A Design Space for Vision Augmentations and Augmented Human Perception using Digital Eyewear

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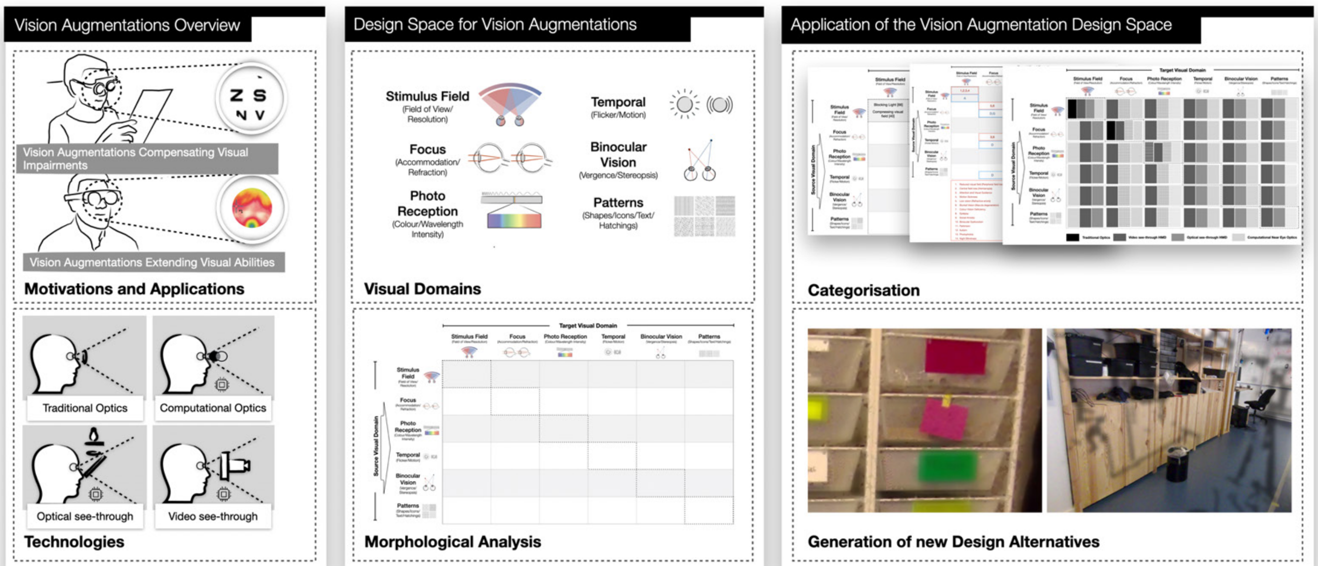

Figure 1: Visual abstract summarising our work on creating a Design Space for Vision Augmentations. As part of this work, we provide an overview on Vision Augmentations, introduce our Design Space for Vision Augmentations, and apply it by creating different views, categorising the field and using it to generate new design alternatives.

ABSTRACT

Head-mounted displays were originally introduced to directly present computer-generated information to the human eye. More recently, the potential to use this kind of technology to support human vision and augment human perception has become actively pursued with applications such as compensating for visual impairments or aiding unimpaired vision. Unfortunately, a systematic analysis of the field is missing. Within this work, we close that gap by presenting a design space for vision augmentations that allows research to systematically explore the field of digital eyewear for vision aid and how it can augment the human visual system. We test our design space against currently available solutions and conceptually develop new solutions. The design space and findings can guide future development and can lead to a consistent categorisation of the many existing approaches.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**; *Accessibility systems and tools*; **HCI theory, concepts and models**.

KEYWORDS

design space, vision augmentation, augmented reality, mixed reality, visual impairments, human augmentation, augmented human, sensory augmentation, accessibility, sensory augmentation

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1 INTRODUCTION

Head-mounted displays (HMDs), near-eye displays, and digital eyewear utilising some form of an Augmented Reality (AR) interface are often seen as possible successors to current mobile technology [13]. As one of the pioneers in developing HMDs [61, 62], Ivan Sutherland was on a journey to develop the ultimate display when his invention became a key technology for the concept of Augmented Reality. Over the years, research on HMDs and AR interfaces has attracted a large number of researchers who worked on improving the actual hardware (e.g. addressing accommodation-vergence conflicts, increasing the field of view), improving the rendering of the displayed digital content, or contributing new interaction techniques that reflect on the (often mobile) use. We can generally summarise these works as improving on the traditional concept of AR, and recent surveys provide an overview of the key developments [27, 32].

Lesser known than traditional AR research is the increasing number of works that have identified the potential of head-mounted displays and digital eyewear to augment the human visual system by re-purposing those devices as visual aids or computational glasses [63] with the aim to compensate visual impairments (e.g. [24, 64, 76]) or to extend visual capabilities (e.g. [47, 48]). These works, often coined *vision augmentation*, human augmentations, perception augmentation, or computational glasses, are fundamentally different to traditional AR research. Foremost, the aim is not to visually integrate 3D information into the user's environment. Instead, vision augmentation research focuses on modulating the visual representation of the physical world according to the user's needs. Integrated cameras, traditionally used in AR research for tracking the position of the user in the environment, are instead utilised as an eye into the user's environment, capturing visual details that need to be modulated (e.g. emphasised or diminished). Research on vision augmentation is highly interdisciplinary, involving researchers from Human-Computer Interaction, Accessibility, Augmented Reality, Ophthalmology, Visual Computing, and Optics. This also reflects the potential applications that can be addressed, including compensation of age-related vision impairments [24], decreasing visual discomfort [20], "superhuman vision" [29, 47], increased spatial awareness [49], social anxieties [56], managing attention [65, 71], and low vision [24] to only name a few (see selected examples in Figure 2). Similarly, existing works vary in character and can be application-oriented (top down, and here often focused on specific visual impairments [51]) as well as technology-driven (bottom up, such as introducing computational near-eye optics [28]).

The different motivations and characteristics of existing works make it increasingly hard to see and understand the possibilities and opportunities of vision augmentations and related technologies in human augmentations. Historically, one approach to overcome this gap is to write surveys or review papers that analyse the field and identify overall challenges and future directions. However, the focus of these papers is often the summation of existing works instead of a holistic categorisation and exploration of design alternatives for the selected field. Instead, the creation of *design spaces* has become a popular tool, in particular in the context of human-computer interaction [7, 19, 36]. A design space can be understood as a conceptual development and exploration of the overall solution space regardless of whether aspects are already addressed in prior work. As such, design spaces provide a more holistic view of the chosen domain that can be used to categorise and understand options for designing a target system, design critique, and, most importantly, potentially generate new design alternatives that otherwise would not be discovered. As such, a design space is often considered to contain pointers to all solutions, while prototyping is the implementation of individual solutions from the design space to gain deeper insights.

