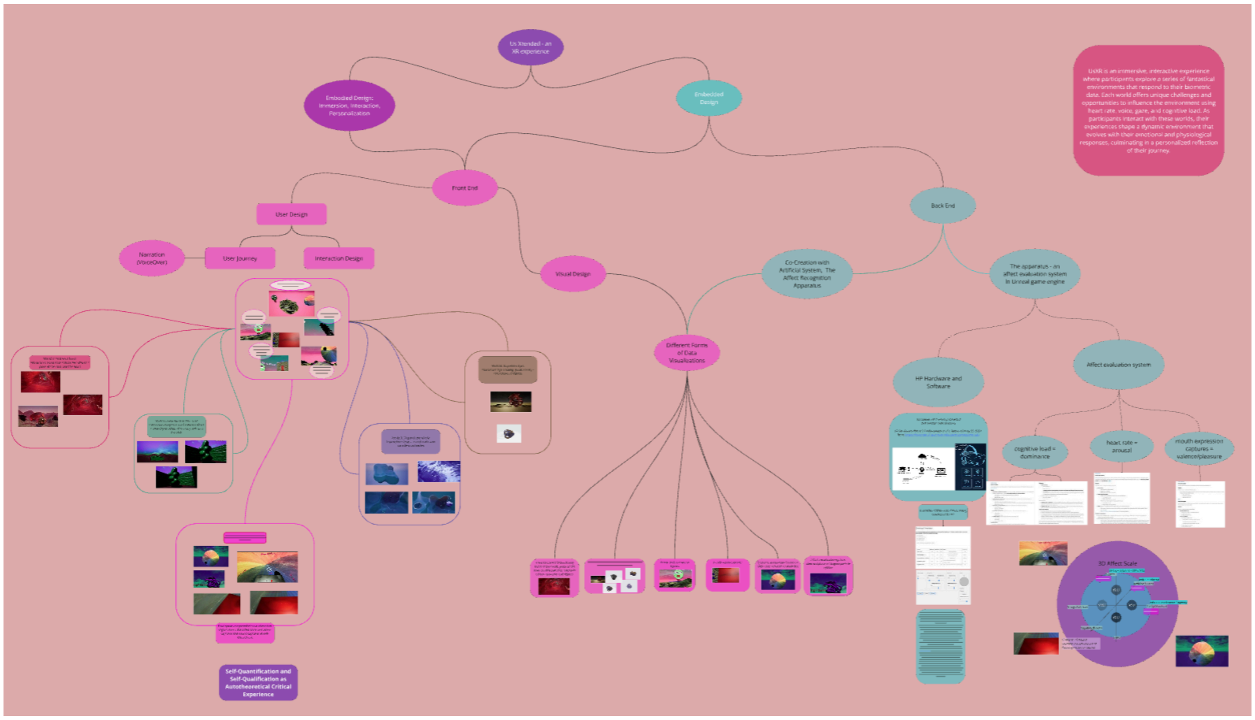

Figure 12: The diagram of final embedded and embodied design in the *Us Xtended* prototype (an illustrative example - use Miro board to explore).

From Hardware to Software, From Back-End to Front-End

HP Omnicept Reverb G2: Sensors, Biometric Data Tracking and Metrics

The Omnicept system is a wheel-and-spoke architecture with two main components: Omnicept runtime and sensor data in one of the two game engines (Unreal and Unity) . The final prototype has been developed in UE4.27 (*The Most Powerful Real-Time 3D Creation Tool - Unreal Engine*, n.d.).

