Sleeping Soundly: an Interdisciplinary Approach to Communicating Individual Sleep Experiences Through a Shared Sonic Domain

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ABSTRACT

Sleep is a universal behaviour, being essential to physical and mental wellbeing, yet it remains an individual and largely incommunicable experience. During sleep, our consciousness is altered, involving diminished perceptions of the external world. The auditory system, however, remains responsive, opening possibilities for using sound as a two-way method of communication during sleep. This paper explores the use of objective measurements to relate two individuals' subjective sleep experiences via a shared sonic domain, and in doing so details an ongoing interdisciplinary project which integrates knowledge from neuroscience, psychology, data science, sound and music computing, and musicology.

The project, once implemented, will transform real-time physiological data from two sleeping participants into abstract soundscapes through sonification, thereby facilitating a reciprocal interaction within a closed-loop system. This forms the basis for a planned immersive public installation, through which synchronised soundscapes, visualisations, and educational content invite audiences to engage with sleep science and reflect on their own experiences.

This paper details an iterative design process, guided by the Double Diamond framework. It addresses conceptual challenges of the project, such as integrating knowledge from multiple disciplines, relating subjective experience to sonic representations, and applying analytical techniques within an artistic framework. Practical and ethical issues regarding the implementation of the system are also discussed. This paper highlights collaborative efforts from ten doctoral candidates, whose expertise shaped the project.

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1. INTRODUCTION

Sleep presents a paradox: it is universal, yet deeply personal, and cannot easily be shared. This unique, altered state of consciousness has long captivated scientists and artists alike, who strive to express its intangible nature in more concrete forms. Across cultures and eras, sleep has been a recurrent theme, appearing in mythological and religious works [1]. For example, the Vedic and Upanishadic literature of the Indus Valley civilisation (11th–16th century BC), as well as ancient Chinese and Greek writings, offer reflections on sleep and dreams [2, 3]. Similarly in visual art, Piero della Francesca's *Dream of Constantine* (1452) and Sandro Botticelli's *Mars and Venus* (1483) offer mythological representations of sleep. In later centuries, attention shifted to the exploration of the subconscious through dreams. Surrealist artworks, such as those of Salvador Dalí (see Fig. 1), depict the sleep experience using the particular characteristics of 'hypnagogic hallucinations'—vivid sensory experiences that can emerge during the transition between wakefulness and light stages of sleep [4].

Figure 1: Salvador Dalí's *Le Sommeil (Sleep)* (1937).

Sleep has also served as inspiration within classical music. Johannes Brahms's *Wiegenlied (Lullaby), Op. 49 No. 4* (1868) remains one of the most iconic cradle lullabies, and Johann Sebastian Bach purportedly composed the *Goldberg Variations* (1741) as a remedy for insomnia [5]. In addition to aiding sleep, orchestral works have also depicted it, as heard in Hector Berlioz's *Symphonie Fantastique* (1830), where a drug-induced slumber carries the protagonist into uncanny visions. More recently, Max Richter created *Sleep* (2015) [6] based on input from neuroscientist David Eagleman. This 8-hour piece, structured to echo Bach's *Goldberg Variations*, is designed to be 'slept through', blending music and neuroscience into an immersive experience which is often performed overnight to explore the interplay between sound and sleep.

In recent years, the exploration of sleep in art has taken on new dimensions, with contemporary artists incorporating multisensory experiences and cutting-edge technology. Works such as Matthew Bird's *Dormitorium* (2017) (see Fig. 2), [7] and Sally Anderson's *Sleep Sounds* (2018) [8] exemplify this interdisciplinary approach. Bird's installation blends clinical aesthetics with familiar comforts, creating an environment featuring pulsing lights that mimic natural sleep cycles, while Anderson transforms auditory sleep aids into visual art, examining how modern technology influences our perceptions of sleep. These efforts build upon historical traditions while integrating neuroscience, music, and visual art, offering fresh perspectives that bridge scientific understanding and artistic expression.

While most art depicts an individual notion of sleep, few have explored what it might mean to interactively 'share' such an experience. Here, we present a project that is novel in its approach, as it intends to address this gap by using modern technology to facilitate such an interaction, transforming the subjective and isolated nature of sleep into a form that can be collectively experienced.

Figure 2: Matthew Bird's *Dormitorium* (2017). [7]

1.1 Sound as a Medium for Shared Sleep Experience

The act of sleeping represents an altered state in which external perceptions fade, yet certain sensory systems, such as hearing, remain active [9, 10]. This characteristic opens the door to using sound as a medium not only for sleep aid [11], but also to express and connect with the otherwise-elusive experience of sleep.

In an era which explores the use of scientific knowledge for media experiences, the potential for sound to communicate subjective phenomena such as sleep offers new avenues for interaction and understanding. In this context, many interdisciplinary collaborations have embraced sonification—the process of translating data into sound—as a powerful tool for making abstract or subjective phenomena more tangible [12–14]. By converting objective data into auditory formats, sonification offers an intuitive and engaging way to discover otherwise-hidden patterns and dynamics, serving both functional and artistic purposes. For example, it has been employed to transform seismic activity into musical compositions [15], represent astronomical data [16, 17], and raise awareness about climate change [18].