Specifically for vision augmentations, the actual design space is not understood. This is primarily because of the complexity of the human visual system and the different ways in which digital eyewear can be used to modulate the view. In this work, we contribute to this identified gap by presenting a first design space for the emerging area of vision augmentations. As part of this work, we holistically explore the space that vision augmentations can address and develop a design space that is the result of a morphological analysis. Furthermore, we demonstrate the utilisation of our design space by showing how it supports different views of the area of vision augmentation. These can be used to generate insights and a conceptual understanding into vision augmentations by categorising existing works and targeted applications of vision augmentations. Finally, we use our design space and show how it can be used to generate new design alternatives. To add to the challenge, we demonstrate this generation of design alternatives for two relatively well-researched areas of vision augmentations and show the results of the prototypical implementation. The results outline the potential for using our design space to identify novel approaches for vision augmentations, including those that can compensate for visual impairments and those that extend human vision (human augmentations, vision amplification).

Overall, our contributions are:

- The development of a design space for vision augmentations using morphological analysis.
- The utilisation of the design space to categorise existing solutions by using different views onto the created space.
- The application of our novel design space to generate new design alternatives when developing vision augmentations.

Besides the key contributions above, we will show that our design space also contributes a terminology and vocabulary that can be used when describing and discussing future vision augmentation approaches. Overall, this work is not only relevant for practitioners in the fields of Human-Computer Interaction, Accessibility and Augmented Reality, but it will also be relevant to practitioners in the fields of Ophthalmology, Optometry, Computational Displays and Optics. It will allow for a holistic exploration of the opportunities for vision augmentations, help with the categorisation of existing work, and support the generation of new research ideas while also reflecting on the specific characteristics of the human visual system and technical requirements within our developed design space.

2 RELATED WORK

This work touches on different research areas that we will briefly introduce. Initially, we provide background work on digital eyewear

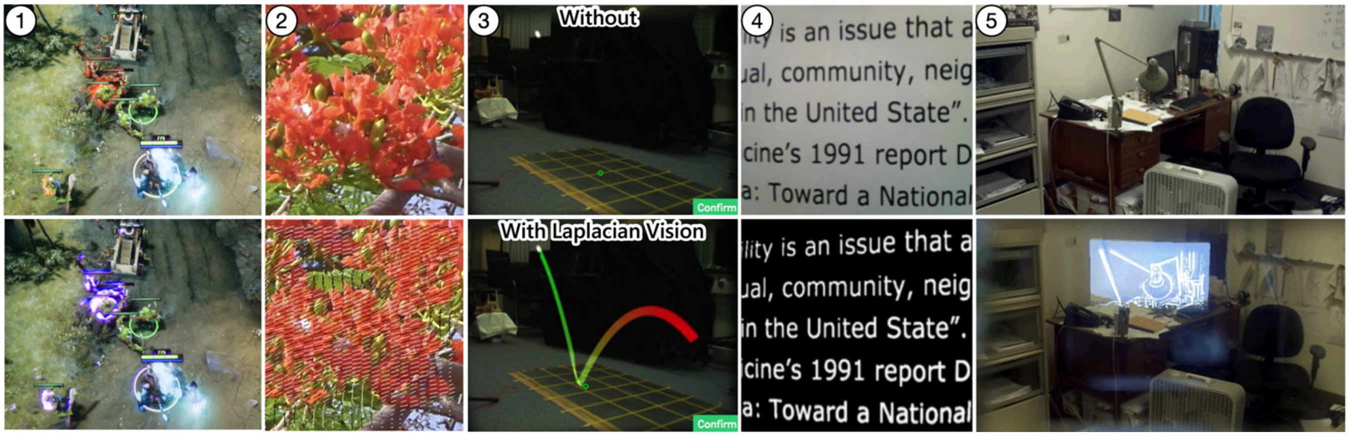

Figure 2: Selected examples of vision augmentation from the literature (top original view, bottom with enabled vision augmentations): (1) augmenting colour shifts using digital eyewear that changes selected colours to support people affected by colour vision deficiency [64], (2) augmenting colours with geometrical patterns to support people affected by colour vision deficiency [9], (3) Overlaying the predicated trajectory of moving objects [29], (4) Inverting the colours to increase the readability for people with low vision [75], (5) enhancing the edges via Google Glass for low vision [24].

and highlight major milestones related to Augmented/Virtual Reality but also link to prior work summarising technologies for digital eyewear. We further introduce the field of human augmentation and, here specifically, vision augmentations utilising digital technology to compensate for visual impairments or to extend non-impaired human vision. Finally, we will cover prior work on design spaces in the HCI and Visual Computing literature and the benefits of design spaces when compared to surveys, reviews, or taxonomies.

2.1 Digital Eyewear and Head-Mounted Displays

Over a couple of decades, research has introduced multiple examples of digital eyewear mainly in the form of Head-Mounted Displays or Near-Eye Displays like those in Virtual- or Augmented Reality. They all have in common that they utilise some form of head-worn computer-controlled optical device that usually aims to mimic the appearance of traditional glasses. However, there are also many differences that either stem from the actual workings of the hardware or the application field for the specific digital eyewear. HMDs are commonly attributed to Ivan Sutherland [61, 62], and nowadays we distinguish several categories (also see Figure 3). Firstly, Virtual Reality (VR) HMDs, closed head-mounted displays capable of displaying VR content that aim to visually decouple the user from reality [32]. Secondly, video see-through HMDs (VSTHMDs) are usually composed of closed VR HMDs that also integrate cameras, thus allowing for the option to display a video feed of the environment. Thirdly, optical see-through HMDs (OSTHMDs) integrate a semi-transparent display in the user's view and allow for overlaying digital information [27]. Finally, over the years, we have also seen other forms of digital eyewear that do not follow traditional designs of near-eye displays and explore different applications beyond typical VR and AR use cases, which can be summarised as computational near-eye optics [63]. Instead of integrating micro-displays emitting light, examples for computational near-eye optics implement a per-pixel filter that changes the perception of the physical environment by filtering environment light [26, 69]. Thus, they can almost be considered as smart sunglasses, albeit with many other demonstrated application scenarios. Other research has started to explore the idea of focus-tuneable lenses as part of computational near-eye optics. Here, the devices do not integrate light-emitting or light-filtering elements but instead change the optical power using the computational near-eye optics (e.g. by changing their dioptric power) [28, 50, 63] with potential to either support people with more complex refractive errors or for providing improved clarity for the unimpaired eye. The general idea of modulating the environment (e.g. by changing the visual appearance) has also triggered research on computational glasses[37, 63], which can nowadays be seen as an umbrella term for near-eye optics and displays that change the perception of the environment to aid the wearer. While computational glasses hardware often shares components with traditional AR HMDs and benefits from the rapid progress in this area, they are increasingly forming a distinctive category of digital eyewear with different requirements (e.g. traditional tracking and 3D graphics are often less relevant when compared to traditional AR) [37, 63].

2.2 Augmented Human and Vision Augmentations

The original idea of human augmentation can be tracked back to Douglas Engelbart when describing a framework for augmenting human intellect with the goal of "increasing the capability of a man to approach a complex problem situation, to gain comprehension to suit his particular needs, and to derive solutions to problems" [8]. More recently the field of human augmentation has gained a lot of traction [14] but is increasingly also considering augmentation of human senses [57] for example by compensating lost senses (e.g. vision) through utilising other senses (e.g. auditory or haptics) [6, 43, 58].

