Visual Noise Cancellation: Exploring Visual Discomfort and Opportunities for Vision Augmentations

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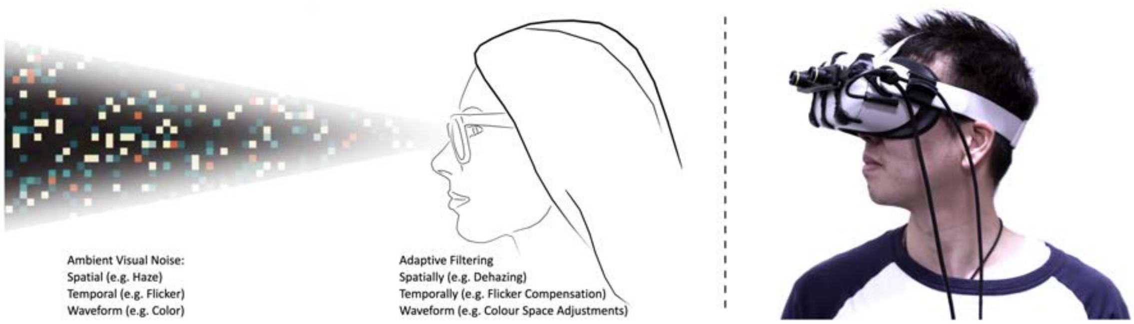

Fig. 1. The concept of Visual Noise Cancellation (VNC). (Left) We are continuously perceiving a stream of visual information. Much of it could be characterised as visual noise with certain spatial, temporal, and waveform (frequency) characteristics. We characterise visual noise and propose active cancellation by way of computerised glasses. (Right) We developed demonstration prototypes to explore VNC using a video-see-through mixed-reality headset with four VNC scenarios identified in workshops with potential end users.

Acoustic noise control or cancellation (ANC) is a commonplace component of modern audio headphones. ANC aims to actively mitigate disturbing environmental noise for a quieter and improved listening experience. ANC is digitally controlling frequency and amplitude characteristics of sound. Much less explored is visual noise and active visual noise control, which we address here. We first explore visual noise and scenarios in which visual noise arises based on findings from four workshops we conducted. We then introduce the concept of visual noise cancellation (VNC) and how it can be used to reduce identified effects of visual noise. In addition, we developed head-worn demonstration prototypes to practically explore the concept of active VNC with selected scenarios in a user study. Finally, we discuss the application of VNC, including vision augmentations that moderate the user's view of the environment to address perceptual needs and to provide augmented reality content.

CCS Concepts: • **Human-centered computing → HCI theory, concepts and models**; **Mixed / augmented reality**.

Additional Key Words and Phrases: Visual Noise Cancellation, Augmented Human, Perception, Augmented Reality, Vision Augmentation, XR, Visual Discomfort

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1 INTRODUCTION

When the first commercially available noise-cancelling headphones were introduced in 1989 it was seen as a revolutionary, innovative step to electronically minimise the environmental noise in airplanes. The active noise control system allowed more clear, intelligible audio communication for pilots without the need to make the headphones bigger and bulkier for passive noise minimisation. Since then, acoustic noise cancellation (ANC) has gone beyond the application in airplanes and is now a commonplace feature in modern headphones for e.g. listening to music and working in noisy office environments. The technology has matured to the degree that the mass production of high-quality headphones (around-, on-, and in-ear) led to the omnipresence of ANC devices helping to overcome negative effects of noise [2, 23, 27].

We propose that it is now time to embrace the concept of ANC in the visual realm—akin to unwanted sound in the surrounding environment there is a plethora of visual aspects that one potentially wants to control and filter. Going beyond similar technological approaches like diminishing reality which tries to eliminate parts of a visual scene or saliency modulation which emphasises aspects like contours or lighting we target adaptive filtering. With adaptive filtering techniques, we modify certain spatial, temporal, and waveform characteristics to make a visual experience more comfortable and to improve the perceived quality of potential augmentations.

Already in 1965, the term *visual noise* was used as "visual noise in the form of unwanted [visual] signals" and first studies showed negative effects in human perception [34]. Recent papers also used the notion of visual noise for example when talking about movements in user's view [25] or for the visual stimulus caused by uncomfortable interpersonal distance [54]. Thus while the term visual noise is already used and first approaches for technical mitigation of visual noise exist the question of what actually constitutes visual noise remains unanswered. In fact, while we have a good understanding of what characterises audio noise, usually undesired frequencies in the audible spectrum, we have less understanding of visual noise and its mitigation. From other fields, we know the concept of image noise, as it usually arises in analogue and digital photo sensors. Furthermore, research has explored the concept of Diminished Reality (the removal of objects from the user's view) [42] and increasingly explores visual clutter and visual saliency [59, 64]. Whether these concepts align with the general perception of visual noise and its mitigation so far remains unclear.

Our inquiry will initially explore the existence and cause of visual noise. Instead of starting our inquiry by directly drawing analogies from audio noise (e.g., identifying undesired frequencies) or reviewing the model of the human visual system, we start with a human-centred approach that explores the character of visual noise in workshops with participants from various backgrounds. The goal is to aggregate examples of visual noise from a human perspective prior to linking back to the human visual system and existing theories of noise. In future work, such as preliminary visual noise cancellation Optical See-Through HMDs, a human vision approach with more quantitative data such as pupil size and gaze attention can provide a more intuitionistic understanding.

In a second step, similarly to active audio noise cancellation, we will conceptually explore how we can actively compensate or cancel the identified sources of visual noise. For this part of our research, we utilise head-mounted displays (HMDs) that have traditionally been used to fully immerse the user in computer-generated graphics (Virtual Reality) or to overlay graphical information onto the physical world as in Augmented Reality. However, recently we saw how HMDs have been used to manipulate the perception of the real world [25, 57, 58, 60] making them an ideal candidate to also explore the perception of visual noise cancellation.

In summary, our research contributes the following insights. Firstly, (1) guided by prior work in *Human-Computer Interaction* (HCI) using focus groups or brainstorming workshops (e.g. [52, 63]), we start from a user-centred approach utilising workshops with participants from different backgrounds to create insights into what constitutes visual noise. We later converge into a first model for visual noise, further considering the literature on specifics of the human-visual system and the causes for visual noise as well as existing work on audio noise.

Secondly, (2) using these findings, we build prototypes for different scenarios of active visual noise cancellation and provide findings from an exploratory investigation on the reception of visual noise cancellation.

Finally, (3) we provide a discussion of the practical relevance of visual noise cancellation also reflecting on the overlap with existing concepts and works including those from Diminished Reality and vision augmentations while also identifying requirements and research opportunities.

2 RELATED WORK

We will briefly introduce the traditional concept of audio-noise which inspired this work before presenting key works on visual noise and vision augmentation. Finally, we will summarise the research gap and provide context from the literature for our research methodology.

2.1 Audio Noise and Audio Noise Cancellation

Our work takes inspiration from the rise in audio-noise cancellation technology and explores its visual counterpart. We are often exposed to different kinds of audio noise, both natural and human-made. Audio noise is usually understood as frequencies in the audible spectrum that are unpleasant, either because of their pitch (frequency) or their amplitude (volume) [29]. Audio noise can lead to hearing loss [10, 13] but can also impair cognitive performance, like memory and language systems [38–40]. Audio noise can even cause symptoms like nausea, disorientation, and general unpleasantness [6, 56]. Exposure to audio noise can also cause long-term symptoms especially psychological ones, like depression, anxiety, and sleep disturbance [3]. Active audio noise cancellation is commonplace nowadays and can be understood as a technological aid to enhance or support human perception. It can reduce the perceived noise, create a calm environment (e.g., in planes or workplaces), or improve the perceived quality of played audio information through the reduction of background noise [29]. There are multiple pieces of evidence in the literature that audio noise cancelling has positive effects on work stress, work strain, and the stress-recovery in noisy open-plan offices [11, 22, 43] and that active noise cancellation headphones with white noise are able to aid sleep [48].

2.2 Visual Noise and Visual Noise Cancellation

When we consider noise, we usually think of auditory noise but there might also be an equivalent in the visual domain. For example, we can characterise photo sensors by how much noise they introduce to photos (perceived as a grain or small random variation in pixel values). We similarly can adjust photo or video material to make it visually more pleasing, for example by adjusting the colour (e.g. temperature, saturation), contrast, or even change pixel noise. However, noise as a perceptually unpleasant sensation in the human visual system is less explored. One of the earliest mentions of visual noise in the literature treats visual noise as a distracting movement in the visual periphery and even reported on the negative effects such as reduced performance [34]. A recent work picked up that idea and blurred the background in an AR system. They conduct a study with four participants but cannot report on any statistical effects due to the limitation of the study [25]. Another work states that visual noise is related to interpersonal distance (or a lack thereof). They do not provide any justification for their assumption, which is also not backed up by the literature. They present a technical approach to control the interpersonal distance using size changes of people in the environment but do not conduct any study or provide results [54]. So far these works assumed certain phenomena to be visual noise but do not provide actual evidence for their choice nor do they aim to holistically explore visual noise. In fact, when considering the human visual system there are other visual stimuli beyond movement in the periphery but it remains unclear if they can create or contribute to visual noise. For example, cognitive psychology points to various preattentive cues that create saliency and draw attention including motion. This could provide a link to the issues with perceived movement in the periphery but saliency is not constrained to movement but also considers colour, texture, or basic shapes [62]. Furthermore, we know of visual stimuli that can cause negative effects such as triggering seizures (photosensitive epilepsy)[14, 50], but apart from passively avoiding those stimuli (e.g., wearing sunglasses) or actively closing our eyes to avoid certain visual stimuli, there is no work reapplying the idea of active noise cancellation.