Similarly, technologies for measuring brain activity, such as electroencephalography (EEG), have been embraced in the creation of musical compositions. Alvin Lucier's *Music for Solo Performer* (1965) (see Fig. 3) pioneered the use of brain waves to generate sound, transforming neural activity into an auditory performance [19, 20]. Similarly, David Rosenboom's *On Being Invisible* (1977) [21] explored auditory-evoked responses, using changes in brain signals to shape musical output. More recently, brain wave sonification has expanded into interactive installations such as *MoodMixer* (2011) [22], in which participants navigate a musical latent space by altering their cognitive states via wearable EEG technology. Projects such as *Music for Brain Waves* (2018) [23] further demonstrate the creative potential of EEG-based compositions using neurofeedback, bridging neuroscience and art in innovative ways.

Figure 3: Alvin Lucier performs *Music for Solo Performer*. Photograph: PR handout (sourced from The Guardian).

EEG is also the primary tool for objective sleep measurement, and its sonic representation has been explored as an alternative medium to both understand the sleep process and express it creatively [24–26]. Sonification can provide novel sonic representations of EEG and other physiological features, thereby offering a more intuitive understanding of sleep patterns. The project described in this paper builds on these developments, employing sonification to explore the ambiguity of the individual sleep experience.

1.2 Project Overview: Designing a Shared Sleep Installation

This project involves real-time sleep measurements from two participants, transforming their physiological data into evolving soundscapes. Each participant listens to the sonified data of the other, creating a shared and reciprocal experience within a closed-loop system. This bi-directional interaction forms the foundation of an upcoming immersive public installation, which serves as the project's final output. Within the installation space, synchronised soundscapes from both participants, along with accompanying visualisations and educational content, will also be presented to an external audience, encouraging them to engage with sleep science and reflect on how this relates to their own experiences.

This project is an ongoing collaborative effort from a network of ten doctoral candidates, working together remotely to integrate diverse disciplines including neuroscience, psychology, human-computer interaction, data science, sound and music computing, and musicology. Neuroscience provides insights into the physiological processes of sleep, while psychology examines emotional responses to sonified data. Sonic interaction design and human-computer interaction play key roles in shaping the immersive installation, being facilitated by the principles of data science. Sound and music computing, meanwhile, provides the tools to create soundscapes, informed by knowledge from musicology.

1.3 Core Challenges

The integration of these fields presents three core challenges in creating a cohesive and meaningful work of art. These challenges are:

- Artistic Engagement with Sleep: Working within an artistic framework to represent the altered state of sleep through music and sound.
- Interdisciplinary Integration: Drawing upon expertise from fields related to the three principal components (PCs) of the research network—music, sleep and data science—to create a coherent and meaningful work of art.
- Communicating Subjective Experience Through Objective Means: Sonifying objective sleep data to reflect the personal, often intangible, experience of sleep.

The following sections detail the stages of the project's development, starting with the methodology used. We then outline the exercises that helped to identify and tackle the core conceptual challenges, followed by a review of the design and ideation process, including ethical considerations. Towards the end, the planned implementation for the final installation is described.

2. METHODOLOGY: THE DOUBLE DIAMOND FRAMEWORK

To address the complexities of this project, we utilised the Double Diamond (DD) framework [1], which offers a structured approach to iterative design [27]. The DD framework (see Fig. 4) visualises a design process that alternates between divergent thinking—broadly exploring an issue—and convergent thinking—narrowing focus towards actionable solutions. It is divided into four distinct stages:

- **Discover:** This phase assists in understanding, rather than assuming, what the problem is. It entails engaging in discussions to understand existing perspectives within the context of the challenge.
- **Define:** This phase uses insight gained during the Discovery phase to define and re-frame the original challenge, as a clearly-stated problem.
- **Develop:** This phase encourages the team to provide diverse solutions to the problem from the Define phase, seeking inspiration from other sources and through various collaborations.
- **Deliver:** This phase entails trialling various ideas on a small scale, dismissing those that do not work and enhancing those that do, thereby reaching a final solution to the initial challenge.

3. THE INITIAL CHALLENGE

The team was initially presented with an open task: to work together in completing an artistic project, with no specific restrictions on the medium or format of the final output. This project was, however, expected to involve the aforementioned three PCs of the network and to draw from the expertise of all ten involved researchers, each of whom has a background in one or more of these components. Observing the DD framework, the first goal therefore became to define an initial challenge which incorporates all of the PCs. The team could then use this challenge as a point of divergence, gathering new knowledge to better understand the context and framework in which the work would be developed.