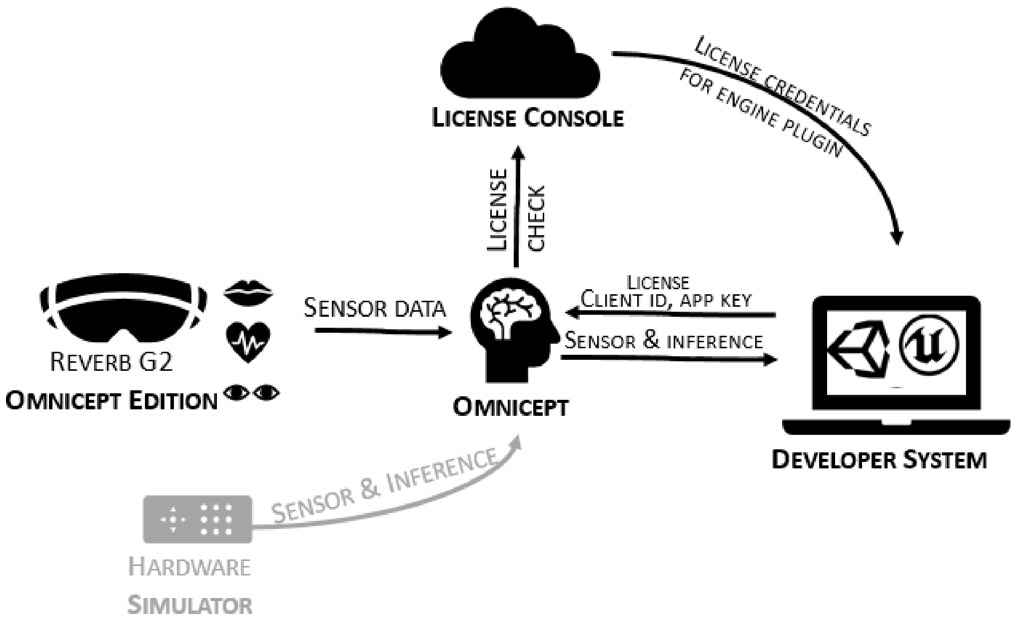

Figure 13: HP Omnicept system visualization (*HP Developers Portal | Fundamentals*, n.d.)

"Omnicept runtime acts as a local server to process and route sensor data among Omnicept clients. Various Omnicept clients that connect to the runtime and send or receive sensor data (including inference engine messages)" (*HP Developers Portal | Fundamentals*, n.d.).

Heart Rate

"PPG (photoplethysmogram) sensor detects the blood volume changes in the microvascular bed of tissue using light signals that reflect onto the skin. The PPG sensor is located on the forehead, represented by two green LEDs. HP does not provide access to the raw PPG data due to security reasons (*HP Developers Portal | Fundamentals*, n.d.)" (Units: Beats Per Minute, Range: 40 to 350 (int), Report Rate: Once every 5 seconds) .

Eye Tracking

“Cameras pointing at the user's left and right eye. The eye camera and eye-tracking on the HP Reverb G2 Omnicept edition is powered by Tobii” (*HP Developers Portal | Fundamentals*, n.d.).

Cognitive Load

HP defines cognitive load as the mental effort associated with performing a task or engaging in a learning process. Real-time biometric indicators of cognitive load are sourced from Omnicept sensor data for analysis, yielding a numerical estimate of cognitive load as a continuous value ranging from 0.0 to 1.0 (*HP Developers Portal | Fundamentals*, n.d.).

Mouth Capturing

A camera located on the bottom of the headset pointing through the mouth of the user. Grayscale images produced by infrared camera positioned beneath headset facing user’s mouth. Image resolution is 400x400 pixels (Units: 8-bit Integer, Range: 0-255 per pixel, Reported Rate: 90 Hz) (*HP Developers Portal | Fundamentals*, n.d.).

Voice Visualization

The voice is visualized via Unreal game engine’s Niagara particle system by getting the microphone’s dynamic input as an audio spectrum node which transforms the normalized particle age into amplitude. This is then multiplied by the velocity of the particles.

Us Xtended - The User Journey and The Narrative Design

The narrative design is formed by a non-linear assemblage of texts throughout the user's journey. These texts occurs in different forms and serve different functions. In each space a 3D text is placed visibly functioning as instruction text. These texts include titles of the worlds and they hint at the user's mission in each world. Another form of text occurs as numbers placed close to the assets which visualize user’s data which is tracked live (percentages, BPM) serving an explanatory role. And finally, the most crucial text emerges as an ambient voice over in the onboarding/intermezzo space.

This voice-over is a dramatized dialogue between two characters accompanying the user while they are in the onboarding/intermezzo space. The voices have been created via the voice AI software Descript (*Descript*, n.d.), while the text has been written by me. Originally, there were three voices: the author (me), my inner voice, and the theoretical voice. In the end the theoretical voice merged with the author voice serving a companion role to the user and contextualizing the work in the given theoretical framework. The inner voice symbolizes a sarcastic 'devil's advocate', which expresses the inconvenient emotions residing in the creator's mind (self-doubt, self-criticism, sarcasm). The voice-over thus attempts to create a personal relationship between the author and the user on a meta-level of the experience.