2.3 Augmented-, Mixed- and Diminished Reality

There has been a lot of prior research within Mixed and Augmented Realities that changed how we see the physical world. Traditionally, in particular Augmented Reality is connected to adding digital information to the physical environment. While Augmented Reality is mainly focused on adding information, Diminished Reality is more commonly connected to hiding or even removing information and as such is immediately more relevant to the concept of visual noise cancelling. More specifically, while Augmented Reality and Diminished Reality are both considered techniques within the Mixed Reality Continuum, Diminished Reality is defined as "a set of methodologies for concealing, eliminating, and seeing through objects in a perceived environment in real time to diminish the reality" [8, 42]. It is commonly used in the context of architecture or marketing where either furniture or advertisement is removed or replaced with different versions. Despite these similarities, Diminished Reality has not been connected to the concept of visual noise nor has it been explored for removing visually distracting or unpleasant stimuli beyond physical objects. In fact, commonly used techniques for Diminished Reality assume knowledge (e.g. prior 3D reconstructions) that makes it less applicable to practical visual noise cancellation.

2.4 Human Visual System and Vision Augmentations

There is a large body of work outlining the general workings of the Human Visual System [12] or the specific requirements that need to be met by digital eyewear [19]. There is also a body of work that tries to understand the human visual system and in particular investigates visual stress [66] usually with a focus on people knowingly affected by epilepsy [35] or migraine [45]. More recently, research within academia also explored approaches that change our sensation and perception of the physical world by modulating the appearance of the environment when seen through digital interfaces. Commonly the appearance modulation is used to support people with visual impairments by emphasising real-world artefacts in the users' view (Vision Augmentation or Computational Glasses)[31, 58, 70, 71]. As such most of these works can almost be considered the opposite of noise cancellations as they further emphasise the actual environment or parts of it. However, there are also several examples that emphasise areas within our environment while de-emphasising others. This includes works on saliency modulation to guide attention [64] that have even been demonstrated through glasses-like prototypes [59]. While originally proposed for improving task performance by real-world guidance, recent related works outline the potential of real-world saliency modulation (e.g. through modulating luminance or spatial features) for increasing the likelihood of fixations in areas of interest and global verbal responses for people affected by autism [4, 5]. The key idea is that modulation of selected scene features helps affected people to better see the "big picture" instead of focusing on less relevant scene details through augmenting the global visual processing. Furthermore, recent works proposed conceptually to modulate the peripheral vision to reduce motion sickness [69] or peripheral movement [25]. Finally, some works proposed technical solutions where the display is actually filtering light information from the real world [18, 65]. These works are usually not discussing noise or noise cancellation but can still be understood as a filter for the real world with applications such as smart dimming sunglasses system based on LCD panels for individuals with photophobia [17].

2.5 Research gap and approach

In contrast to the field of audio noise and audio noise cancellation there is little knowledge of what constitutes visual noise and the general concept of visual noise cancellation. While the term visual noise was first brought up in the context of the human visual system as early as 1965 and recently first demonstrators for visual noise cancellation emerged [25, 54], these works presented technical solutions without actually exploring the actual characteristics of visual noise or running user studies. Similarly, there is no general exploration of what is perceived as visually unpleasant or as visual noise and the few existing works have a strong focus on people who are knowingly oversensitive as they are affected by epilepsy or migraine. As we do not understand the general character of what entails visual noise, we also have only a limited understanding on what technologies are needed for its cancellation. In this work, we start from a human-centred approach taking elements from participatory design and concept ideation within workshops or focus groups to explore what visual noise is and where it affects participants. The use of workshops and focus groups is widely accepted in HCI research for speculative design, brainstorming, or participatory design to better understand the problem space or to drive the design (e.g [9, 20, 30, 49, 63]). In a second step, we interpret the findings and converge to a first model for visual noise that is based on the findings from the workshops while linking them to the literature covering the human visual system and audio noise cancellation. Finally, we report on an exploratory study for compensating identified visual noise sources.

3 UNDERSTANDING VISUAL NOISE

Most of the findings on unpleasant visual sensations refer to actual visual impairments or injuries and there is only limited understanding of unpleasant sensations in healthy humans apart from when exceeding sensory thresholds (e.g., excessively bright displays or light [44]). As such, in the first step of our research, we aimed for creating a better understanding of what visual noise is. Given our background in HCI, instead of systematically analysing the boundaries of the human visual system and creating a purely hypothetical definition, we built our investigation around a series of workshops that brainstormed and aggregated findings with human participants. The key questions are what our participants considered to be visual noise and what are examples and scenarios in which they have experienced visual noise or unpleasant visual stimuli.

3.1 Workshops on Visual Noise

As part of initial discussions among the research team, we hypothesised that visual noise can be very subjective and depends on the context. For example, neon lights in nightclubs can excite and elevate the mood of some people but can be annoying to others. Similarly, neon lights can be unpleasant in a different context such as a library. To capture the different notions of visual noise but also to identify the contexts in which visual noise is experienced we took inspiration from speculative design space [1] and design fiction [36] and decided to organise workshops[26, 41] with participants from different backgrounds and follow the brainstorming steps and rules from IDEO[46, 55]. As part of these discussions in the workshops, participants had to: 1) brainstorm the concept of visual noise and identify scenarios in which visual noise arises; 2) brainstorm possible categories or dimensions for visual noise utilising the findings from 1).

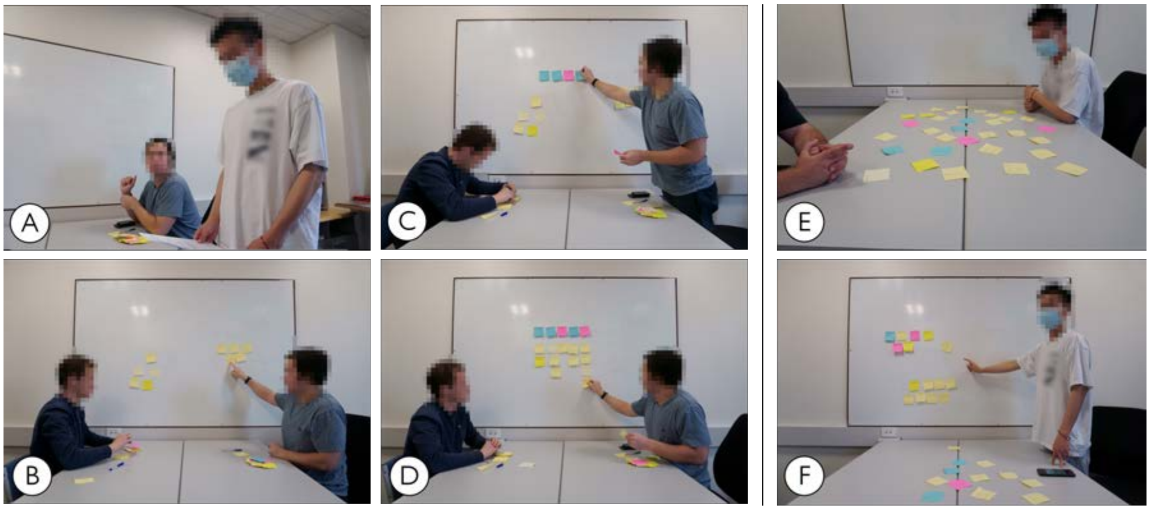

Fig. 2. Illustrative procedure for our workshops. Left (A-D) shows the main workshops. (A) Participants were first introduced to the purpose of the workshop and the concept of ANC by the facilitator. (B) After writing down initial ideas for visual noise, participants shared these with the rest of the group and discussed them. (C) Participants then brainstormed categories of visual noise and discussed them with the group. (D) As the final step of the workshop participants collaborated to place their ideas of visual noise under the identified categories. Right (E-F) illustrates the convergence workshop. (E) Initially, all the categories raised from the workshops were gone over, referring back to the workshops for understanding. (F) Categories were then grouped and discussed to converge to an overall understanding of what entails the concept of visual noise.

Procedure. The workshops always followed the same procedure and were initiated by the same moderator. They started with an *Introduction* in which the moderator introduced themself and the main objectives of the workshop. To create some common ground for all participants, we introduced the topic of visual noise by drawing from the concept of active audio noise cancellation which was well-known to all participants. We explained to participants, that instead of focusing on auditory noise we were focusing on visual noise. Overall, this step lasted 5-10 minutes. The introduction was followed by the first *Brainstorming on Visual Noise*. Following standard processes in IDEO brainstorming, we had 3 minutes of silent thinking in which participants created their first ideas and noted them on post-its before sharing their ideas with the others, ensuring everyone has a chance to develop and then present ideas to the group. After sharing, participants jointly discuss the current ideas and identified overlaps but also gaps that lead to new ideas (See Figure 2 Left). We continued with a second *Brainstorming on Visual Noise Categories* in which participants brainstormed and discussed categories for visual noise based on the identified sources and scenarios from the first brainstorming. We again started with silent individual brainstorming and then followed up by sharing individual categories before having an open discussion to integrate existing ideas. Throughout the workshops, participants utilised post-its to support the brainstorming and discussions and we took care to not exceed 60 minutes overall. The study was approved by the ethics board of the university.