The first PC, music, was selected as the principal medium of artistic output. This was a straightforward choice, being itself a common form of creative expression which could draw from related domains present within the network, such as musicology and sound and music computing. While this decision was taken unanimously early on in the project, the mechanisms through which the music should be both produced and presented remained unclear. Initial discussions were therefore focused on exploring conceptual issues relating to the second PC, sleep, with the idea of tackling these through some form of musical representation. This was particularly approached through the lens of the third PC, data science; all members of the team are from analytical and/or descriptive research backgrounds, providing a motivation to incorporate data-driven science communication into the work. These discussions thereby produced a core question, which served as the initial challenge for the team: *How can we use music to express scientific knowledge regarding sleep, in a way which encourages audience reflection on the topic?*

[1] Link to Double Diamond design framework: `https://www.designcouncil.org.uk/our-resources/the-double-diamond/`

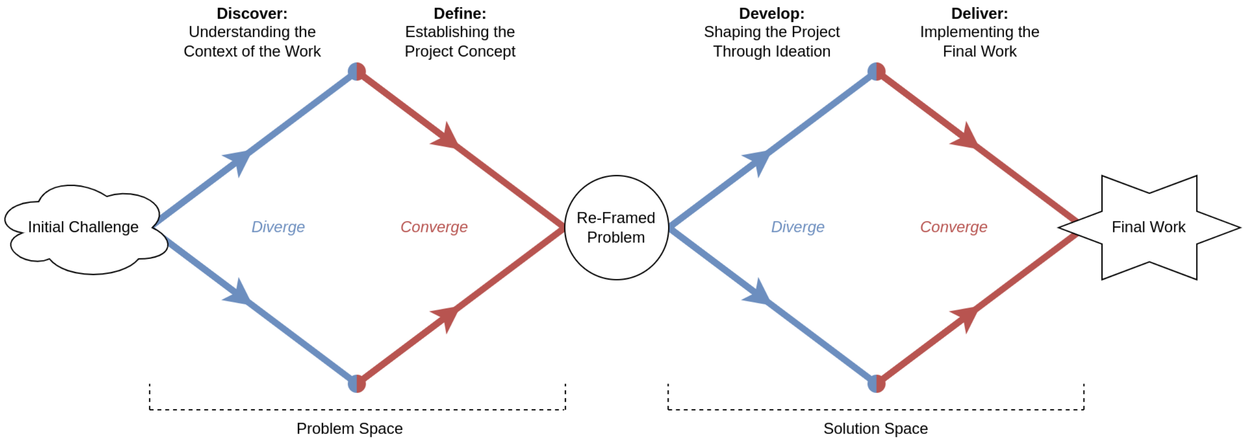

Figure 4: An illustration of the Double Diamond framework.

4. DESIGN PROCESS

4.1 Discover: Understanding the Context of the Work

To begin addressing this question, the team was encouraged to share existing works of art (music, visual art, literature, film, ...) which relate to sleep, and to explain what the work communicates about sleep that is captivating to them. Resultant themes ranged from the individual to the collective, including the impact of sleep deprivation in modern society, representation of dream experiences, and the diversity of sleeping environments across different cultures. These ideas were compiled through open discussion, including brainstorming sessions and virtual 'idea boards' (e.g., Miro [2]) onto which researchers could contribute their thoughts collaboratively. One criterion applied when evaluating these different ideas was novelty. For example, many of the surveyed works, particularly those of the surrealists, were focused on the contents of dreams, and there was therefore a desire to avoid replicating these depictions. A decision was ultimately reached to focus the project on sleep experience at an individual level, as this would allow members of the audience to directly relate the piece to their own personal experience of sleep.

Having reached this consensus and conducted a general review of existing works on the topic, the team also explored their own instinctive notions of how different qualities of sleep could be represented. One exercise involved separately expressing verbal accounts of the sleep experience through metaphor (e.g., '*the feeling of melting*', '*floating on a calm river*', '*a thick, misty atmosphere*'), before reviewing the different descriptions to identify points of congruity. Fig. 5 shows a word cloud, produced from these written accounts to visualise the common themes. The use of shared online documents was a key component within such exercises, due to the remote nature of the collaboration.

The team also began relating sleep experiences specifically to music. This involved separately selecting pieces of

[2] Link to Miro: `https://miro.com/`
[3] Link to word cloud tool: `https://www.jasondavies.com/wordcloud/`

Figure 5: A word cloud produced from various written descriptions of sleep metaphors, using an online tool [3]. The size of each word is determined by the frequency of its occurrence across all descriptions.

music which represented their own sleep experience, and justifying these choices to the other researchers by delineating the musical qualities which held sleep-like connotations. Further exercises included collectively analysing existing works by contemporary composers, noting the perceived meanings and associations presented within these works. This included works such as the aforementioned Richter's *Sleep*, which exemplified the integration of neuroscientific knowledge within a musical composition. A key takeaway from these exercises was the inherent ambiguity in representing subjective experiences of sleep – both when described verbally and when conveyed through an abstract musical domain. Rather than fighting this attribute, the team chose to embrace sleep's lack of clear definition, using sound to express the different subjective states of consciousness that can be inferred from sleep measurements rather than explicitly communicating the objective measurements themselves to the listener.