Figure 3: Example of different different computational near-eye displays or computational near-eye optics. (1) Autofocals, an example of computational near-eye optics adjusting for presbyopes [50], (2) computational near-eye optics using semi-transparent LCDs to change the appearance of the real world, (3) computational glasses based on optical-see through HMDs that have been used to compensate for CVD or guide attention [64, 65], (4) video-see through HMDs that have been used among others as a low vision aid but also to extend the human visual field [70, 76].

Within human augmentations, the field of vision augmentations is a steadily growing area. The first usage of the term vision augmentations or augmented vision dates back to the 2000s, when it was introduced by Eli Peli in the context of compensating tunnel vision and a reduced visual field by using different forms of digital eyewear [39, 51]. Since then, the research field has expanded and not only includes approaches that compensate for visual impairments but increasingly also explores extending human vision, sometimes referred to as superhuman vision or human augmentations and is used in multiple disciplines, including ophthalmology, augmented reality, augmented humans, human-computer interaction, and psychology, making it a highly interdisciplinary research field. So far, research on vision augmentation has not focused on specific digital eyewear but has been open to different forms of head-mounted displays (e.g. VSTHMDs, OSTHMDs) as well as computational near-eye optics. More recently, there has been an emphasis on the term computational glasses to differentiate the term from the traditional notion of head-mounted displays and near-eye displays when used for the specific purpose of augmenting human vision [63].

While we have seen applications of vision augmentations in many areas, some areas have been more commonly addressed. Probably the best-studied examples are the compensation of Colour Vision Deficiency (CVD, often casually called colour blindness) using digital eyewear [37, 45, 64, 66] with the goal of supporting users in distinguishing colours that otherwise look similar. This is generally achieved by changing the appearance of hard to distinguish colours through computational glasses. Besides CVD, age-related vision impairments have been repeatedly explored as they are commonly hard to compensate for with traditional approaches. Examples include compensation of tunnel vision or a reduced visual field [39, 51] and low vision [21, 28, 60, 75]. Vision augmentations have even been used to simulate age-related visual impairments to create more empathy [33, 72]. Vision augmentations also offer potential where purely optical solutions exist, but people struggle with their usage, e.g. bifocal glasses for correcting refractive errors [28, 50]. Computational near-eye optics offer the potential for adjusting the optical strength according to the current needs (e.g. for close proximity or distance) by tracking the environment. However, computational near-eye optics go beyond compensating for refractive errors and also allow for zooming in or out, thus even providing potential benefits to users who are not affected by refractive errors [28].

While earlier works in vision augmentations arose from the aim to compensate for specific impairments, later work also explored the potential for enhancing the non-impaired human visual system. Examples include magnification of distance objects [28, 41, 54], reducing the effect of haze or fog [18], increasing attention [31, 65], improved night vision [22], field-of-view expansion [49] improved peripheral vision [39, 70], or even motion prediction [29].

Besides original works, first works started to looked into reviewing the field of vision augmentations but focused on applications in assistance or therapy [38]. The potential for vision augmentations to serve as an assistive aid is also emphasised by recent works that study the perception of human augmentations [67]. The authors found in their mixed-method study that the general acceptance of human augmentations in general and sensory augmentations in specific is higher if it is known to support people with disabilities.

2.3 Design Spaces in HCI

Historically, there are different approaches to structuring a research field and identifying trends or research gaps. The most common approach is to survey a research field based on the existing literature. Several works are surveying the related field of Mixed and Augmented Reality [5, 27] but only two reviews capture certain aspects of vision augmentations. One review targets vision augmentations in therapy or as assistive aid [38]. Another work reviewed approaches that compensate for colour vision deficiency, including works that we would consider vision augmentations (changing the visual perception of the environment), as well as work that focused on changing the colour palette for desktop user interfaces [64]. The issue with many surveys and reviews is that they look mainly backwards and try to identify opportunities and trends by what has been published instead of methodologically exploring the problem space. As such, possible alternative solutions from a surveyed area are more likely to be overseen. Taxonomies, another approach, focus on the classification and organisation of a given area (e.g. for see-through tools [4]). Taxonomies and surveys are not mutually exclusive. Ideally, they are both addressed (as in for interaction in AR [17] or visualisation techniques in AR [77]), but that is often not the case and sometimes not the objective of the authors. Instead of focusing on prior published work, design spaces aim to more systematically explore a given problem space by conceptually considering all possible solutions with the benefit of potentially revealing alternative solutions [7]. As such, they focus less on the existing works and more on identifying the overall solution space to a given problem domain. Design spaces have increasingly been used in the field of human-computer interaction where they capture all possible solutions with prototyping as the actual implementation and study of one (or more) of the solutions within the design space. In fact, recent papers promote the idea of integrated experiment design in which design spaces play a key role [1]. While there is no standard for conceptually developing or even presenting a design space, repertory grid [36] and morphological analysis [7, 19] are techniques that have been used among others. The latter creates an axis for the main parameters or dimensions of the covered problem. The multidimensional space created by these axes represents the design space in which solutions can be found [78].

2.4 Research Gap

Overall, with the ongoing miniaturisation of technology, progress made in optical architectures driven by industry interest in head-mounted display technologies for Virtual- and Augmented Reality, and the general trend of directly supporting the interaction of humans with their environment through computing technology [23, 57], we see the need for a more structured approach when exploring the potential of human augmentations and specifically vision augmentations. While there are already ongoing activities to analyse the field of assistive technologies and assistive augmentations [43], we see the need to systematically explore the fast-growing area of vision augmentations, not only from the perspective of compensating for lost or missing capabilities but more generally also with a perspective on extending the capabilities of the human visual system.

3 A DESIGN SPACE FOR VISION AUGMENTATIONS

When conceptually approaching a design space for a specific area, the biggest challenges are the initial scoping followed by the development of the actual space that is usually defined by its main axes and dimensions. The latter is because there are different methodologies used for creating the actual space, and different dimensions exist that could form the space.

3.1 Vision Augmentations

The area of vision augmentations and general human augmentation is a quickly evolving field with no widely used definition or scope for both [14]. Schmidt identified several areas for "Augmenting Human Intellect and Amplifying Perception and Cognition" [57] with one area being amplified perception. He identified two main directions for amplified perceptions: The enhancement and amplification of existing senses and the "extension of perceptual abilities to domains where humans have no perception but technical sensors exist" [57]. While we largely agree with the notion and definition of amplified perceptions, it misses the ever-so-important domain of compensating lost or impaired senses. Other recent works identified that human augmentations aim to improve "the physical, intellectual and social capabilities of human beings"[14]. They also identified three distinct areas: (1) Augmented physical capabilities are achieved through the interpretation of the augmented senses and the actions they produce. Vision, taste, touch, smell and hearing can be physically augmented. (2) Augmented intellectual capacities are achieved through acquiring knowledge, cognitive processing and reasoning (e.g. memory). Finally, (3) Augmented social skills are considered through the interpretation of basic and complex social skills (e.g. empathy). For the initial scoping of our work, we see vision augmentations in a first category (Augmented physical capabilities).