Onboarding/Intermezzo Space: users explore the environment composed of their biometric avatar which mirrors their eye-movement by pupil position and dilation and well as trace lines. There is also an two-dimensional affect scale measuring their arousal (axis y, 0 - 140 BPM) and dominance (axis x, 0 - 1 as cognitive load) in real time. User's data are abstracted to a simple black dot moving on the scale. users explore their biometric avatar. Cognitive load is reflected in the intensity of the material colour of the circle, whereas the 3D heart object changes its scale according to the frequency of the BPM (see Figure 4). The values are simultaneously transformed into dynamic text. User approaches the self-reporting booth which captures their mouth expressions and voice. This introductory phase sets the stage for self-exploration, asking, "What do you feel?" It introduces the key concept that their biometric data will continuously shape the experience. The mouth also serves as a portal between worlds, framing each environment as both a literal and metaphorical reflection of the user.

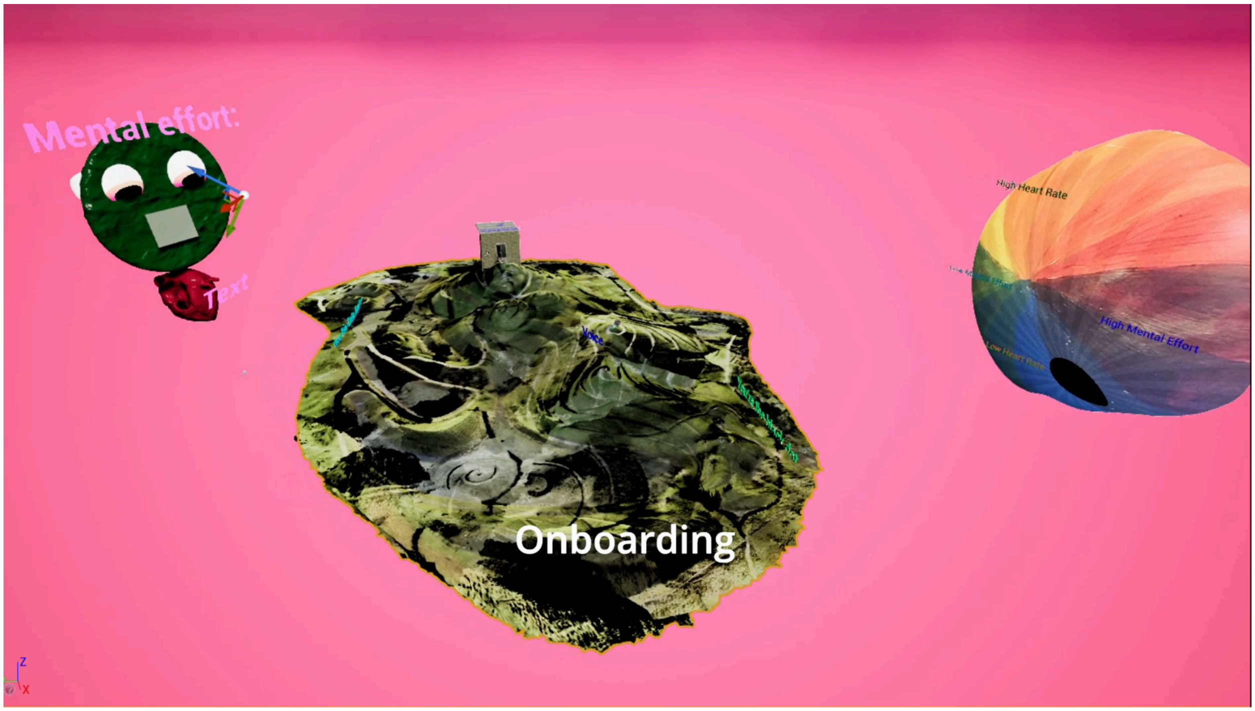

Figure 14: Onboarding/Intermezzo space.

World One - Your Heart Is a Cave: Pink and red tones dominate this world, with the cave's amplitude mirroring the participant's heartbeat. The soundscape simulates the heart rate, creating a rhythmic, immersive environment. The amplitude and intensity of the vibration of controllers attunes to the amplitude of the heart beat. A cave leads users to a heart-shaped object they can grab. Their challenge is to calm or excite the cave depending on what they would like to feel by controlling their heart rate, exploring the feedback loop between their emotions and the environment. The heart object quantifies the heart rate numerically as well. At the cave's end, the mouth takes them back to the intermezzo space. At the cave's end, the mouth takes them back to the intermezzo space.