Nevertheless, meaningful communication remained a core concern of the development process, as a purely aesthetic approach would neglect the fundamental research-based character of the project. Alongside exercises involving listening to music, the team engaged creatively with sound as a medium of expression; this was particularly motivated by the diversity of background within the network, which meant that not all researchers were familiar with musical concepts or sound production tools. The team experimented by developing 'sound collages', produced by digitally arranging and layering audio samples using simple software such as Audacity[4]. These were developed both individually and collaboratively within small groups. Once produced, 'games' were played in which other members of the team speculated on the intended meaning of the sound collages. This encouraged self-evaluation on the part of the researchers regarding the assumptions made when producing a piece of music, and led to introspection over the associated meanings that were communicated through their pieces. These reflections were furthered by exploring psychological accounts of the subjective listening experience, such as Auditory Scene Analysis [28]. This helped to decompose the approached creative works into separate perceptual streams, thereby clarifying and formalising analogies between the different layers of the respective piece and the individual concepts they represent.

4.2 Define: Establishing the Project Concept

Over the course of these exercises, two contrasting goals emerged within the project: the artistic expressivity gained through a non-explicit approach to sleep representation, combined with a desire for communicating knowledge on sleep with a basis in scientific clarity. A natural tension therefore lay between the inherently objective approach of the researchers' own disciplines, paired with the subjective nature of the artistic task. This conflict was addressed by adopting sonification at the core of the project's musical output. By converting objectively-measured sleep data to a musical domain, sonification serves as a natural link between all three PCs of the network (music, sleep, and data science), and allows the project to employ objective domain knowledge within an artistic framework.

While the project had now converged on sonification as a general method for producing the artistic output, the format of the presentation still had yet to be determined. Building on the chosen technique, the team now began engaging with existing sonification-based art, sharing works together and meeting with artists who had worked directly with the sonification of EEG data. EEG (and accompanying physiological measurements) was soon chosen as the data to be sonified within this project too, due to its widespread adoption within sleep science. These measurements could now be approached within the context of specific frameworks such as the Data Sonification Canvas [29], which introduced new ways of thinking about the framing and presentation of sonified data. The team was now searching for a format in which sonified EEG data could be used to address the core aim of the project: inducing a reflection of individual sleep experience within the audience.

[4] Link to Audacity: `https://www.audacityteam.org/`

Producing a sonified output which could be related directly to the audience's own sleep behaviour brought with it a suggestion of personalisation, something which could be achieved computationally using skills present within the network. Such an approach necessitates some form of interactivity within the system, and led the team to decide upon a live installation as the format of the work, taking inspiration from contemporary multisensory experiences such as the aforementioned *Dormitorium*. While the details of this implementation had yet to be determined, a notion emerged of having individuals' own sleep data be measured and sonified in real-time. Thus, those participating in the work cease to be passive, impartial observers, and instead form critical components of the piece itself, forming a continuation of Lucier's *Music for Solo Performer* which applies the expressiveness of EEG sonification to communicating subconscious mental states. The three core challenges of the project (listed in Section 1.3) now followed from this stage, becoming critical points of discussion within the team, and acted as starting points for further ideation, towards an explicit design for the installation.

By this point in the project, the team had developed a collective understanding of the context in which the piece would be implemented, and had used this knowledge to define a re-framing of the initial challenge. A new question now arose: *How can the experience of sleep be communicated from one individual to another, through real-time sonification of sleep measurements?*

4.3 Develop: Shaping the Project Through Ideation

The transition into the development stage of the DD framework marked a return to divergence. This is the current phase of the project, in which ideation sessions have up to now focused on exploring varied approaches to sonification and user interaction, specifically aiming to transform sleep into a shared experience through sound.

To ensure a comprehensive exploration process, contributors were free to focus on aspects of the project aligned with their skills and interests. All individuals could therefore participate freely across the ideation tasks, encouraging collaboration and communication within the project. A combination of tools and techniques were used to facilitate creative thinking, including further brainstorming sessions and idea boards, as well as individually producing mockups of the envisioned sonic and visual final outputs, which were then reviewed jointly as points of discussion. This approach was instrumental for integrating perspectives across the team's different backgrounds, ensuring that everyone was involved in contributing to the evolving vision.

These ideation sessions have been critical in synthesising individual ideas towards a cohesive design concept. A significant outcome was the establishment of the project's central system design: two sleepers in separate spaces, each hearing the sonification of the other's physiological signals, while an external audience experiences a combined representation of both their data. This design encapsulates the shared experience as a dialogue between the subconscious minds of the two sleepers. Their internal states, inferred through EEG and other physiological data, are externalised as sound, creating an interaction that connects the sleep of the two individuals. The audience, observing from a central shared space, experiences a combination of both sonifications, alongside accompanying visualisations, thereby allowing them to notice points of synchronicity between the two sleepers. This installation encourages the audience to reflect on the nature of sleep, as both a personal and a collective experience.