Taking inspiration from the definition of Schmidt [57],we define **Vision Augmentations** as *extensions of visual perceptual abilities to extents or domains where technical sensor and optical devices exist that exceed human capabilities due to no, inferior, or impaired perception.*

3.2 Design Space Dimensions for Vision Augmentations

Within the literature, we see many different approaches to developing or structuring a design space (e.g. [7, 40] and they vary widely in their complexity. From all the existing approaches to building a design space, morphological analysis is potentially the most common when it comes to creating a design space [7, 78]. The key idea here is to create and analyse a multi-dimensional problem space by considering (analysing) all possible dimensions or parameters of the space. This requires systematically removing redundancy in the dimensions and deciding on the best-suited dimensions for the space. After considering the options, such as repertory grid, here we follow this concept of a morphological analysis for the design space on vision augmentations. In the following, we will discuss key design decisions when approaching our design space for vision augmentations and here mainly the dimensions that form our space and the characteristics of the final design space.

After deciding on the general approach (morphological analysis), the authors, all experts in vision augmentations as well as mixed- and augmented reality, had repeated brainstorming sessions to identify candidates for key dimensions used as part of the morphological analysis. After these first brainstorming sessions, we realised the need to maintain the initial scope that comes from our definition and existing categories of human augmentations [14, 67]. For example, possible dimensions from the initial brainstorming included modalities (e.g. haptics to vision or audio to vision) or psycho-physical factors (e.g., perception, cognition, action) [12]. Drawing from our initial definition, which is also supported by the literature on vision augmentations, we decided to focus on visual perception alone and not consider cross-modalities (e.g., such as [6, 42, 43, 58]) while also focusing on perception rather than cognition (the augmentation of intellectual capabilities). This follows existing literature on vision augmentations but considering cross-modalities or intellectual augmentations would have also added several other dimensions to cover the additional modalities and capabilities distracting from the original main of this work. After

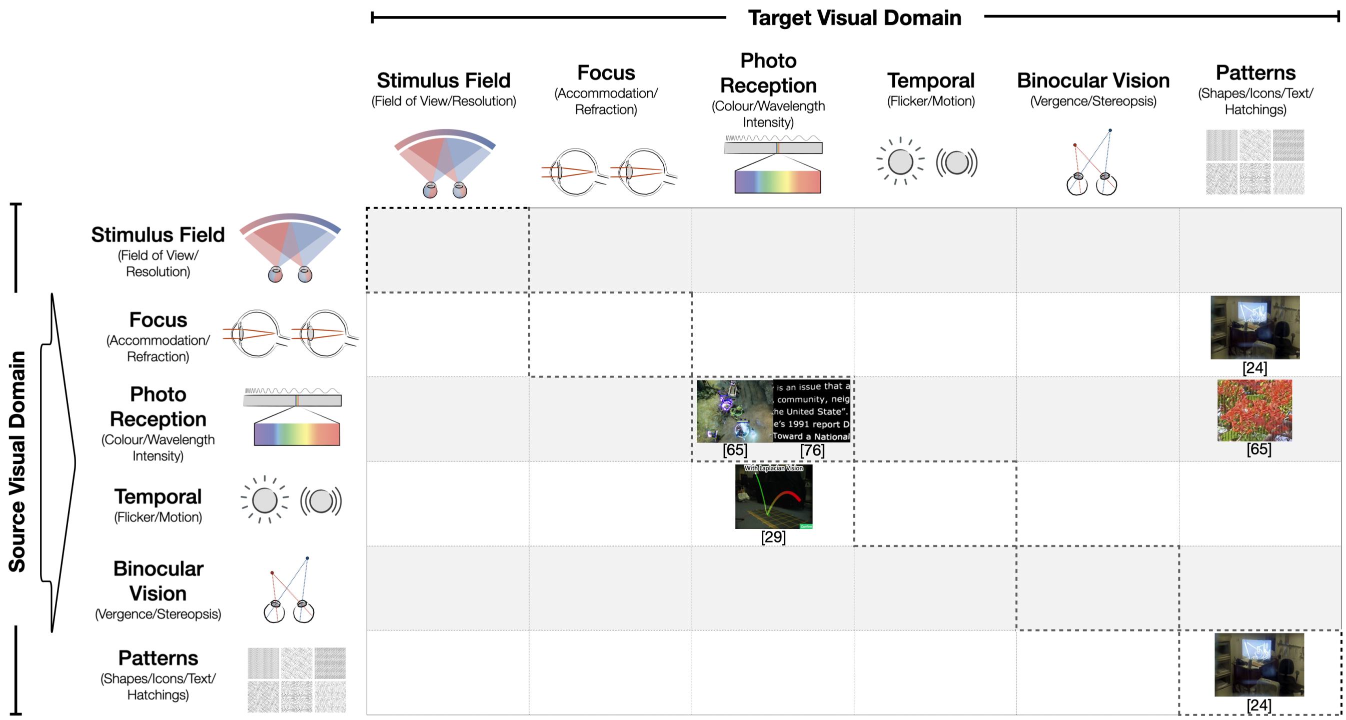

Figure 4: The overall design space developed from a morphological analysis on vision augmentations. The space maps from a source visual domain to a target visual domain. For clarity, we added the earlier examples to their respective locations. Note that the work by [24] appears twice as it can either highlight existing patterns (patterns to patterns) or create patterns from otherwise out-of-focus elements (focus to pattern).

that, we conducted another round of brainstorming for possible dimensions, applying the initial scope more strictly.

This second round of brainstorming led to several dimensions. Some of them, however, have not been used as key axes in our final design space. Examples include the purpose of vision augmentations, which could be seen as a continuous scale ranging from compensation (e.g. for visual impairments) over enhancement (e.g. improving existing visual capabilities) to extending (e.g., adding new visual capabilities). Other discarded categories include the operation of vision augmentation, which could include a categorical scale (e.g., vision augmentations that introduce information by filtering specific visual cues, modulating specific visual cues, or adding new visual cues), type of use (e.g., constant vs. sporadic), the stage within the human visual system (e.g., cornea, lens, photoreceptors, etc.) or technical criteria (e.g., properties of devices for vision augmentations). The latter two were discarded because visual stimuli are dependent on an interplay of different parts within the human visual system, while the technical criteria were discarded as key axes because they constrained the space to the capabilities of current or foreseeable display and eyewear capabilities, which is an area of fast development (e.g., see recent works on eyewear technology for Virtual and Augmented Reality [27, 32]).

It is important to note that despite not being key axes of the design space, we will later show that our design space can still support these criteria via dedicated views of the space (e.g., technical view, or applications view).