Intermezzo Space: Here users can reflect what they feel when they compare the affect scale, their avatar and self-report via their mouth expressions how they really feel.

World Two - Sing with the Whale: This underwater-themed world features blues and greens, with a particle based voice-visualizer which reflects participant's voice pitch and volume. It also remixes it into a new soundtrack together with the other surrounding sounds. Engaging with a whale that visualizes their remixed vocal sounds as particle effects in the water. At the end of the underwater space, their mouth-reflection takes them back to the intermezzo space. At the end of the underwater "wobble", the mouth takes them back to the intermezzo space.

Intermezzo Space: Here users can reflect what they feel when they compare the affect scale, their avatar and self-report via their mouth expressions how they really feel.

World Three - Superhero Eyes: Move the World Through Your Eyes: Browns, yellows and pinks color this world. Eye movements and pupil dilation allow users to manipulate floating celestial objects, testing their ability to control the environment through sight. The gaze direction is represented by trace lines. An eye in the sky mirrors the user's pupil position (vector) and dilation (float value) and transforms it into a scalar parameter value of the eye material. Pupil direction controls location and rotation of the objects. The pupil dilation manipulates the scale of the objects.

Intermezzo Space: Here users can reflect what they feel when they compare the affect scale, their avatar and self-report via their mouth expressions how they really feel.

World Four - Mental Effort - Find the Centre of the Labyrinth Visual and Audio Design: This world features a labyrinth of green, with its brightness reflecting cognitive load. In the labyrinth’s center, a sculpture reacts to cognitive activity, challenging users to navigate through the labyrinth.

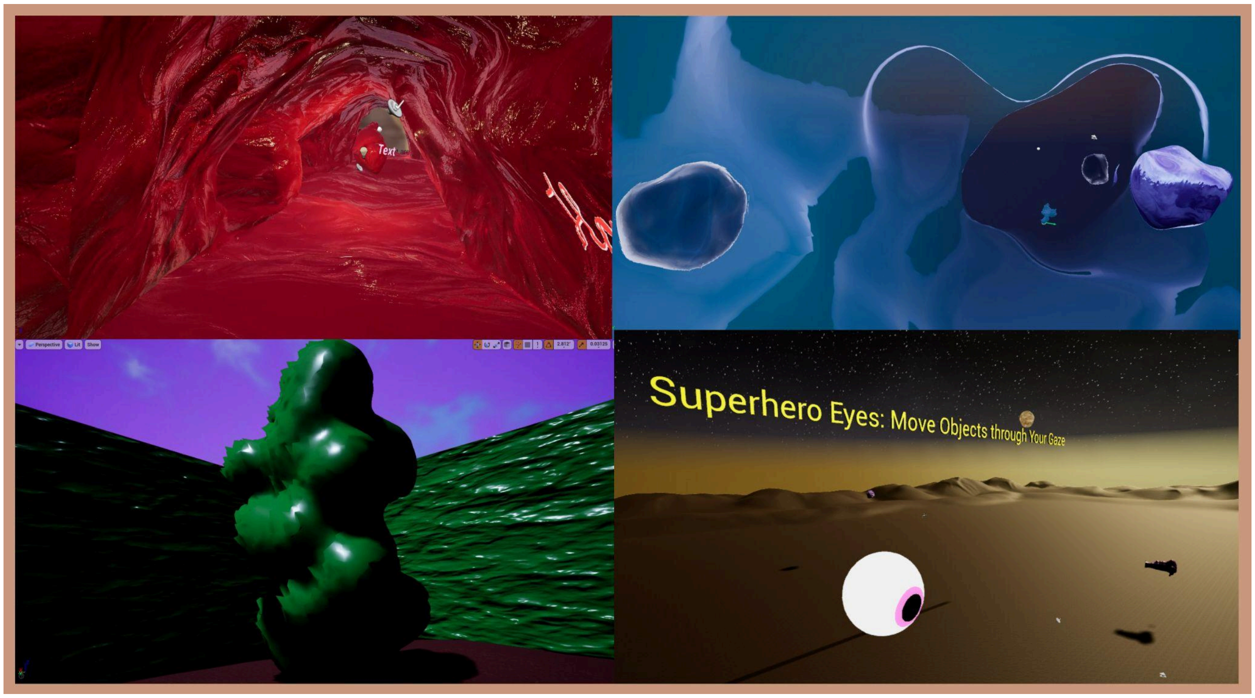

Figure 15: The four embodied worlds.