Participants. We used snowball sampling to recruit for our workshop and reached out to people via university mailing lists and personal relations. The main inclusion criteria for our workshop recruitment is either a background in Human-Computer Interaction, Graphics and Design, Psychology, but also from the general population. We settled on these inclusion criteria as we looked for creative people who had a strong visual sense (Graphics and Design) and we wanted to capture if there are related concepts in the design disciplines (e.g. the concept of noise is present within photography) or in cognitive sciences and human visual system (Psychology). Finally, we wanted to have a representation from our own discipline (HCI) as well as a cohort with no specific expertise to off-set the special backgrounds of the former participants and increase external validity. Overall, we recruited 17 participants that we organised in four groups (age: M = 34.235, SD = 10.038, five females, 12 males).This is in line with recent human-centred HCI research utilising workshops for understanding of subjective concepts which often used 4 to 15 participants [9, 20, 30, 49, 53, 61, 63] including the work exploring the concept of Diminished Reality [8].

Eight of the participants were affected by mild visual impairments such as refractive errors or colour vision deficiency. We grouped our participants in the following groups: Group 1 were experts in HCI, Group 2 was our general group that was mostly composed from students and administrative staff from around the campus, Group 3 contains experts from visual communication, photographers, design and psychology, and Group 4 is formed by postgraduate students within HCI). The rationale between these groupings was to group people with the same expertise while we also want to emphasise that the IDEO principles and procedures already compensate the effects of introverts and extroverts in the same group by giving each participant a similar amount of time.

Workshop Results. For the data analysis, we collected and analysed the original post-its from the workshops and referred back to our notes and audio recordings from the workshop in case we lacked information or context from the post-it notes. In the following, we present the results of our workshops and follow IDEO Convergence rules[60, 68].

Overall, the 17 participants from four sessions created almost 120 descriptions/scenarios for visual noise and identified 31 categories (including duplicates). In accordance with IDEO rules, in this initial step for presenting our results, we did not remove any identified categories from the workshops. Table 1 provides a summary of the workshops, their created post-its information, and audio recordings.

One thing that immediately emerged during the discussion in the different workshops is that visual noise is subjective, confirming one of our initial assumptions. While there were often several participants bringing up similar themes and visual noise concepts yet sometimes with different names or categories, we also often heard in the final discussion that others understood the specific example of visual noise but felt less affected by it and thus did not consider it initially. Despite these individual differences, there were also many common patterns that emerged. Most importantly, as a general notion of visual noise, almost all participants believed visual noise to be things they would rather not see as they are distracting or things that participants even deemed harmful to the eyes, alongside those who mentioned that unseen things they wanted to see could also constitute visual noise.

As we can see from Table 1, despite visual noise being quite subjective, there were many common scenarios and categories that were brought up in the different groups. For example, two groups proposed "Peripheral" as a way to categorise visual noise, being noise that only occurs as a part of peripheral vision, such as phantom objects or motion in the periphery. Background motion which would be in the periphery was also commonly mentioned, such as sudden motion from birds or people moving while you are studying. Another common category was "Obstructions" which was raised in both Workshop 2 and 3. Typical scenarios for obstructions came from: objects being in the distance or cluttered together; dust, air pollution, and fog, which could generally be covered as haze; and glass modulating the view such as when it is dirty, broken, or rain spattered. One scenario where participants were also in consensus was being bringing up the topic of being blinded by the headlights of oncoming traffic. This scenario was part of the more general topic of light or sensory overload which was one of the most frequently named topics in the workshop, also covering general brightness, neon lights, fluorescent light flickering, and reflection. The use of salient advertisements to draw

Table 1. An overview of the resulting categories from the workshops before meta analysis. We provide the categories mentioned alongside a description based on the workshop discussion and some of the scenarios and conceptual terms associated with them. We do not repeat categories covered in multiple workshops and only provide a selection of scenarios.

	Category	Description and typical scenarios
Workshop 1 (W1)	**1.** Too Much Light	When there is an excessive amount of light that is detrimental to vision or makes it hard to focus. Examples: *neon lights; blinding headlights; dark when cooking.*
	2. Blinking Frequency	Blinking or flickering lights at a perceivable frequency. Examples: *flickering lights in an elevator, blinking bike lights, a stroboscope.*
	3. Light Temperature	The temperature of an environment based on that of light sources. Examples: *the cold lighting in a hospital; eyes automatically white balancing based on a wall.*
	4. Peripheral	Noise that only occurs as a part of peripheral vision. Examples: *Phantom objects; motion in the periphery.*
	5. Shapes	Specific shapes and annoying objects in the vision. Examples: *Lots of objects in view; phantom objects in periphery.*
	6. Motions	Sudden movenments and distracting things in the view. Examples: *Casting/moving shadows; birds suddenly moving.*
	7. Dynamic Patterns	Temporal changes in the vision. Examples: *Eye floaters in vision; grainy noise; high frequency patterns; other people moving while I'm studying.*
	8. Spatial Patterns	visual changes in spatial domain. Examples: *Noise in photos; dirty glasses; patterns in carpet; salient objects.*
Workshop 2 (W2)	**1.** Information Burden	When there are large chunks of information or too little information presented. Examples: *Advertising posters in supermarket; fluorescent lights flickering.*
	2. Extreme Brightness	Bright points in the view that are excessive. Examples: *Sun glare; light; reflections; bright headlights.*
	3. Darkness	A lack of light making things difficult to see or when in areas that the eyes are not adjusted to. Examples: *Shadows; blur; gradient.*
	4. Natural Lights	Visual Noise that occurs naturally. Examples: *Obstructions; extreme brightness; darkness; natural phenomena.*
	5. Artificial Lights	Visual noise that is caused by human activity or from human-made sources. Examples: *Advertising poster; unreal texture shape in games; old photography.*
	6. Obstructions	When targets cannot be seen due to interference blocking clear perception. Examples: *Objects in the distance or cluttered; blinding; dust/rain/air pollution/fog; meshed glass.*
Workshop 3 (W3)	**1.** Misplaced	Things in confusing or overwhelming sensory positions. Example:*fatigue.*
	2. Language Decoding	Decoding signs requires mental effort, and if many are present can be cognitively overwhelming. Examples: *Road signs; numbers prefixed with "$" and ending with ".99 "; nation flags; emojis.*
	3. Changing Reality	Visual story telling such as in photography. Examples: *Visual rhetoric; media aesthetic; believability/authenticity; clutter; people in the background.*
	4. Technology	When the limits of technology introduce artefacts. Examples: *Mechanical limits; camera; low light; digital noise; advertisement; blur.*
	5. Sensory Overwhelming	When impact on the senses is saturated it can be considered overwhelming . Examples:*Moving; brightness; fatigue; clutter/overcrowding; website colours/text/fonts.*
	6. Distractions	Being forced to focus on something one is not intending to focus on. Examples: *Bright spots; advertisements; attractive/controversial people; food; violence/gore; animals; large textures.*
	7. Peripheral	Check Workshop 1 for details.
	8. Obstructions	Check Workshop 2 for details.
Workshop 4 (W4)	**1.** Semantic Properties	The individual semantic properties that someone can attribute to a source. Examples: *Important/unimportant; ugly/beautiful; context.*
	2. Caused by Personality	Visual noise determined by people's personal preferences. Examples: *Subjective noise (depending on environment); people do not want to see; uncomfortable things.*
	3. Want to see but can't	Things people want to look at but should not due to ramifications. Examples: *Dangers; epilepsy triggers; distracted driving.*
	4. Don't want to see	Things people do not want to see or do not need to see but are apparent in vision regardless. Examples: *Imperfect rendering texture; low resolution; ugly/busy advertisement/objects/distractions.*
	5. Low Level Properties	Sources that are based on basic, objectively quantifiable properties. Examples: *Frequency; information; abrupt changes; specific colours (pink); busy patterns (carpets); too bright.*
	6. Visual Presentation	Noise caused by the manner in which things are presented. Examples: *Visual information and fidelity; photo/video composition/framing; video distractions.*

their attention was also a common scenario. In fact, advertisements were covered in Workshops 2,3, and 4 while salient objects generally were covered in Workshop 1, indicating it as a generally prevalent and accepted form of visual noise. Participants even discussed advertisements more deeply, subdividing them into advertisements in real life, like posters on the wall, and website advertisements. The actual colour of environments or light temperature was also a reoccurring topic, sometimes directly as light temperature (Workshop 1) or as artificial lighting (Workshop 2) and the main theme was that some participants expressed a dislike for cold or blue light as it is prevalent in LED lighting or fluorescent light as used in many public buildings. Similarly, in all workshops the issues of temporal changes in the lighting (or flicker) came up but were coded differently (e.g. as a side effect of artificial light, a low-level property, or sensor overwhelming). Finally, given our special constituent for the workshop participants, there were also many distinctive ideas. Participants who had a photographic background held the view that there were many forms of visual noise when they took photos or looked at photos, like the low resolution and distortion of old photos, and the visual rhetoric or artistic manipulations used. Another interesting idea was the language decoding category from an artist, which was given as targets people dislike due to having to decode and understand them. Typical scenarios of the language decoding were road signs, numbers prefixed with "$" and ending with ".99 ", national flags, and emojis. There was another high-dimensional visual noise consequence that one participant mentioned. They thought people would feel "numb" if they stay in a visually noisy environment for an extended period of time.