3.3 Design Space for Vision Augmentations

When revisiting the existing literature on vision augmentations, we came to realise that all existing works on vision augmentations did one of two tasks: They either 1) modulated certain visual domains, that is, they either emphasise or de-emphasise a visual domain or visual cue or 2) they transformed visual domains. That is, they communicated through a different visual domain or visual cue. More specifically, the most generic concept of vision augmentations can be described as increasing the information available through the visual domain (V). As we are focused on augmenting human vision (compensating for lost visual abilities or extending visual abilities), we can express vision augmentations as a function that maps from a source domain (S) (which is a subdomain of V) to a target (co)domain (T) (also a subdomain of V) through a modifier (m). Note that S and T can be the same domain (.i.e., $m : S \longrightarrow S$) and T can alternatively consist of several subdomains of $V (T = v_1 \times ... \times v_n, v \in V)$ (e.g., we can augment perception by communicating information through multiple domains). Consequently, through the modifier m can be that we either introduce, modulate, or reduce/diminish certain visual stimuli.

As an example, the work by Sutton et al. on improving colour perception for people affected by CVD maps from the source domain

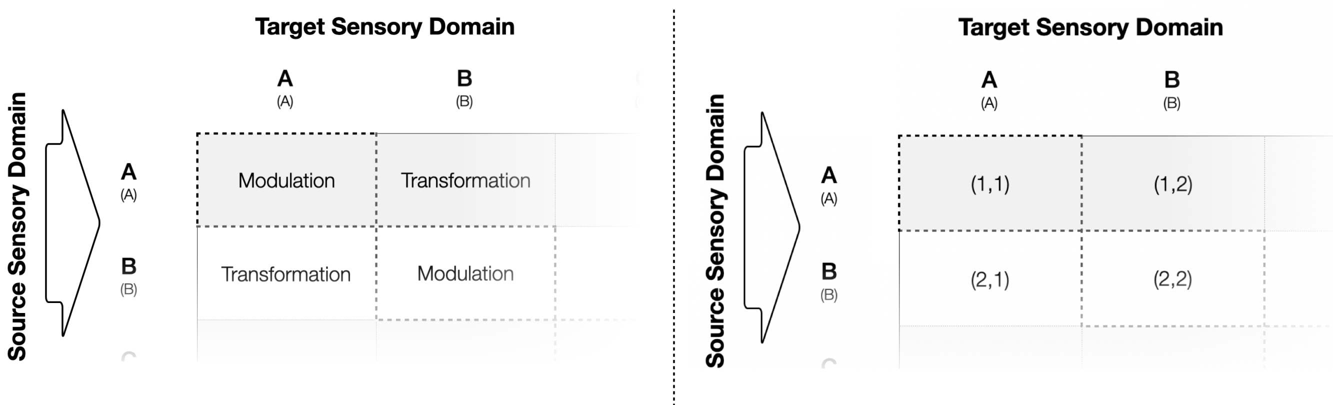

Figure 5: Details of certain characteristics of our developed design space. (Left) The diagonals within the design space are modulations (manipulations within the same visual domain), while all other fields are transformations (a transfer from one visual domain to another visual domain. (Right) Convention for referring to individual cells within the design space, the top left cell being (1,1) and the lower right one (n,n) with n being the maximum dimension.

(colours) to the same target domain (colours) with a modifier being the modulation by shifting colours (see Figure 2(2)) [9]. Another work by Flatla et al. on improving colour identification for people affected by CVD maps from the source domain (colours) to a target domain (geometric patterns) with a modifier being the introduction of the patterns (see Figure 2(2)).

This observation led us to the conclusion to use categories that are more inspired by the human visual system for describing the visual domain (V) and the mapping from the source domain (S) to a target domain (T). Unfortunately, the human visual system is very complex and the detailed understanding of some processing of visual stimuli is still an active research area, which makes it hard to identify categories or dimensions that are clearly separated. Similarly, the processing of visual cues often depends on multiple key structures in the anterior visual pathway (mainly eye and optical nerve) and posterior visual pathway (mainly different stages in the visual cortex). As such, using the stages of the human visual system was not an option. We settled on using the different visual domains (or visual cues) as the best categories for systematically building the space. Visual cues are visual information that humans gather from their environment and help to build a visual representation of their environment. During our discussion, we identified the following high-level visual domains that form the main categories for our design space:

Stimulus field Our first visual domain is the spatial array of visual sensations, which is commonly known as the stimulus field, that decides the objects seen (external stimulus field or distal stimulus) and the resulting earliest retinal events (internal stimulus field or proximal stimulus) [59]. While traditionally not considered a visual cue, the stimulus field, its resolution, and size actually decide if we perceive any visual stimuli at all. It relates to the concept of the visual field, but the latter is often used to describe different aspects [59]. The stimulus field can be constrained, e.g., through tunnel vision as well as there are examples in nature with an extended stimulus field or extended visual field when compared to humans (e.g., some animals have a stimulus field covering almost 360°). Similarly, the stimulus field also affects our perceivable resolution as the resolvable spatial resolution depends on the stimulated area (the area of the retina).

Focus The second visual domain is focus cues such as accommodation and refraction. This category mainly relates to the distal stimulus (the physical distant stimulus that might already be defocused) and proximal stimulus (the image created in our eye through accommodation and can be unfocused due to refractive errors). An image's perceived focus or sharpness is important to perceiving details and high contrast and is important to form our scene understanding. Perceived sharpness, or the lack thereof, is also a factor that influences visual attention through perceived saliency. Research also showed that an unnatural contrast (e.g. too high or too low) is connected to visual discomfort [20, 30] so certain limits have to be respected to avoid negative effects.

Photo Reception The third visual domain is photo reception, our ability to perceive different colours and intensities. This ability depends mainly on the biochemical processes of the photo receptor (rods and cones in our eye) and mainly controls our ability to see (or not see) certain electromagnetic waves (visible light) and perceive them as different colours and with specific intensities. Overall, we are able to perceive a dynamic range of approximately 46.5 stops [35] and the unimpaired eye can easily distinguish more than hundreds of thousand colours.

Temporal The fourth visual domain is temporal cues that are caused by temporal changes in the distal stimulus and how they are processed in the human visual system. While much of this processing of temporal cues such as flicker or motion is constrained by the photo receptor cells (rods and cones) and their intrinsic critical flicker frequency, it is known that flicker and motion is a complex process and an interplay of different parts of the human visual system. Change blindness is one example of a side effect of this complex interplay. While the critical flicker frequency is not constant across the visual field, it is often given at 90Hz, and it is known that perceptual temporal changes can create a very salient stimulus.