Final World - Offboarding: users are suddenly inside the affect scale, which became three-dimensional from the two-dimensional model in the intermezzo space. The third dimension is represented by the mouth captures recorded throughout the experience as self-assessment of valence/pleasure placed on the z axis replaying the video footage of their mouth expressions. The 3D affect model is now reflecting all biometric data simultaneously and interprets the heart rate as arousal/activity, cognitive load as dominance/agency and the black circle represents user's affective journey throughout the experience. At the same time, a video is playing the sound and the mouth images on the valence axis. Simultaneously, the moving data-artifact visualizes the remixed sound effects and voice throughout the journey and it also continuously responds to the tracked data. In this final space, users can observe their digital selves and reflect on how the system interpreted their emotional and physiological journey. Moreover in the moving data-artifact, they can observe the "artistic" representation of their inner world they co-created with the system. Is this place symbolizing the intransparency and abstractions of the artificial system that interpreted their data? How do they feel?

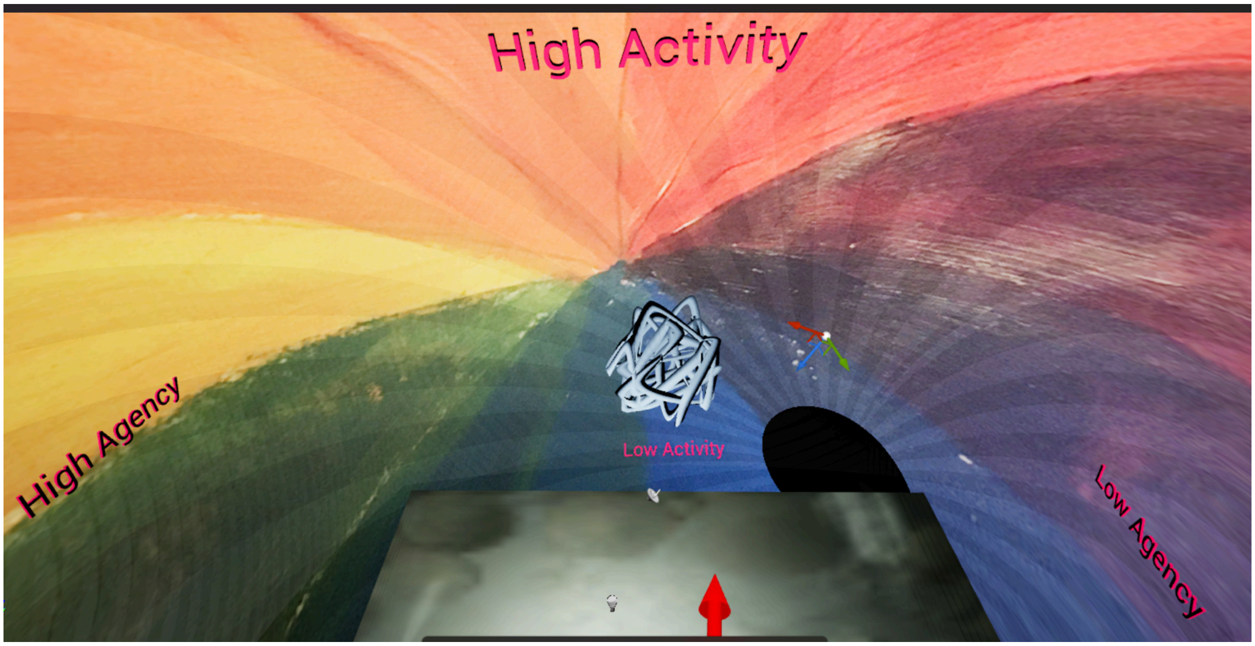

Figure 16: Inside the three-dimensional affect scale with the data-artifact.

Conclusion and Next Steps

Us Xtended not only provides an engaging experience but also prompts users to consider the relationship between their physiological responses and their digital representations. This journey through biometrically responsive environments explores themes of identity, perception, and the interplay between the physical and digital selves.