3.2 Convergence Discussion and Classification Model for Visual Noise

After the collation of the workshop data, we organised several sessions in which we held a meta-discussion among the authorswith the main goal of refining ideas provided by the participants of the initial workshops and synthesising information, following the IDEO concept of convergence (See Figure. 2 Right). We started the discussion by summarising the categories provided by the participants. In this meta-discussion, we agreed to not create any new ideas, instead focusing on refining ideas provided by the participants throughout the workshops. This avoids the issue of diverging in the meta-discussion and producing new ideas, rather than converging to a summary. We then started to organise the identified examples and scenarios into new categories while also removing duplicates.

The main challenge here was to identify these new categories, as categories and scenarios from the workshops did not necessarily create a well-defined space. As such, while focusing on the categories provided by the participants, we revisited in our meta-discussion principles from audio noise cancellation and the human visual system [12]. In audio noise cancellation, audio noise is typically categorised not by its source (e.g. airplane noise) but by the frequency domain (e.g. high frequency or low frequencies). This is also because depending on the frequency, audio noise cancellation is less efficient at higher frequencies [29]. While the details depend on the manufacturer, several sources state that at 1kHZ audio noise cancellation becomes less efficient which includes frequency used by human voices. However, visual signals are more complex as there are multiple frequencies domains that can be considered, namely the electromagnetic frequency of the visible light (optical waveform's properties that include frequency and intensity or amplitude), their temporal properties (temporal changes in the optical waveform), and their spatial properties (the periodic spatial structure in space). Coincidentally, these three frequency domains are also processed differently within the human visual systems.

We consequently converged in our discussion on using the frequency domain for the first categories for categorising visual noise. They can be described as:

- *Waveform Visual Noise:* The noise is directly caused by the frequency and intensity of the visible light as perceived by the viewer. While this category mainly arose from the frequency domain analysis it was also raised in discussions in the workshops such as in categories on "light temperature" and "low-level properties" from Workshops 1 and 4. As an example, high amplitudes such as sun glare (W2), bright headlights (W2, W3, W4), and reflecting light (W2) were considered sources of visual noise. Particular frequencies of light or colours were also considered visually noisy (W1) alongside the overall colour temperature of an environment caused by the frequency distribution of light sources with some people having an aversion to cold colour temperatures (W1, W4). When linking these examples to the human visual system, it is clear that where the light intensity is too high, we see a sensory overload where the distal stimulus (the light rays emitted from our environment) exceeds the limits of our sensory receptors (here rods and cones on our retina) [28]. However, some provided examples are also caused by the colour temperature or at light levels that are not exceeding the limits of our sensory receptors and as such not primarily caused by receptor processes. Unfortunately, the interplay and perceptional processes that cause the discomfort are to our best knowledge not yet understood as they are often highly subjective. We also refer here to the more severe discomfort in people who are affected by migraine that often comes with hypersensitivity to light or certain light temperatures [45].
- *Temporal Visual Noise:* The visual noise caused by changes or variance in stimuli over time is commonly referred to as blinking or flickering lights (W1). Alternatively, the location of a light stimulus can change over time causing it to produce noise. Examples of this include background motion such as people moving while studying (W1, W3, W4), peripheral motion (W1), or sudden movements such as birds (W1, W4). Temporal visual noise was also directly brought up as categories in Workshop 1 as "blinking frequency" and "dynamic patterns" but combined during our meta-discussion. The sensory processes as a reaction of light are relatively well understood, including the critical fusion frequency (frequency at which light is perceived as temporal static) for different receptors such as rods and cones that changes not only with the intensities but is also dependent on other factors (see [35]). However, it is also known that temporal changes in light "is a complex stimulus, processed by many brain structures that work closely together" [35]. As such, it is not yet fully understood why even for people who are not affected by epilepsy flickering light can cause negative side effects such as headaches or discomfort [67] as also brought up in our workshops. As pointed out, temporal changes are not only blinking lights but also movements of visual signals on our retina. We are more sensitive to movement in our periphery because of how the signal is processed [7] which can be problematic as motion is affecting bottom-up saliency, something anecdotally confirmed by our participants who provided examples of being distracted by motion in their environment.
- *Spatial Visual Noise:* The noise caused by the structure or location of the stimuli. The presence of stimuli in specific spatial areas, the overall visible form of the stimuli that is perceived and large variances within the stimuli, can all cause visual noise that is dependent on their spatial structure, positioning, or distribution. This was primarily derived from the categories of "shapes" and "spatial patterns" from Workshop 1 and example sources and scenarios that would fall under spatial visual noise were covered in all the workshops. Spatial sources and scenarios included internal structures such as patterns, salient areas, or textures (W1, W3), specific structures such as shadows, controversial faces, or advertisements (W2, W3), and the location of noise such as distal, cluttered, or overcrowded (W3, W4). This feedback is in alignment with works reporting on visual stress [35, 66] that seems to be overly present in people affected by epilepsy but is also present without known epilepsy or other impairments. Identified triggers have been specific patterns (stripes) or general patterns with strong

contrast. However, there have also been reports that blur, and as such low contrast patterns, cause discomfort [47] which was reflected in our workshops on visual noise. While we could not find clear explanations of the psycho-physical processes in the literature, theories suggested that this visual discomfort is caused by a statistical deviation from natural scenes and as such processed less optimal leading to the experienced discomfort [21]. We should also highlight the research on people affected by autism and how they are affected by overly salient and bright environments that expose them to too many details [4, 5].

It is worth pointing out that the identified categories for visual noise sources are not mutually exclusive as some sources have properties that overlap with several categories as shown in Figure 3. For example nightclub lighting often contains aspects of both waveform (brightness and colour) and temporal (flicker).

Beside the character of the stimuli, another category that emerged during our meta-discussion was to use of the actual cause for the perception as noise as a category. Initially, it was thought that a sensory overload or reaching the limits of the receptors could be a category. However, as already pointed out in the existing categories on the frequency domain, the actual cause and the details of processing for some identified stimuli are still the subject of active research. However, we still saw differences in the impact the visual noise or discomfort can have on the affected individuals. While subjective for the individual we still saw general patterns. For example, some stimuli cause affected people to be absolutely overwhelmed and almost unable to perceive other information and consequently perform their normal actions (examples here would be high light levels as caused by a sun strike or to a lesser degree flickering lights). This perception of being overwhelmed by the specific stimuli is contrasted by the other end of the continuum of being interfering. Here the visual noise is perceivable and comes with discomfort but still allows affected people to perceive their environment and perform tasks even though with a likely reduced level of effectiveness. An example of this would be to feel uncomfortable with the light temperature. We consequently summarise the 2nd dimension of our visual noise space as a continuous space between interfering and overwhelming. We defined these as:

- *Interfering Visual Noise:* When visual noise directly interferes with humans and their visual system to the extent that they can still perceive their environment and can perform tasks but with reduced performance. Workshop 3 puts this into the category "Distractions" like blinking bike lights (W1), sudden movements (W1, W4), motion in the periphery (W1), and people moving around while studying (W1, W3, W4).
- *Overwhelming Visual Noise:* When visual noise becomes so prevailing that it starts to overwhelm our visual sensing and prevents the senses from functioning properly due to an increased perceptual load. This was typically given in scenarios where light could completely overwhelm areas of the visual perception such as blinding headlights (W1, W2) and general brightness (W3) with other stimuli only falling into this category to a lesser degree and only for some individuals. This kind of impact was noted in the first three workshops as "too much light", "extreme brightness" and "sensory overwhelming".

Overall, based on our workshops we identified several examples and scenarios that participants considered visual noise and caused them discomfort. During our meta-discussion, we identified main patterns and propose a first categorisation for visual noise. As part of our meta-discussion, we also found support for the identified examples and categories even though much of the literature is exploring visual stress and discomfort from the perspective of people who have a history of being overly sensitive such as through being affected by epilepsy or migraine. However, it seems that many of us are affected by similar discomforts, yet at a much lower level with different symptoms, while it is also again important to highlight the subjective nature of experienced discomfort among our participants.

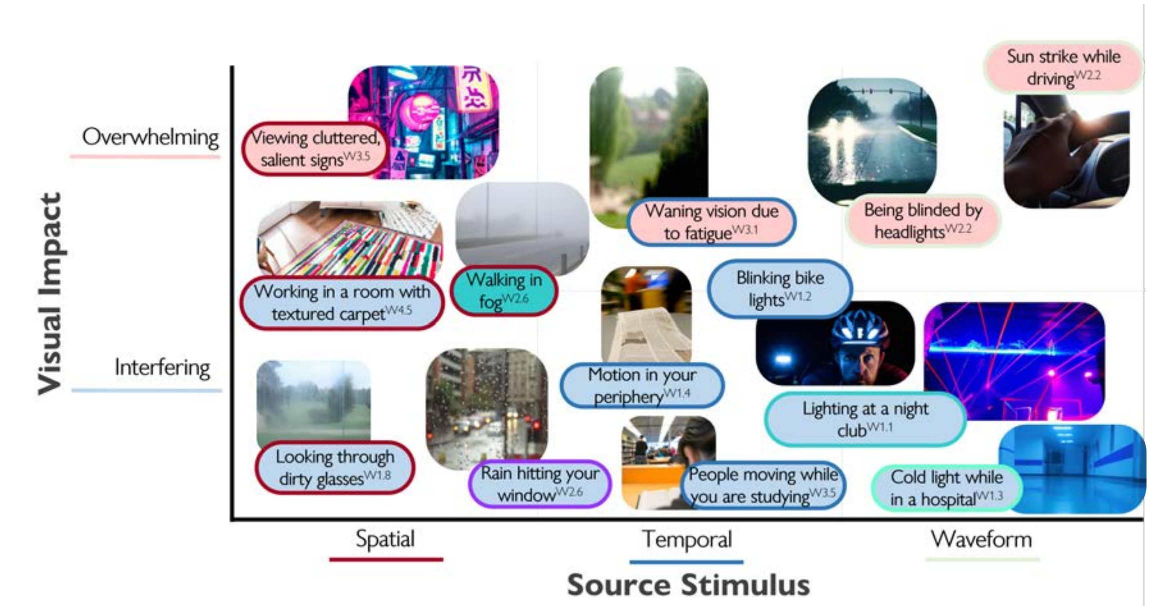

Fig. 3. Examples of visual noise scenarios taken from the workshops. We colour-coded the scenario labels based on their source stimuli (border) and visual impact (fill) with scenarios that cover multiple categories coloured to reflect this.