Having established this central design, thematic meetings took place for focused discussions on components such as sound production, visual composition, and spatial design. These helped to identify common elements within the ideas of the researchers and establish a consensus on the aesthetic direction. In ideation sessions centred on sound, for example, the team would express their ideas for the musical component and share inspirational pieces. Visual inspiration also played a role in shaping the auditory aesthetic; a collage of images (see Fig. 6) showcases some of the ideas presented during a meeting on visual aesthetics, highlighting recurring motifs such as *waves* and *flow-like* elements that also subsequently informed ideas on sound design. These ideas aligned on an emphasis towards the dynamic nature of electromagnetic signals, these being measured directly from brain activity (through EEG) before being transmitted as data and sound. Additionally, the team noticed a shared vision for gradually evolving soundscapes with soft, delicate harmonies and a slow tempo, aiming to create an atmosphere that mirrors cyclic sleep patterns. These choices reflect the team's goal to balance data-driven design with an engaging, immersive experience.

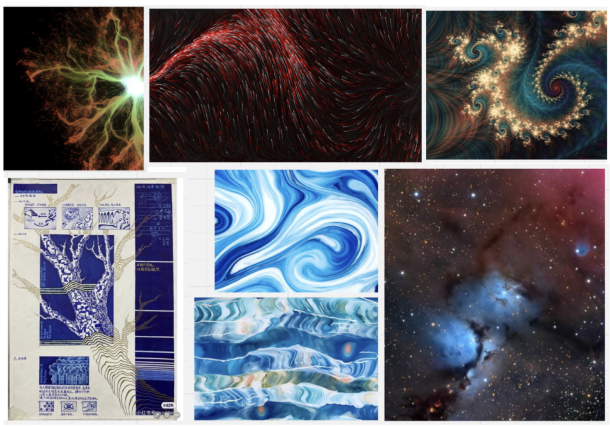

Figure 6: A collage of images that were shared by members of the team during an ideation session, as inspiration pieces for visual aesthetics.

While smaller thematic meetings allowed for in-depth exploration of such ideas, larger group discussions synthesised the insights and integrated them into the overall design concept. All final creative decisions were made collaboratively, ensuring a balanced and inclusive approach. Where possible, elements from various suggestions were combined into a single concept. For example, a dome-shaped setting and the involvement of two sleepers had initially been separate ideas, which were then brought together for the final design.

Ideas were evaluated against criteria such as feasibility, alignment with project goals, technical constraints, and potential for audience engagement. Concepts that effectively balanced artistic creativity with scientific rigour were set as a focus. However, some ideas had to be reconsidered due to practical constraints. For example, the concept of a large-scale dome for visual projections was adapted to fit within a feasible space, evolving into an open, dome-shaped structure without a roof. These limitations prompted the team to re-focus on designs that could be implemented effectively given the available resources. This iterative process ensured that the final concept remained grounded in the project's core motivations, while adapting to real-world constraints.

An ethical constraint concerns the inclusion of an appropriate audience to the installation. The venue where it will be presented is open to people of all ages, and the groups of people which will attend the exhibition were therefore considered. The team discussed including minors as participants in the sleeping experience, but eventually agreed to exclude them, due to concerns regarding privacy, data protection, and informed consent, which are particularly sensitive regarding individuals under the age of 18. Moreover, for the adult participants who are included, the team decided that all collected data will be anonymised.

A crucial consideration also remained to maintain a balance between scientific or pragmatic perspectives and the more artistic aspects of the project. Much of the initial focus naturally gravitated towards practicalities, such as space configurations and data accuracy. While these considerations were important, they overshadowed deeper reflections on the aesthetic and experiential values of the installation. This imbalance prompted the need for further 'framing' sessions focused on the project's creative and artistic potential. This allowed the team to collectively re-balance the dual goals of the project: an artistic depiction of subjective sleep experience, implemented through science-based analysis of objective measurements.

To contextualise the piece to an audience unfamiliar with sleep science, the team explored ideas of framings centred around the existing design concept. For example, one focused on the interaction between the two sleepers (see Fig. 7), while other ideas included a 'sleep archive' which stores sleep experiences akin to books in a library, a dystopian narrative imagining a future without sleep, and a narrator which guides participants through the stages of sleep. One recurring notion was the previously-explored emphasis on shared experience of the subconscious, as the piece facilitates a dialogue between the subconscious minds of the two sleepers. Another common thread was audience immersion: rather than merely observing, the audience is invited into a sensory environment that evokes the experiences of sleep for them too, thereby opening a window into the interaction between the two sleepers. A central theme emerged from these ideas: communication between two subconscious minds and a conscious audience. The sonifications could here be viewed as personal, improvised performances by the sleeping individuals, in which their subconscious minds hold an expressive influence over a creative output. This framing prompted the question *"Who are you when you are asleep?"*. The researchers reflected on the inherently personal nature of sonified sleep data, emphasising that transforming someone's sleep into sound creates an intimate auditory narrative. This personal aspect, in combination with the public audience experience, underscored the installation's dual focus on individual identity and shared connection.