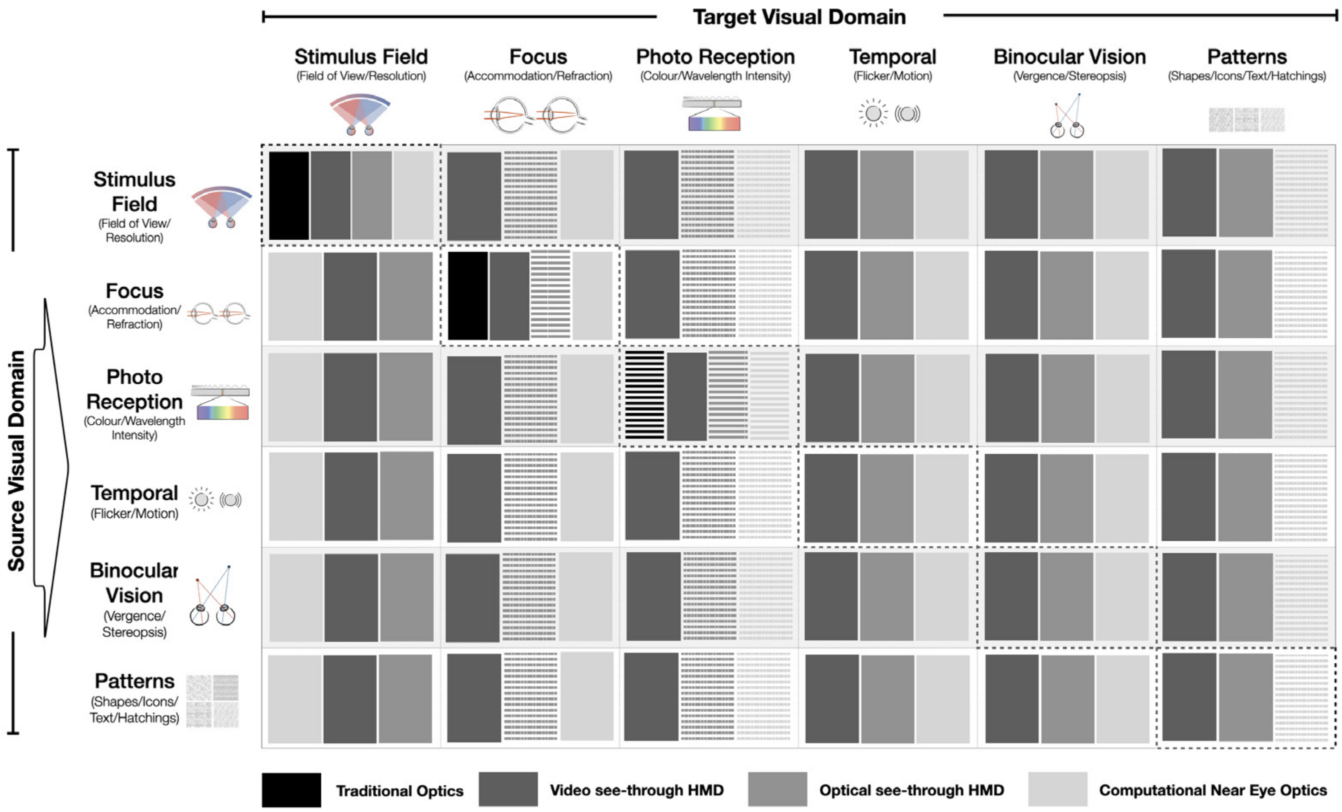

Figure 6: A technology view on our design space illustrating which technology can be used for delivering which vision augmentations with a focus on traditional optics, video see-through HMDs, optical see-through HMDs, and other computational near-eye optics (e.g. tuneable lenses, LCD see-through optics). Solid areas indicate that the given technology can deliver a large part of the needed functionality for the specific combination of source and target visual domain while hatched areas indicate that the indicated technology has substantial limitations in delivering the specific vision augmentation. If a technology is not shown, it cannot deliver the specific combination of source and target visual domain.

Binocular Vision The fifth visual domain are visual cues that are mainly caused by our ability to see the world with two eyes. In this work, we mainly refer to cues and processes related to stereopsis (depth perception caused by the different views of each eye) and binocular fusions (e.g. binocular rivalry for effects created by presenting different images to each eye).

Patterns The last visual domain encapsulates visual cues such as shapes, patterns, or other geometric primitives. The processing of these is in several areas of the visual cortex that depend on their complexity (e.g. edges vs. simple structures and patterns vs. more complex patterns or even icons). We can usually distinguish different shapes or patterns easily, even with high complexity. Therefore, techniques that use hatching or other geometric primitives have often been used as illustrative techniques to emphasise differences when dealing with a reduced colour palette or in case colours cannot be used (e.g. [55]). At the same time, some patterns can also be highly salient.

These identified visual domains form the dimensions of our design space for vision augmentations. While there are other concepts and visual cues, e.g. depth perception or visual saliency, it is worth pointing out that these are usually combinations of the domains that we identified for our design space (e.g. depth perception depends on focus and binocular vision, while spatial bottom-up saliency depends not only on focus but also on photo reception and patterns).

The key idea of our design space is that it expresses the earlier mentioned mapping from a source visual domain to a target visual domain, with each source domain and target domain being composed of the six key visual domains that are introduced above. Figure 4 shows the overall design space with the source domains on the left and the target visual domains on the top. This design space allows us to identify and describe all possible mappings in the visual domain. For clarity, we added in figure 4 the earlier examples modulating colours and intensities [64, 75], colours to geometrical patterns [9], motion to colours [29], and finally, the work by Hwang and Peli that can be used to emphasise patterns and help to see otherwise unfocused pattern details (focus to patterns) [24].

From looking at the final design space, it is obvious that vision augmentations change either the same visual domain (we call this

Modulation) or using a different visual cue (we call this *Transformation*) (see detail Figure 5). We also emphasise this difference in the full design space in Figure 4 with the highlighted diagonal for modulations within the design space while all other fields indicate transformations.

4 UTILISATION OF THE DESIGN SPACE - GENERATING INSIGHTS

Our design space resulted from a morphological analysis in which each cell describes the modifier and the axes describe the visual source and target domain. Overall, this space describes the changes in how we perceive the environment achieved through vision augmentation. For simplicity, from here on, we refer to individual cells by their coordinate (s,t), with s being the coordinate on the source visual axis, and t being the coordinate on the target visual axis with (1,1) being in the upper left-hand corner (see Figure 4 (Right)). As a first utilisation of our design space, we decided to generate different views on the design space with the goal of generating insights into the overall field for vision augmentations. This utilisation also serves as a first evaluation as a design space should be flexible enough to support these different views of the design space.

Key technologies view. As outlined earlier, different technologies can be used for vision augmentations (see Figure 3), such as video see-through HMDs, optical see-through HMDs, and computational near-eye optics. However, not all technologies can be used for all possible combinations that define specific vision augmentations, as described in our final design space. Thus, as a first test, we created a technical view of the design space to indicate the suitability of different technologies to achieve different vision augmentations but also to show how our design space can handle criteria that are not directly part of the space, such as the used technology. We included in this technical view traditional glasses (non-computerised glasses used mainly for compensating refractive errors or as sunglasses), as well as VSTHMDs, OSTHMDs, and computational near-eye optics (see Figure 6).