3.3 Limitations

There are several limitations that should be mentioned. Firstly, there are other ways in which visual noise could be categorised as provided in our workshops but were not adapted in our meta-discussion as we did not find them to be within the design and intention of our model and therefore are not directly reflected within it. For example, while natural and artificial light can be used to further categorise sources, we did not include this increased complexity in our model. Other categories set aside from the model are: peripheral, as we do not consider where the stimuli fall on the eye; technology, as a particular set of sources; and changing reality, which was focused around the expression of photography. Furthermore, the finding of the subjective nature of visual noise raises a problem as we cannot be sure of having covered all visual noise descriptions and scenarios. In fact, we are confident that there are other examples for visual noise. That said, we saw a high saturation in the results from our initial workshops and similar scenarios kept on getting repeated yet put in different categories or given different names which is why we stopped after those 4 workshops. Similarly, when referring back to literature on visual stress and discomfort [47, 66] and also autism we did not find any aspects that have not been brought up by our participants in some form. As such we feel confident in having captured the main themes but cannot claim completeness. Though, having people with different backgrounds gives us assurance in sufficient depth of our brainstorming. Finally, while we consider the perceptual system in our model, using frequencies of noise does not map well against it, as shown in Figure 4. Alignment with the underlying processes may be beneficial to targeted investigations of sources and counteractions. However, given that the aforementioned general limitations in the understanding of the perceptual processes still exist, we believe that for the general understanding of visual noise presented a frequency view remains appropriate. Instead, we refer to referenced literature for further reading.

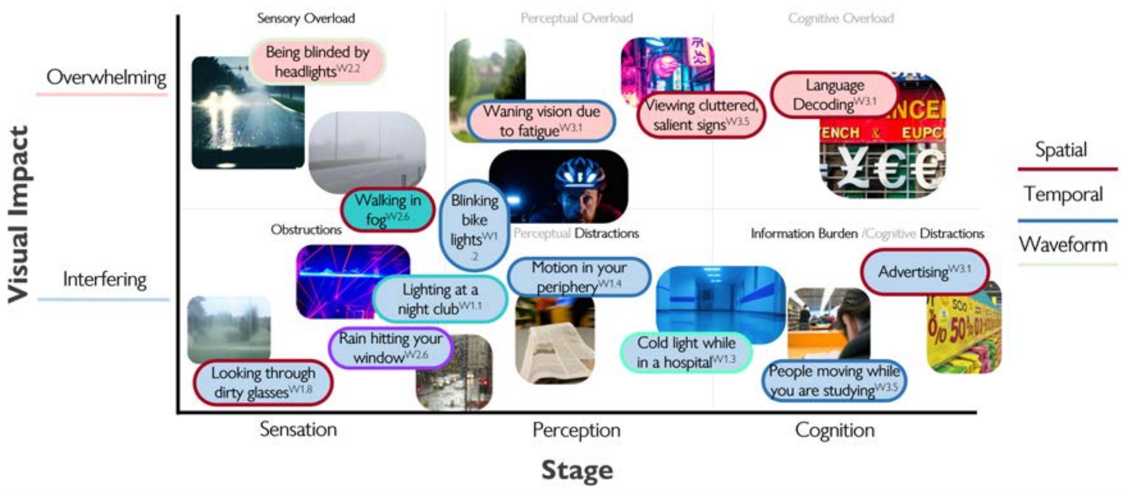

Fig. 4. When viewing our model from the perspective of perception, we can see that the frequency categories can occur at various stages. They can also involve various processes within the stages or border stages. The dark labels indicate terms raised in the workshops that correspond to those areas in the view. Grey terms are introduced by the authors and have not been directly stated in the workshops .

4 PROTOTYPING VISUAL NOISE CANCELLATION

As an initial exploratory investigation into the concept of visual noise cancellation, we wanted to gather an understanding of the perception of visual noise cancellation as a general concept. We wanted to expose users to visual noise and then demonstrate how cancellation might affect this noise. Unfortunately, the identified categories show a wide range in what can be considered visual noise, and with this, finding a unified way to effectively compensate for visual noise is challenging. A visual noise cancellation device (of the future) would a) have to be able to identify or sense the presence of visual noise in the user's field of view, b) do so for (sometimes very small) regions of the view, c) have to have mechanisms to compensate for the source stimulus, and d) have an acceptable form factor similar to standard sun or prescription glasses or ideally contact lenses.

As we are not yet in a position to meet all criteria for an "ideal device", we implemented visual noise cancellation demonstration prototypes using video see-through (VST) HMDs (VR HMDs using cameras for a pass-through mode that allows a mediated perception of the real environment). Video see-through HMDs are commonly used for MR/AR research but also to simulate future smart glasses for correcting vision impairments [72]. VST HMDs also give us more control over the manipulation of the user's view overcoming the current limitations of optical see-through HMDs (e.g., the inability to darken the environment or modulate the environment on a per-pixel level)[19]. In our work, we chose the Oculus Quest 2 HMD for its ergonomics and availability. It also offers a simulated video pass-through mode, but only in greyscale. Hence, we utilised a Zed mini stereo camera that is attached to the Oculus Quest 2 to provide stereo see-through viewing. To minimise the perceived latency and rolling shutter effects introduced by the Zed Mini, we used a resolution of 2560x720 captured with 60fps which is streamed to the Oculus Quest 2 and rendered with the same frame rate. The general implementation is done within Unity on a desktop computer with an NVIDIA GeForce RTX 970

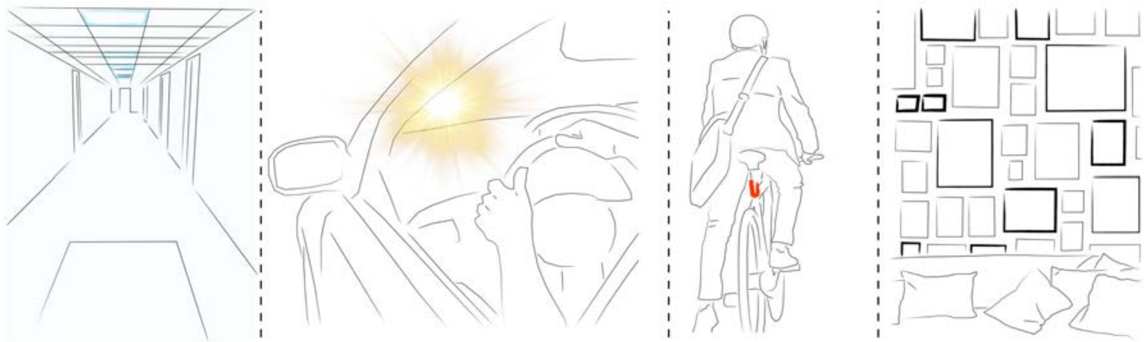

Fig. 5. Visual noise scenarios selected for prototypical development and exploratory investigations. (From left to right) Cold (fluorescent) lighting, sun glare or extreme brightness, flickering lights such as blinking cycling lights, and a wall of pictures creating an extremely salient environment distracting from focusing on individual pictures.

and 12GB RAM. Using this general framework, we implemented a simulation of four different scenarios that arose from the workshops, each compensating for a different case of visual noise while covering all the main stimuli (see Figure 5). .

4.1 Light Temperature

Being sensitive to *Light temperature*, as in many hallways, was commonly mentioned by participants and is an example for visual noise caused by a waveform stimulus. For example, one participant described feeling anxious in hospitals and attributed the cool light temperature as a major contributing factor to this. Other participants also felt more comfortable with warmer lights at home. We simulated our scenario with a pair of light sources that can be controlled in colour temperature and was set to to produce light at a colour temperature of 5600k (bluish white light) with everything above 5000k generally being considered a cold light. To mitigate this form of visual noise we adjust cool colours. We manipulate the source stimuli by controlling the overall colour temperature perceived towards a warmer one (See Figure. 6, Scenario 1). This is achieved using a transform function based on Charity's original blackbody values[1] that is applied to the pass-through camera image. In the user study on cancelling visual noise introduced by a cold or uncomfortable light temperature, we set the target colour temperature to 3200K, which is close to sunset (3500K) and incandescent lamp (3000K) and is significantly different to the actual light used in our study environment at 5600K.

4.2 Light Amplitude

As another example for visual noise caused by the actual waveform of the stimulus, we looked to prototype a cancellation for a scenario in which high light amplitude is causing noise, mentioned by participants as *extreme brightness* caused by vehicle headlights at night or *sun glare*. In our scenario a pedestrian is faced with bright light from the front of a bicycle. To cancel the visual noise we limited perceived brightness in camera space. The brightness from the pass-through camera image was evaluated in the *HSV* colour space to determine bright spots. The luminance in that region of the image is then reduced to a set level (we set the center light point as 65% luminance as it was). In order to make the boundary transition between center light and normal area smoother, we apply a linear ramp at the boundaries. We divided the boundary into four steps and each step occupies 0.1% length of the total image's sampling length. (See Figure. 6, Scenario 2).