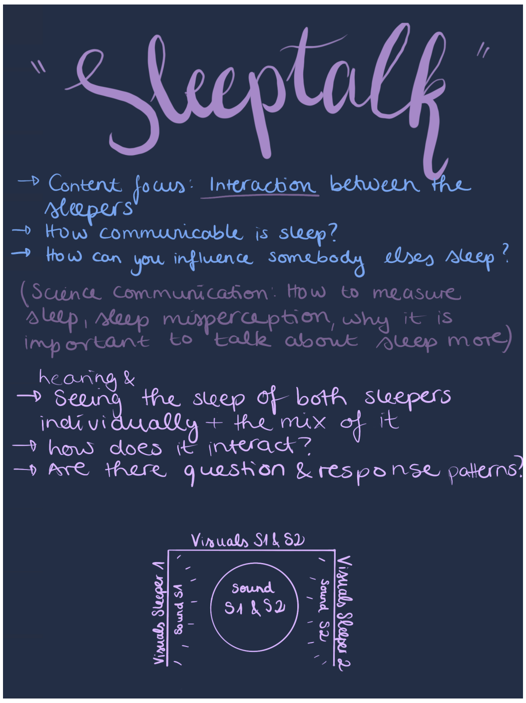

Figure 7: Example of a framing which explores the interaction between two sleepers, created by a member of the team (Annika Partmann).

The team worked to ensure that efforts consistently aligned with the core challenges, stepping back regularly to reflect on the broader purpose of the installation. This allowed for adaptation to practical constraints while preserving the integrity of the work, ultimately laying a strong foundation for now-refined concepts to be transformed into the final implementation. Having determined the design concept, the current question now stands: *How can this design be actualised as a physical installation, while adapting to the practical constraints of the project?*

4.4 Deliver: Implementing the Final Work

We will now delineate the prototyping, testing and final implementation of the installation - tasks which are still upcoming.

4.4.1 System Design

Building upon the outcomes of the Develop phase, the planned installation will consist of a dome-shaped environment and two separate 'pods' - secluded, private environments which are separated from the dome, where two individuals will be invited to nap (see Fig. 8). These pods were chosen partially for ethical reasons, considering the psychological effects that sleeping in public might have. This will ultimately also be beneficial for the installation itself, creating an environment in which participants feel comfortable and are able to fall asleep.

Participants will be provided with earbuds and a Hypnodyne ZMax [5] , a non-invasive headband for real-time sleep measurement. The ZMax measures EEG signals through two channels, as well as physiological data such as movement, respiration, and heart rate. The two participants will then enter the pods, where they are encouraged to relax and sleep for 30 minutes. Meanwhile, real-time measurements will be transmitted wirelessly from the ZMax to the custom software, which transforms their data into soundscapes. For sound generation, the team will use Pure Data (Pd) [30] [6] , an open source visual programming language often used for audio and multimedia purposes. Pd was chosen due to being modular, flexible, and accessible, thus making it particularly suitable for real-time sonification. Shared repositories, using Git version control, further facilitate the remote collaboration by hosting sleep feature extraction pipelines, written in Python. Through a combination of both Pd and Python, a dynamic mapping is applied between raw physiological measurements and the parameters of a real-time audio synthesis system. The audio system is expected to be multi-layered, including harmonising drone-like musical sounds, procedural elements which emulate natural sounds (e.g., ocean waves, rainfall), and coloured noises (e.g., pink, brown), all of which will be combined and subsequently passed through digital effects (e.g., reverb, delay). Examples of these sonic layers have already been produced during the Develop phase, via the aforementioned mock-up exercises. The overall aim is to immerse the listener in a spacious, fluid sonic environment consistent with previously-explored sleep metaphors. To emphasise the continuity of the space and avoid jarring changes which might disturb sleepers, a decision was made to exclude percussive elements, instead emphasising soft melodic components, which are gradually modulated based on the sleep data. A conscious decision was also made to avoid high frequencies, which are perceived as disturbing to sleep [31], instead focusing on sounds most prominent in the midrange.