The main contributions to knowledge stemming from this research are advancements in software experience design, critical perspectives on affective computing, enhancements in user experience design via embedded and embodied design. The dissertation thus contributes with insights into developing more sophisticated, emotionally intelligent XR systems, it adds new knowledge to ethical discussions around the use of emotion-recognition technologies and creates guidelines for creating more engaging and responsive interactive systems based on user affect and embedded and embodied design.

Embodied and Embedded Design Tool for UX Development in XR Headsets

The embedded and embodied design tool will be centered around the development and application of an affect analytics apparatus for XR headsets with biometric data tracking as well as additional wearable hardware such as smartwatches. This technology serves to optimize user design and involves several steps organized into data collection, AI implementation, data analysis, and user experience validation. The initial stage involves the collection of biometric data from users while they interact within an XR environment. The data will include physiological responses such as heart rate, eye tracking, facial and vocal expressions that can be captured via the headset and the wearable sensors (e.g. smartwatches and other tracking technologies). This phase is crucial for gathering raw inputs that reflect the users' emotional and physical states in response to various stimuli within the XR space. This phase will encompass several empirical studies of the stimuli in a controlled XR environment working with a controlled participant group of minimum 30 people to validate this process.

In the past research, valence has only been measured by self-assessment techniques. In order to have a valid comparison between self-assessment and systemic assessment of the pleasure dimension of the scale, two AI models will be implemented: face and voice recognition. Valence can be thus measured via microphone input and/or a face camera attached to the XR headset. Nonetheless, there are several challenges that need to be considered when implementing the models. First, most face recognition models rely on the facial action coding unit system (Ekman et al., 1997; *Noldus | Advance Your Behavioral Research*, n.d.). These units include mouth, eyebrow and nose movements and many other facial cues. The issue arises when the user puts on an XR headsets and half of their face is covered. For this reason, voice recognition is applied as a control mechanism. Moreover, a mask is used as the face of the avatar that users can put on and form according to their self-assessment. The mask thus becomes a SAM-Mask developed from the Self-Assessment-Manikin tool (Bradley & Lang, 1994; Ekman et al., 1997; Handayani et al., 2015; Stevens et al., 2016; Xie et al., 2020). To implement face recognition, a mask dataset collected by the University of Mainz will be used. Regarding the affect voice recognition model, the Audeering dataset will be applied. This way, both models control each other in an adversarial way. And last but not least, they are put to the test by the self-assessment of the user themselves. This way a three-fold audit unfolds, where alignment between these three tools is searched.

Once data is collected, it appears to be visualized in various representations - the changing mask or as an abstract sculpture resulting from the waveform as shown in the images. These visualizations transform raw biometric data into a more interpretable form. For instance, the waveforms depict changes over time and can be specifically applied for the user design analysis or more complex 3D representations that show patterns or trends like the mask object which also represents embeddedness of this technology into the narrative of the given XR experience. This step is essential for making the data accessible and comprehensible to researchers and designers, facilitating further analysis.

The validation phase consists of several sub-steps:

- Empirical Measures: Utilizing the affect scale to evaluate different design interventions and their impact on user experience. This might involve controlled experiments where different variables within the XR environment are manipulated to observe changes in the affect scale.
- Comparison with Baseline: Comparing these empirical measures against baseline conditions or control groups to assess the effectiveness and sensitivity of the affect scale.
- Iterative Refinement: Based on the outcomes, the affect scale and the XR design may be refined to improve accuracy and user engagement. This iterative process ensures that the scale reliably represents user emotions and can guide design decisions effectively.
- Comparison of the self-assessment data and systemic data analysis on the VAD scale.
- Implementation of the technology to the pilot project *Us Xtended*

The final step involves implementing the refined designs back into the XR system and observing further changes in user responses. This feedback loop is critical for continuous improvement and for ensuring that the XR environment evolves to meet user needs more effectively. The methodology also includes ongoing adjustments based on user feedback and additional data collection, maintaining a dynamic approach to user-centered design in XR. This comprehensive methodology uses a scientific and iterative approach to understand and enhance user experiences in XR through biometric data tracking. By focusing on empirical validation and continuous refinement, it aims to create more engaging and emotionally responsive XR environments that are grounded in quantifiable user feedback.

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