[1]http://www.vendian.org/mncharity/dir3/blackbody/

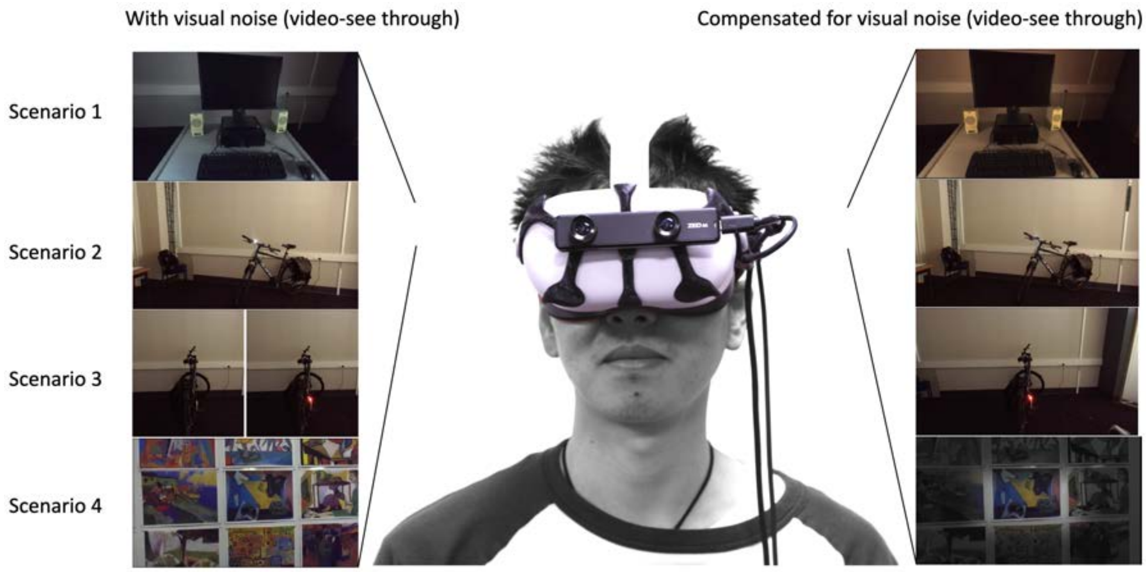

Fig. 6. Overview of the developed prototype addressing the four scenarios. From top to bottom: Light temperature, light amplitude, blinking lights, and spatial saliency

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4.3 Blinking Lights

Another commonly mentioned example of visual noise was *flicker or blinking lights*. This temporal visual noise stimulus commonly appears with varying (distracting) frequencies. E.g. fluorescent lights might flicker with about 25 Hz, a bicycle light switches twice a second and both have been mentioned by participants in workshops. For our scenario we looked at blinking red lights used by cyclists (See Figure. 7 Left). To cancel the noise we implemented a temporal inpainting method that gave the perception of the light being constantly switched on rather than blinking.We applied a threshold segmentation in *HSV* space to detect the red light as the *HSV* space performs better than *RGB* space in detecting red objects[37]. From earlier experiments, we identified that to robustly segment the red target areas on our camera image we use a range of [312, 0.16, 0.18] to [20, 1.0, 1.0] in *HSV* colour space. We analyse prior frames (former 50 frames) to detect the actual flicker. Upon detection, we inpaint red pixels with the red pixel value in former frames to cancel the blinking or flicker effect (See Figure. 6, Scenario 3). Hence, with this approach, the warning function of the blinking is still maintained for an initial period of time and then turns into a less visually noisy form of a static light.

4.4 Spatial Saliency

The final scenario simulates spatial stimulus for visual noise by presenting overwhelming highly salient areas in the user's view(See Figure. 7 Right). It was inspired by workshop comments mentioning highly salient objects and strongly textured regions, e.g., carpets. Our scenario used several images of salient paintings to produce conflicting salient areas in the view when trying to focus on one image such as when looking at clustered and cluttered salient objects, such as advertisement signs, notice boards, or larger salient scenes. To cancel the noise we reduced the saliency outside of the central viewing region. We achieved this by linearly reducing the saturation and brightness of the pass-through camera image outside the central target area. We set the final saturation to 0.0, however, maintain some brightness to support peripheral perception (See Figure. 6, Scenario 4).

5 EXPLORATORY INVESTIGATION OF VISUAL NOISE CANCELLATION

We ran an explorative investigation to provide initial feedback on the concept of visual noise cancellation and the developed prototypes. The general idea was to test our concept of visual noise cancellation by simulating the four detailed visual noise scenarios that arose from the workshops. As we learned that visual noise is a subjective perception that might differ between the participants, we focused on qualitative feedback with respect to the observed differences in the perception of the environment. Given the subjective nature and individual differences, we also assumed that some participants might not consider the presented scenarios as visually noisy or distracting, but we decided not to filter for this. Finally, we want to point out that current digital eyewear and head-mounted display technology that can be utilised for visual noise cancellation is far from perfect and known to introduce artifacts that can itself cause visual discomfort beyond just simulator sickness (e.g. blurry vision [19]). As such, we focused on this exploration of the general concept of visual noise cancellation instead of demonstrating the actual effectiveness of a specific technique over an extended period of time.

Apparatus. Participants wore our demonstration prototype for cancelling visual noise which is composed of a Oculus (Meta) Quest 2 HMD and a Zed Mini stereo camera. Both devices are connected to a standard desktop computer. While being connected to the desktop computer via long cables, participants were still able to move relatively freely in the room. Within the room we prepared several scenarios replicating the selected visual noise scenarios illustrated in Figure 5. For the first scenario we placed two controllable lights with adjustable luminance and colour temperature next to the participant to illuminate the scene. For the second scenario, we put a bicycle with a bright white headlight in the room to simulate the beam of an oncoming bike. For this scenario the bike was placed in a way that the light is directly shining towards the participants. We also used the bike for the third scenario, but this time a blinking red light was attached. To increase the effect of the lights, and to simulate viewing in dark conditions, we reduced the brightness in the room. Finally, for the fourth scenario, we placed 16 highly salient pictures on a wall creating a 4x4 grid that the participants could visually browse.

Procedure. Participants were initially introduced to the study and its purpose. After signing a consent form, they were introduced to our prototype for visual noise cancellation. Once any questions from the participants were resolved, participants donned our demonstration prototype. Thus, for the visual comparison the participants perceived scenarios through the HMD to compensate for likely confounding variables such as reduced resolution, dynamic range, or field of view that are created by the HMD or Zed mini stereo cameras used for capturing the environment. Once participants were happy with the fitting of our prototype, we invited them to view one of the scenarios. We gave them time to explore and look around in the scenario. After the exploration, we asked participants if they had identified any visual noise in the scene and if so to inform us as to what it was. We also asked them generally about the scene in regards to intended visual noise (e.g., asked how they felt about the colour temperature in the room generally).

Once they answered these in-between questions to collect their first impressions, we switched on the visual noise cancellation for the scenario. We asked participants to look around in the scenario again. Once finished we again asked high-level questions regarding the presence of visual noise and the scene perception. We then followed up with a semi-structured interview that mainly focused on the perceived effect of the visual noise cancellation, if they are generally sensitive to this kind of visual noise, and how open they would be to the actual application of such kind of

Fig. 7. Illustration of the study setup and environment. (Left) Blinking light scenario. (Right) Spatial saliency scenario.

technology if miniaturised into standard glasses. We repeated these procedures for all four scenarios. The study was approved by the ethics board of the university.

Participants. Overall, we collected responses from 13 participants (age: M = 31.00, SD = 9.04, six females, seven males). We tried to re-recruit at least half of the participants from participants of our workshops as they have driven some of the developed scenarios and could reflect on this. Nine of these participants were recruited while the remaining four participants were newly recruited and provided a "fresh perspective". Five participants wore corrective glasses.

Results and Findings. Given the limited understanding of visual noise and subsequently visual noise cancellation, we looked at gathering qualitative feedback around the impression of visual noise cancellation, rather than focusing on performance in specific areas quantitatively. In the following, we present the main patterns identified and highlight some noteworthy responses.

Firstly, the forms of visual noise identified in our workshops were also considered to be noisy in our exploratory study with participants expressing aversion to the induced visual noise in all scenarios. However, as with our earlier workshops, we also saw the subjective nature of visual noise. Across all the participants, aversion was expressed to the visual noise in 63.5% of the scenarios.

Looking at the feedback from the individual scenarios, the first scenario (cold light temperature) can be considered as very different from existing techniques from Diminished Reality or Vision Augmentation while also being the one with the most positive responses to the impact of the cancellation. We saw the majority of participants (12 out of 13) preferred the scenario in which we cancelled the cold light temperature by adapting the colour temperature of the scene. Participants commented that the cancellation was "*more pleasant*", being "*less harsh*", "*cozy*" and "*looks soft*". They also noted that "*I can see details better*" and that it was "*more comfortable for me*". Interestingly, despite the participants' preference, only six of the participants actually identified the cold light as a source of noise with three mentioning it generated anxiety. The others initially did not mind the cold light. This observation suggests that visual noise cancellation is perceived even when not initially identified as problematic or recognised as visual noise. In their responses, participants raised interest in applying this specific noise cancellation not only to artificial light but also to change specific scenarios caused by natural light (e.g. due to weather). They noted the use on grey days and wanting to be able to apply the visual noise cancellation during winter, a notion that extends beyond our initially intended scenarios. It should be pointed out that existing glasses can sometimes change the temperature of the light via filters but usually do not allow the adaptation of strength or temperature.