This generated view of key technologies shows several aspects that are of relevance for researchers and practitioners in vision augmentations. Foremost, it shows the limitations of traditional optics when considering the full potential of the vision augmentation design space. Traditional optics can only be used to implement a few modulations within the design space but not transformations, as those would require some computational control. Specifically, traditional optics can be used to modulate the stimulus field (1,1) through optical magnifications, reductions, or blocking a distal stimulus. Further, it can be used to modulate focus (2,2) as it is commonly used to correct refractive errors. Finally, traditional optics can be used to modulate photo reception but only partially, as they can only produce target colours and intensities through filtering and usually only for larger areas.

Our generated view of the design space also shows that video see-through technology is currently the only technology which can deliver almost all combinations to modulate or transform human vision. This is unsurprising as it is the only technology that fully separates the human visual system from any real-world distal stimulus and replaces it through a fully computer-mediated stimulus that allows for almost any modification (e.g. changing the stimulus field, changing photo receptions, temporal cues, etc.). Vision augmentations using video see-through HMDs have some limitations in the Focus target domain (e.g. they can only blur or sharpen in software), but we still argue that they cover most of the needed functionality.

Finally, vision augmentations using optical see-through HMDs or wearable computational near-eye optics are suitable for many areas but have limitations and are unsuitable for some specific areas. Most of the limitations of optical see-through HMDs stem from the fact that one can only add light (e.g. one can usually not darken the environment, with the exception of the recent Magic Leap that can only darker larger areas) [27]. As such, one is limited in the ability to modulate or transform to the Photo Reception domain as one cannot create certain colours or intensities. Furthermore, optical-see-through HMDs can render a sharp image, but changing the focus of the physical world is limited to blurring by rendering specific patterns that give the perception of a blurred scene [65]. Computational near-eye optics perform in many ways the opposite of optical see-through HMDs. Different computer control optical components allow for an interactive focus adjustment (focus tuneable lenses) but the ability to modulate or transform to the Photo Reception domain is limited. Unlike optical see-through HMDs, computational near-eye optics can only filter the light and do not have a light emitting component and thus cannot increase the brightness or achieve certain colours [27]. Finally, computational near-eye optics struggle with creating smaller patterns requiring smaller pixels (equals a higher resolution) in the light filter. Creating high-resolution light would create issues with diffraction thus, existing approaches using per-pixel light filters usually have a lower resolution to minimise diffraction [73].

Overall, we show that our design space can support this technical view, which can help practitioners when deciding on the technology they can use for achieving specific vision augmentations.

Survey-based view. Besides a technical view, our design space can also be utilised for categorising and presenting existing works in the area of vision augmentations (see Figure 7). As such it can be used in the future to structure existing works as part of a survey. Our primary goal for this work was not to create a survey. As such, we provide for each cell only a selection examples, but a full survey would show that for cells with entries, more works exist in the literature. For example, the modulation from Photo Reception to Photo Reception and the transformation from Photo Reception to Patterns are both widely explored in the context of compensation for Colour Vision Deficiency (CVD), and recent surveys provide an extensive list with more than 15 approaches targeting wearable devices and substantially more (>50) when also considering other devices [64].

As such, the view we generated for this work not only shows which techniques, to the best of our knowledge, have been implemented but also, which techniques have not yet been realised. Generally, one can see that using Photo Reception and Patterns as the target domain is relatively well explored. That is not surprising as colours and patterns can be very salient and can transport additional semantics (e.g. we can easily group structures based on similarity in their colour or pattern structure). However, prior work

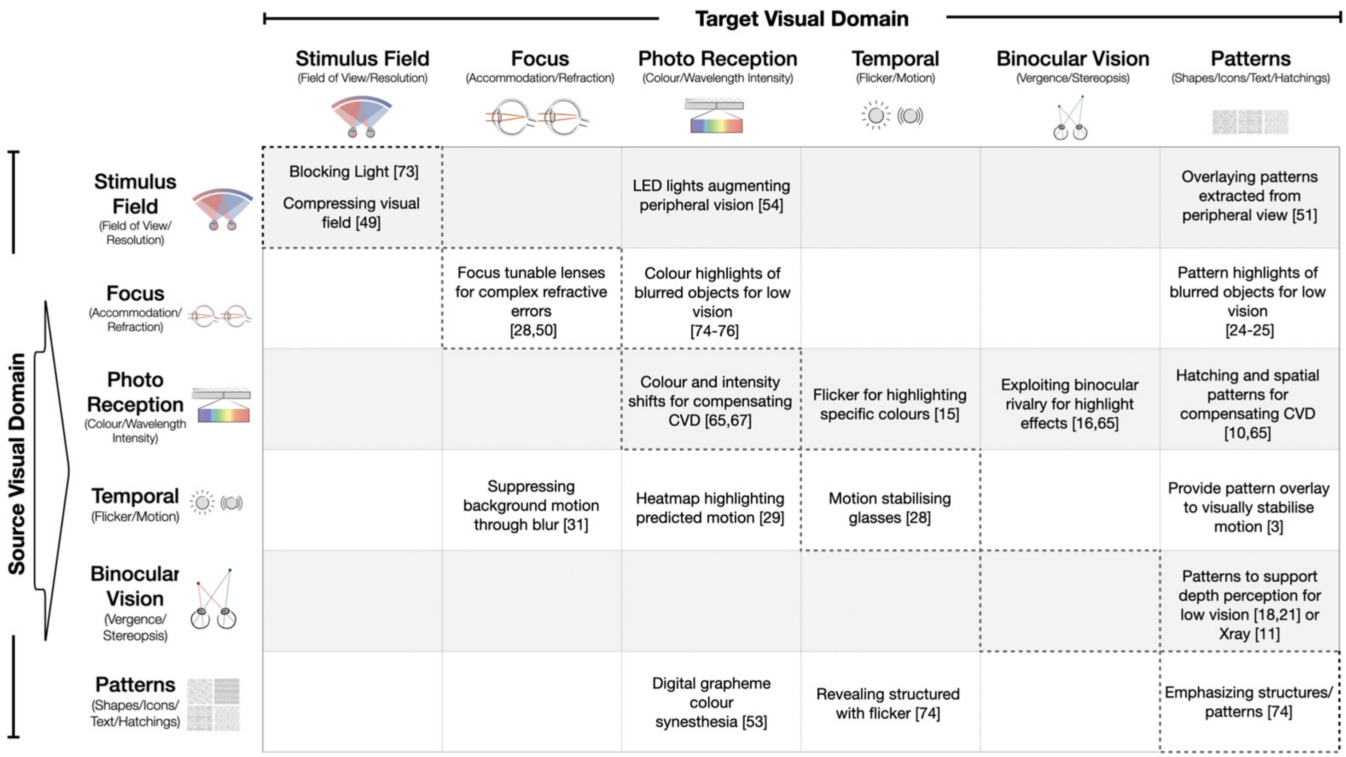

Figure 7: Survey-based view on our design space listing works representing approaches for each modulation and transformation. While some areas have seen multiple works (and not all are listed here) some others have not yet been considered. Source Domain Stimulus Field: [49, 51, 54, 73], Source Domain Focus: [24, 25, 28, 50, 74–76, 76], Source Domain Photo Reception: [10, 15, 16, 64, 64, 64, 66], Source Domain Temporal: [3, 28, 29, 31], Source Domain Binocular Vision: [11, 21, 74] Source Domain Patterns: [53, 74].

also showed that using cues from the focus domain can be highly salient (e.g. how much something is in focus decides not only if we can perceive it but also how much relevance we give to it). At the same time, cues from the Temporal domain (e.g. flicker) or from the Binocular Vision domain (e.g. binocular luster) can also create highly visual effects but they seemed to be less explored. More importantly, a comparison of using different cues in controlled lab and realistic field studies is missing.