Since participants are asked to nap for 30 minutes, they are expected to enter a state of light sleep (stages N1 and N2), characterised by alpha (8-12 Hz, indicative of relaxation) and theta (4-8 Hz, a marker of drowsiness) brain waves. Ratios between different frequency band amplitudes will be applied to gradually modulate the musical sounds, selecting harmonic intervals representative of the sleep experience. To account for noise within the measurements, highly reactive musical components will be less prevalent, and controls (e.g., low-pass filters) will be used to exclude rapidly-changing elements in the data. Simultaneously, consistent, slow sounds will be added, to allow for participant relaxation. Deeper sleep (N3) may also be reached, entailing an increased presence of slow-waves

[5] Link to Hypnodyne: `https://hypnodynecorp.com/index.php`
[6] Link to Pure Data: `https://puredata.info/`

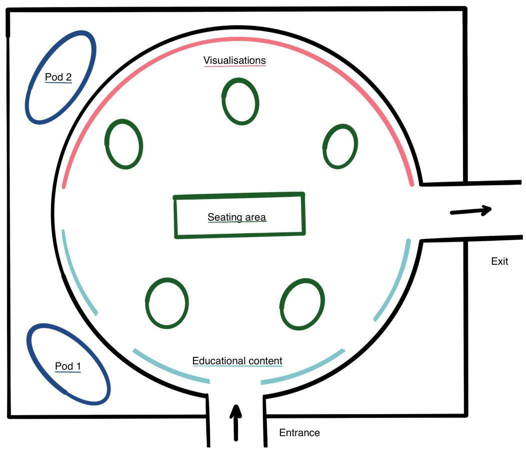

Figure 8: Draft sketch, showing an idea for the floor plan of the space.

(delta frequency power, 0.5-4 Hz) characterised by a consistent oscillatory behaviour. This will also be accounted for, by embedding these oscillations directly within the sonification. The soundscapes will also be subject to high-level musical constraints, such as a shared key or tempo, which ensure the paired sleepers' outputs retain some coherence between one another regardless of the two sleep states.

Simultaneously, EEG-based visualisations which evoke the shared motif of waves will be projected in the dome-shaped space, to accompany the synchronised soundscapes. These will be created using TouchDesigner [7] , a visual programming environment widely used for interactive multimedia applications due to its modularity and real-time data capabilities. The visuals will be generated through a combination of techniques, including particle systems generally used for dynamic cloud effects, noise-based generators to create fluid textures and abstract shapes, and geometry manipulation to produce evolving, dynamic geometric forms. Additionally, the visuals will be audio-reactive, synchronising with the soundscapes to create a cohesive, immersive experience. Educational content will also be incorporated within the installation, including written content, diagrams, and graphs, for the audience to learn and reflect on the scientific foundations of sleep.

4.4.2 Prototype Development

Having planned a general system design, the next steps will focus on development of a prototype. For this, the team will start discussing more deeply how to shape the physical installation, considering six components: sound, visuals, data collection, space, content and communication, and coordination and presentation. This new phase of the project will involve two parallel workflows. On one side, the team will organise into flexible smaller groups based on domain expertise, as well as personal interest and knowledge built during previous stages of the project. On the other, time will be reserved for broader discussions involving the whole group, to reach a consensus on common aspects of the installation. This aims to simplify the approach to each facet of the installation, facilitating rapid generation of ideas and implementation of project features. The subsequent joint discussions then allow the team to re-examine these developments, expanding the perspective and exploring them in detail to reach a common ground.

[7] Link to TouchDesigner: `https://derivative.ca/`

4.4.3 Development Challenges

The implementation of this installation entails some practical challenges. One is that the members of the team are based in several different locations across Europe, making the need to meet to work together on system testing and practical construction before the exhibition particularly important. Another important challenge is resource constraints for the implementation. As previously mentioned, limitations in equipment, space, and budget occasionally forced the team to scale back ambitious concepts or rethink aspects of the project. Such practical restrictions may compel the team to adapt or simplify conceptual elements to align with what is realistically achievable, leading to further adaptations before the presentation. Finally, data privacy should be considered, relating to the processing of sensitive measurements (i.e., neuroimaging recordings such as EEG), which requires providing participants with the knowledge to give fully-informed consent. This includes preparing for any psychological effects that recording their data might encompass, and explaining the measurements themselves, which they may not be familiar with beforehand.

5. CONCLUSION

In this paper, we outlined the context for a novel interdisciplinary art project, along with the phases of divergence and convergence that led to the design of an interactive installation, which explores sleep as a shared experience through sonification. An overview was also given of the next steps to be followed for implementation of this installation. Throughout the paper, we emphasised the importance of this project's background: a collaboration between ten researchers from different disciplines, using objective measures to explore and share the subjective experience of sleep through music.

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6. REFERENCES

[1] C. M. Shapiro, F. Boquiren, V. Boquiren, and D. Sherman, "Sleep in art and literature," *Atlas of clinical sleep medicine*, pp. 1–10, 2009.

[2] S. Datta and R. R. MacLean, "Neurobiological mechanisms for the regulation of mammalian sleep–wake behavior: reinterpretation of historical evidence and inclusion of contemporary cellular and molecular evidence," *Neuroscience & Biobehavioral Reviews*, vol. 31, no. 5, pp. 775–824, 2007.

[3] J. Barbera, "Sleep and dreaming in greek and roman philosophy," *Sleep medicine*, vol. 9, no. 8, pp. 906–910, 2008.