For the second scenario, extreme brightness, only a few participants saw improvements. However, two participants who had earlier also participated in the workshops did immediately note the usefulness of such a cancellation when facing the lights on oncoming vehicles. Looking at the participants' responses, we found results were mainly caused by a limitation of our study apparatus. The brightness presented to users is limited by the used display. While all the participants identified the light, only half considered it as visual noise or distracting as the limited dynamic range of the used display reduced the actual dynamic range of the scene to acceptable levels. Other comments addressed the visual appearance of the modulation with participants finding the presence of the dimmed light unnatural and therefore "*more obvious*" or even "*confusing*" and "*introducing new noise as it also blocks the environment*" (due to replacing the colour rather than reducing the size of the glare). However, there were also positive comments such as that the "*visual noise cancelling mode is less distracting*" and draws less attention because participants were "*not interested to look at when the light disappeared*".

Looking at the blinking light scenario a large number of participants agreed that it being distracting and considered it visual noise (10 out of 13). Participants described it as being irritating and annoying, dangerous, and triggering migraine. One participant even commented that they were driven to immediately try avoiding the light. However, in their discussions and feedback participants suggested that our cancellation was also introducing distracting elements that could be considered visual noise. This is because our cancellation of the blinking lights or flicker was based on infilling when the light is off in a way that the light appears as constant "on". However, quick head movements caused the infilling to appear to move because of system latency which was perceivable and was mentioned by 7 participants who preferred the condition with the blinking light. Notably, one participant noted that the "*red light is too bright*" so by giving the impression of being always on, we created similar issues as in our second scenario. An interesting aspect mentioned by participants was that the noise served a crucial safety purpose. Thus when producing active visual noise cancellation the context of use must be taken into consideration when deciding if and how to reduce noise. This is akin to audio cancellation products which indicate they should not be used when they could impact safety and can allow pass-through for some sounds.

All participants were positive about the effects of the visual noise cancellation in the final scenario compensating for a salient scene by reducing the saliency in the periphery. Participants expressed that the paintings and shown information were initially distracting and found the cancellation had a calming effect, allowing them to focus more as the visual clutter of the environment was reduced. They noted that "*I couldn't pick one painting because they are similar*", "*information is overloading and I don't know where to start*" and "*some pictures are too sharp, too saturated and the red, orange one distracts me*". Other common comments in visual noise cancellation mode were also around: "*it is still subtle in the focus area*", "*it looked like torch vision and helped me investigate certain areas*". Notably, the potential positive effects of visual noise cancellation are indicated not only in task performance but also in user comfort. Participants thought this style of visual noise cancellation would be helpful when "*I want to explore and have enough time*", "*I need to focus on a part of the screen*", "*in a gallery*", "*I want to examine a busy landscape*" or "*highlighting a person in a concert*". Contrary to previous scenarios where participants commented on the potential negative effects of visual noise cancelling, we were surprised by a lack of concern for the reduced peripheral information, given this was done in conjunction with the field of view limiting HMD.

From our exploratory study, we saw several patterns of responses that are important to consider when conducting further research on visual noise cancellation. We found that participants' consideration of what they found to be noisy compared to when they found cancellations improved the scenario was not consistent. In several cases (10 total) even those who did not find the scenario noisy preferred the scenario with the noise cancellation active. we found that both the identification of visual noise and the acceptance of visual noise cancellation are highly individual which is a pattern already emerging in our first study. While all prototypes found some support, none were universally accepted as improving the situation. Generally, we found two participants found all forms of visual noise cancellation preferable, and all participants found at least one of the cancellations a subjective improvement. A theme that showed throughout the study was that participants expressed concerns about visible artefacts created as part of imperfect noise cancellation (e.g. compensating of blinking lights or flicker) creating its own visual noise and concerns around the impact of visual noise cancellation on safety. Much of the former could be addressed with revised prototypes (e.g. with lower latency) but it also points to the potential issue of visual noise cancellation introducing new forms of distracting visual artefacts noise which is a challenge given the wide range of identified visual noise and requirement an equally large set of compensation algorithms.

6 DISCUSSION

In the following, we provide a discussion of our main findings and the relevance for the research community. We also discuss our limitations and identified research gaps.

Findings and Relevance. From our work and the initial workshops on understanding visual noise, we identified the following main aspects. Firstly, all participants immediately accepted the term visual noise and it remained unquestioned that there is something that can be called visual noise. In fact, the participants immediately had examples on hand that they could provide. As such, based on the feedback from our participants, we can clearly give a positive answer to the question if there is something such as a sensation of visual noise. Secondly, for the first time, we gained a deeper understanding on the notions of visual noise and real-life scenarios in which they arise. To that end, we learnt that visual noise is highly subjective and while there were examples of visual noise that were brought up by several people, we rarely found a consensus among all participants (this was also apparent in our later investigation with our developed demonstration prototypes). Despite the personal differences in visual noise perception, through our work, we also identified different patterns and categories of visual noise. Similar to the frequencies in audio noise, we categorised the identified visual noise types dependent on their source frequency domain (e.g., waveform, temporal, or spatial) and their perceived impact. These findings are relevant as we see a rising number of publications dealing with the concept of visual noise (e.g. [25, 34, 54]) that make assumptions about the nature of visual noise that so far have been unproven (e.g. movement in the periphery). In fact, our first study showed that there is a wide range of different stimuli that can create the perception of visual noise. Therefore, using a human-centred approach our work provides an actual basis for this existing research and identifies the character of visual noise including scenarios in which visual noise arises. While some instances of visual noise are already discussed in the literature (movement in the periphery, cluttered or salient scenes, which could generally be considered as being caused by undesired preattentive cues [62]) others are rarely mentioned in the literature (e.g., sensitivity to colour temperature, local amount of light, sensitivity to flicker or blinking lights). These findings should be considered in future works exploring technical solutions for visual noise mitigation.

From our exploratory study investigating visual noise cancellation, we were also able to identify important patterns in responses to active cancellation. Firstly, we again confirmed the subjective nature of how visual noise is perceived with some participants clearly responding to the shown noise and its cancelling while other where less affected and thus benefited less from the cancellation. Still, even when less affected by the noise, participants commonly preferred the noise cancellation. Besides corroborating our initial observations from the workshops, our findings have consequences for future studies on visual noise and testing the efficacy of visual noise cancelling. We can expect that not everyone may respond and certainly not respond in the same way to specific visual noise and therefore will not benefit from cancellation. Thus, future studies require either careful screening of participants, need to consider objective measures beyond task performance, or the use of qualitative methods to mitigate subjective biases. These observations have relevance to both further investigations into visual noise cancellation as a generally applied concept, as well as to approaches to individual forms of noise. Importantly, we also found that from our exploratory study that all forms of visual noise cancellation found some support, showing the general potential for visual noise cancellation. This is also supported by the comments from the participants even in cases where they did not agree with the specific scenario or cancellation. Finally, participants' comments as well as our own discussion revealed the need for research on the ethics of computer-controlled world mediation used to cancel noise. These are also considerations for visual noise cancellation glasses and are also being discussed elsewhere (e.g., in recent work on continuous visual augmentations and its ethical implications [51]).

Relations to Diminished Reality, Mixed and Augmented Reality, and Vision Augmentations, Reflecting on the understanding of visual noise from our workshops and reflecting on the related work, we indeed see that approaches within Diminished Reality and saliency modulation touch on niche areas of what can be considered visual noise cancellation. In Figure 8, we illustrate which niche areas of visual noise compensation are partially addressed by research from other domains. In particular, we can see that most existing work within Diminished Reality, Mixed Reality, and saliency modulation address spatial visual noise, caused by the spatial structure (e.g. highly textured or salient, or cluttered objects) or location of the stimuli (e.g. in the periphery). Approaches to tackle visual noise in media via editing, such as that provided by editing software, also demonstrate means to reduce spatial visual noise. This only represents a small area of what we identified as visual noise and large domains have almost been untouched (e.g. temporal and waveform stimulus). We should also mention that some of the identified works do not directly consider the notion of visual noise but do provide wearable technology to control potential sources of noise that could mitigate the impact (e.g. saliency control[59], brightness reduction [18, 65]). More importantly, our research provides an empirical foundation for the perceptual issues identified in existing papers on visual noise (e.g. [25]). Often these existing works present technical solutions but did not evaluate their results with actual users or assume what visual noise is without evidence from the literature or human studies. Overall, we can provide some evidence that research in visual noise cancellation is not only warranted because it addresses actual users needs but it also is a field that is distinct from existing research considerations.

Requirements for visual noise cancellation. Our work provides pathways for researchers in the field of human augmentation and wearable computing by identifying perceptual issues that are not caused by impairments but by sensory impacts. However, the identified range of causes for visual noise also poses significant challenges for cancelling all sources of visual noise. In particular, we can see that many sources of visual noise (e.g., with spatial or temporal source stimuli) are hard to cancel with traditional filters or optics and as such would benefit from computational approaches. In our prototypical implementation, we utilised video see-through HMDs in which the entire environment is camera-mediated. This means the environment is captured by a camera, the camera feed is processed for visual noise and displayed to the users of the system. However, a practical implementation of visual noise would not fully decouple

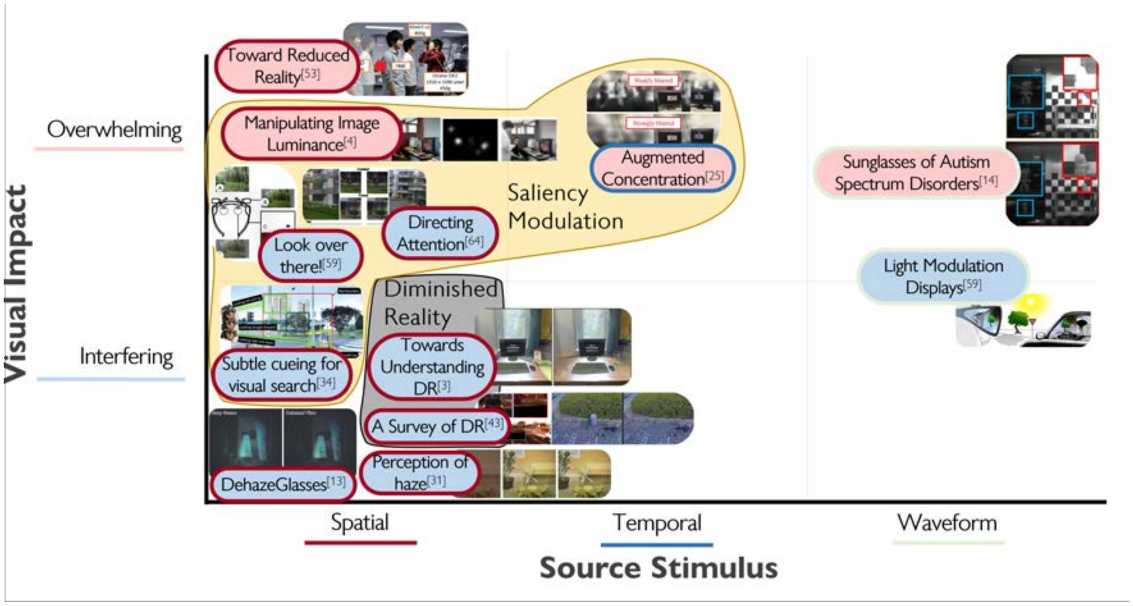

Fig. 8. Prior research efforts that have already developed potential solutions to some issues areas of our model. We illustrate the areas currently encompassed by efforts in Diminished Reality, Mixed Reality, and salieny modulation outlining areas that remain largely unconsidered. Note that here we only integrate works already noted in this paper. Further works in Diminished Reality could be demonstrated as particular forms of dealing with spatial noise, for example those covered by [42].

the users from the environment while also utilising a system that is better resembling traditional glasses or vision aids such as optical see-through (OST) HMDs.

Unfortunately, commercially available OST HMDs are still limited in their ability to modulate the environment as would be required for active visual noise cancellation. When considering the source stimulus, compensating for spatial visual noise often requires hiding or cancel objects (as in Diminished Reality) or filtering for spatial frequencies (e.g. by blurring high frequencies as in saliency modulation). The few existing approaches either used video see-through prototypes (e.g. [25] or developed prototypes for occlusion-capable OST HMDs [15]. The only exception is the work on saliency modulation [59] which showed promising results but also expressed that occlusion-capable OST HMDs would likely improve the results. From our own experiments on temporal visual noise, we experienced the need for fast update rates and low latency not only for the display but also for the used cameras. Unfortunately, current hardware is likely not fulfilling these requirements (e.g. using cameras with 30fps), and thus might introduce visible artefacts as revealed in our study. Finally, controlling visual noise caused by the waveform of the visual stimulus (e.g. amplitude or colour) requires local selective filtering as it can only be achieved with computational aids (e.g., [18, 65]) that are yet only available in research prototypes. However, the recent introduction of the Magic Leap 2 with global dimming and wearable prototypes that can locally filter light ([69] shows that progress is being made to fulfill the requirements). Fortunately, most of these requirements are also beneficial for producing a convincing Augmented Reality experience in general [19].

These limitations of currently available hardware also affect the potential studies on visual noise. As current hardware is imperfect, it often introduces visual artefacts that can again be considered visual noise and cause visual discomfort (e.g. blurry vision, vergence/accommodation conflict, reduced visual field [19]). Thus future work and studies need to carefully separate the potential advantages of visual noise cancellation from current shortcomings of the hardware prototypes.

Limitations. Our work has several limitations. Foremost, similar to other work, we intentionally decided against workshops composed of participants with similar backgrounds. Instead, we opted for a mixture that balances diversity in terms of demographics and background. That said, we have a bias in our sample towards male participants and a relatively low average age of 34. As both age and gender are known to affect visual perception our cohort will limit the range of responses represented and better distributions would be desirable. While this potentially might lead to an even better understanding of visual noise, we already saw a saturation of feedback with an increasing number of repeating concepts in later workshops. In fact, our participant numbers are in line or even exceed the numbers of similar documented research and thus we share some of their limitations. Furthermore, the IDEO process is intended to ensure all voices are heard. As such also underrepresented groups, with individuals present in our workshops, are considered in our exploration of visual noise and sufficient for the level of understanding gained. Similarly, our exploratory study is affected by the limited number of participants that is in line with other works but would preferably be higher. However, we again point out that this second study was mainly to receive qualitative feedback.

One could also argue that not presenting a definition or perfect model of visual noise limits the scope of this work. However, this was never our intention and we wonder if this is even possible given its highly subjective nature. Instead, we aimed to show that prior work is often technically motivated (e.g. as in Diminished Reality), existing models and views on visual noise are often based around the authors opinion rather than an actual exploration, and thus only consider certain aspects of visual noise. To that end, our current model for visual noise can be considered as a space that is based on the feedback we received. We think that there is potential for future work to add to the space of what can be considered visual noise, including input from other groups that have not been considered in our workshops.

7 CONCLUSION AND FUTURE WORK

In this work, we explored the concept of visual noise and visual noise cancellation. We took inspiration from the commonplace active audio noise cancellation and existing work on the benefit of noise cancellation (audio and visual) to explore the characteristics of visual noise and provide prototypical solutions for general visual noise cancellations. Contrary to the few existing works on visual noise we took a holistic approach toward visual noise. This means we have not focused on specific forms of visual noise (e.g., distracting motion) and initially left it to the participants of our workshops to identify unpleasant visual stimuli. When then refined the results in our meta-discussion and related them to known processed and theories in human visual processing and prior concepts from audio noise cancellation. We acknowledge that visual discomfort and a reduced visual performance is already a large topic within other areas, however, usually with a focus on people with a known medical condition (e.g. epilepsy) or development disorders (e.g. autism). In this work, we emphasise that many people without any medical history are also sensitive to different visual stimuli which they linked to the notion of visual noise.

In our work, we also prototypically explored possible mitigation techniques for selected visual noise types using HMD technology traditionally used in Mixed Reality. With the current demonstration prototypes in an early stage, sufficient for conducting an exploratory study, we gathered general feedback on the technology. This demonstrated an interest in the technology and the potential improvements it could bring. We emphasise again that this initial study was focused on exploring the general concept rather than a detailed analysis of a specific compensation technique that was explored over an extended period. We argue that those more targeted studies are needed and can benefit from our findings, but are subject to future work.

Similar to headphones that can display sound but nowadays also integrate active audio noise cancellation, we expect that future OST HMDs as proposed for Mixed and Augmented Reality will be capable of cancelling visual noise, and active noise cancellation will be a feature that becomes a key component. As such, we believe that there are several factors that will further contribute to the potential development of visual noise cancellation techniques: a) The expected further miniaturisation of HMD technology for VR and AR that is caused by the massive industry investments and is likely to bring their form factor closer to traditional glasses as used for correcting refractive errors. b) The high social acceptability of traditional glasses in particular when AR glasses can meet their form factor. While one needs to carefully design around ethical issues of smart glasses or glasses for AR [24, 51] we hypothesise that technologies that serve as a visual aid will see higher acceptability. Finally, c) Given the current progress in optical see-through HMDs development, future iterations will be capable of also filtering light instead of only adding light via the integrated display [18, 19] and as such will be a better alternative to the video-see through HMDs used in our demonstration prototypes as they can directly show the real environment.

Overall, we believe that the findings in this work contribute to a general understanding of visual noise as perceived unpleasant visual stimuli and the potential for computing technology to assist in cancelling some or all visual noise. Much of the sources of visual noise are human-made and unfortunately unlikely to recede in the foreseeable future, increasing the imminent relevance of this work. We also see a potential application for humans with a diagnosed attention deficit or autism as these often come with specific sensitivity to visual noise or specific visual stimuli. In this work, we also acknowledge the related field of Diminished Reality, vision augmentations or computational glasses, and human augmentations. While they share commonalities with our work, they often do not consider visual noise or unpleasant visual stimuli but mainly focus on simulating the removal of physical objects (Diminished Reality) or helping the visually impaired (computational glasses). Finally, this work creates a more holistic view of the potential of active visual noise cancelling and applications for modulating the environment to support the user.

AUTHOR CONTRIBUTIONS

Junlei Hong performed writing - original draft, investigation, software and conceptualisation, Tobias Langlotz performed writing - review & editing, conceptualisation, supervision, project administration and funding acquisition, Jonathan Sutton performed writing - review & editing and conceptualisation, Holger Regenbrecht provided conceptualisation and supervision.

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