[4] M. Caraccio and M. H. Kryger, "Salvador dalí: hypnagogic hallucinations in art," *Sleep Health: Journal of the National Sleep Foundation*, vol. 9, no. 1, pp. 1–2, 2023.

[5] P. Williams, *Bach: The Goldberg Variations*. Cambridge University Press, 2001.

[6] M. Richter, "Sleep," CD, 2015.

[7] M. Bird, M. McMahon, S. W. Rajaratnam, S. Drummond, and C. Parry, "Dormitorium," in *Matthew Bird: Dormitorium*, 2017.

[8] "2018 sleep sounds / sydney contemporary art fair — sally anderson," https://sallyleeanderson.net/forthcoming-sleep-sounds-2018, (Accessed on 11/17/2024).

[9] E. B. Issa and X. Wang, "Sensory responses during sleep in primate primary and secondary auditory cortex," *Journal of Neuroscience*, vol. 28, no. 53, pp. 14 467–14 480, 2008.

[10] T. Andrillon and S. Kouider, "The vigilant sleeper: neural mechanisms of sensory (de) coupling during sleep," *Current Opinion in Physiology*, vol. 15, pp. 47–59, 2020.

[11] E. Capezuti, K. Pain, E. Alamag, X. Chen, V. Philibert, and A. C. Krieger, "Systematic review: auditory stimulation and sleep," *Journal of Clinical Sleep Medicine*, vol. 18, no. 6, pp. 1697–1709, 2022.

[12] S. Pauletto and A. Hunt, "A toolkit for interactive sonification." in *Proceedings of the 10th International Conference on Auditory Display (ICAD)*, Sydney, Australia, 2004.

[13] T. Hermann, A. Hunt, J. G. Neuhoff *et al.*, *The sonification handbook*. Logos Verlag Berlin, 2011, vol. 1.

[14] D. Worrall, "Sonification design," *Cham: Springer*, 2019.

[15] R. McGee and D. Rogers, "Musification of seismic data," in *Proceedings of the international conference on auditory display (ICAD), Canberra, Australia*, 2016.

[16] N. Misdariis, E. Özcan, M. Grassi, S. Pauletto, S. Barrass, R. Bresin, and P. Susini, "Sound experts' perspectives on astronomy sonification projects," *Nature Astronomy*, vol. 6, no. 11, pp. 1249–1255, 2022.

[17] M. Quinton, I. McGregor, and D. Benyon, "Sonifying the solar system," in *Proceedings of the 22nd International Conference on Auditory Display (ICAD)*, Australian National University, Canberra, 2016.

[18] P. Lindborg, S. Lenzi, and M. Chen, "Climate data sonification and visualization: An analysis of topics, aesthetics, and characteristics in 32 recent projects," *Frontiers in Psychology*, vol. 13, p. 1020102, 2023.

[19] A. Lucier, *Music for solo performer*. Lovely Music, 1982.

[20] V. Straebel and W. Thoben, "Alvin lucier's music for solo performer: experimental music beyond sonification," *Organised Sound*, vol. 19, no. 1, pp. 17–29, 2014.

[21] D. Rosenboom, *On being invisible*. Music Gallery Editions, 1977.

[22] G. Leslie and T. R. Mullen, "Moodmixer: Eeg-based collaborative sonification." in *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME)*, Oslo, Norway, 2011, pp. 296–299.

[23] L. Forcucci, "Music for brainwaves: Embodiment of sound, space and eeg data," *Body, Space & Technology*, vol. 17, no. 1, 2018.

[24] A. Väljamäe, T. Steffert, S. Holland, X. Marimon, R. Benitez, S. Mealla, A. Oliveira, and S. Jordà, "A review of real-time eeg sonification research," in *Proceedings of the 19th International Conference on Auditory Display (ICAD)*, Lodz, Poland, 2013.

[25] G. Weinberg and T. Thatcher, "Interactive sonification of neural activity," in *Proceedings of the 2006 conference on New interfaces for musical expression*, 2006, pp. 246–249.

[26] S. Sanyal, S. Nag, A. Banerjee, R. Sengupta, and D. Ghosh, "Music of brain and music on brain: a novel eeg sonification approach," *Cognitive neurodynamics*, vol. 13, pp. 13–31, 2019.

[27] D. Gustafsson *et al.*, "Analysing the double diamond design process through research & implementation," Master's thesis, 2019.

[28] A. S. Bregman, *Auditory scene analysis: The perceptual organization of sound*. MIT press, 1994.

[29] S. Lenzi and P. Ciuccarelli, "Designing tools for designers: the data sonification canvas," 2024.

[30] M. S. Puckette, "Pure data," in *Proceedings of the International Computer Music Conference (ICMC)*, Thessaloniki, Greece, 1997.

[31] R. J. Scarratt, O. A. Heggli, P. Vuust, and K. V. Jespersen, “The audio features of sleep music: Universal and subgroup characteristics,” *PloS One*, vol. 18, no. 1, p. e0278813, 2023.