Application-based view. Similarly to using our design space to show key technologies and their suitability for vision augmentations or to show recent works on vision augmentations, one can also approach it from an application view. For example, prior work suggests that reducing the stimulus field also reduces motion sickness as it blocks any stimuli in the visual periphery, and there are already prior works using that effect [73] (see Figure 8(1,1)). We similarly analysed and mapped other applications for vision augmentations that have either been proposed or have already been implemented. Again, as already visible in the survey view, some areas are repeatedly targeted while others have not yet been considered in applications. At the same time, it is important to point out that we include here areas that have been proposed as well as those that have also been implemented. We did not map applications to specific vision augmentation techniques that would make sense but have not been proposed in the literature (see also our later discussion on generating new design options).

Overall, we presented different views that results from a utilisation of our design space, either mapping key technologies and their capabilities, existing works, or application areas. It is essential to point out that our aim was not to declare completeness (e.g. mapping all works or possible applications) but to demonstrate a utilisation of our design space and identify possible issues with our design space. To that end, we could successfully map the above-mentioned views and did not identify works and concepts within the scope of this work that we could not successfully map to our space. Similarly, the generated views reveal options for selecting target devices and their implementations, as well as they reveal gaps in the design space, such as mappings from source to target domains that have not been explored. We can already see how one can approach the design space with a certain application in mind (e.g. compensation for a specific impairment), and one can see which options exist for utilising cues from a different domain as well as whose have already been proposed.

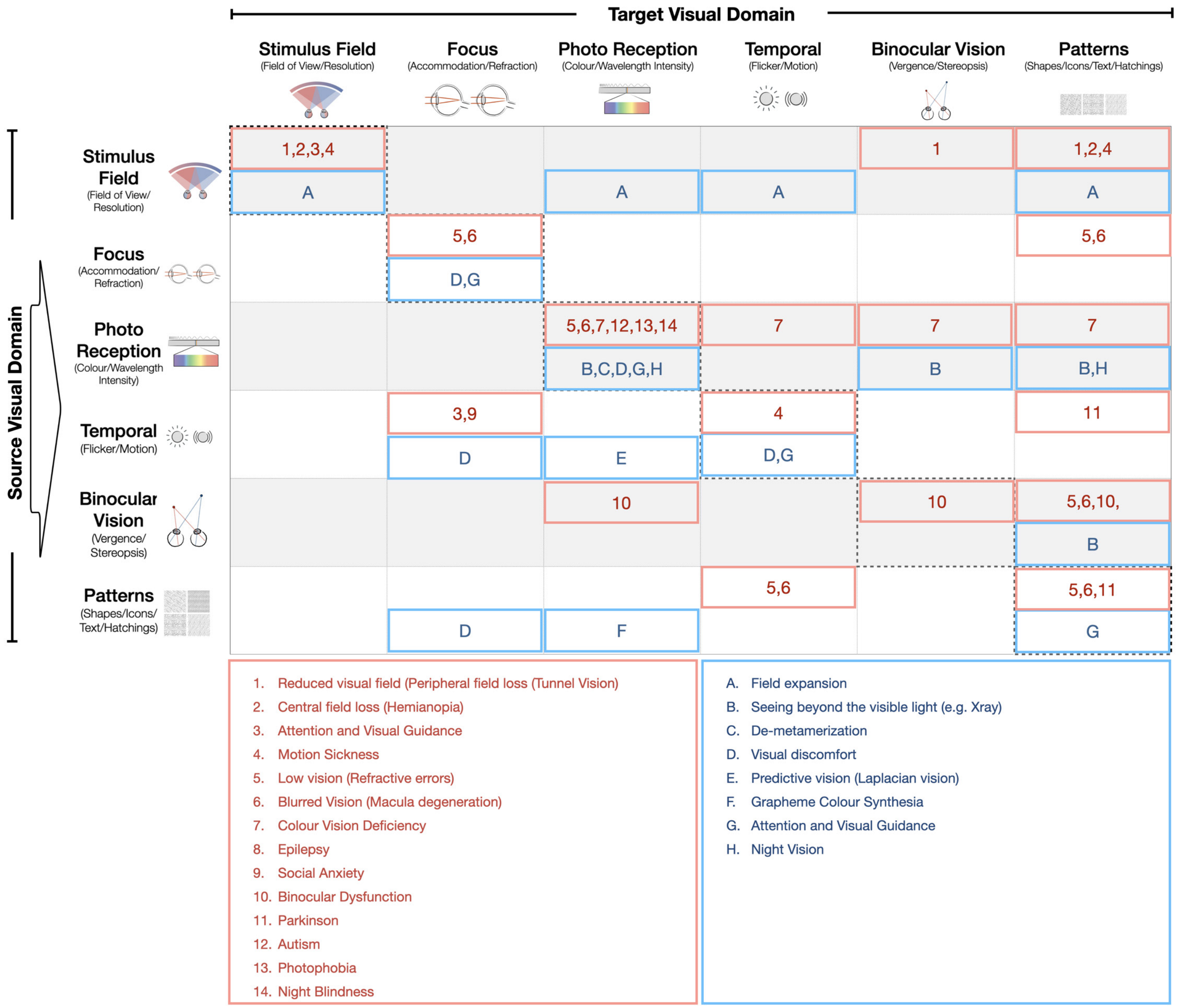

Figure 8: Overview on applications for vision augmentations that have either been proposed or actually been implemented in the literature. Numbers in red indicate applications that compensate for visual impairments or address accessibility issues, while blue characters indicate applications for extending visual capabilities. Note that some applications have been explored for one area but not for the other even though similar concepts could equally be applied.

5 UTILISATION OF THE DESIGN SPACE - GENERATING NEW DESIGN ALTERNATIVES

Design spaces generally serve two main purposes. Firstly, the categorisation of techniques or approaches for the addressed area with the goal to give researchers and practitioners insights and allow for a more systematic overview of the field. Secondly, to support researchers to gain deeper understanding of the actual design choices and support creativity and consequentially the generation of new approaches. We already demonstrated the utilisation of our design space, allowing practitioners to gain insights through different views categorising vision augmentation techniques and approaches.

In the following, we provide two examples of using the design space to generate new design alternatives. We specifically picked two relevant application areas for vision augmentations: Colour Vision Deficiency (CVD) and visual field expansion. Both have already attracted a large body of work (e.g. for an overview of the literature in CVD see Sutton et al. [64]), thus making it more challenging to identify new design alternatives. Furthermore, CVD is a typical example of vision augmentation as an assistive technology. At the

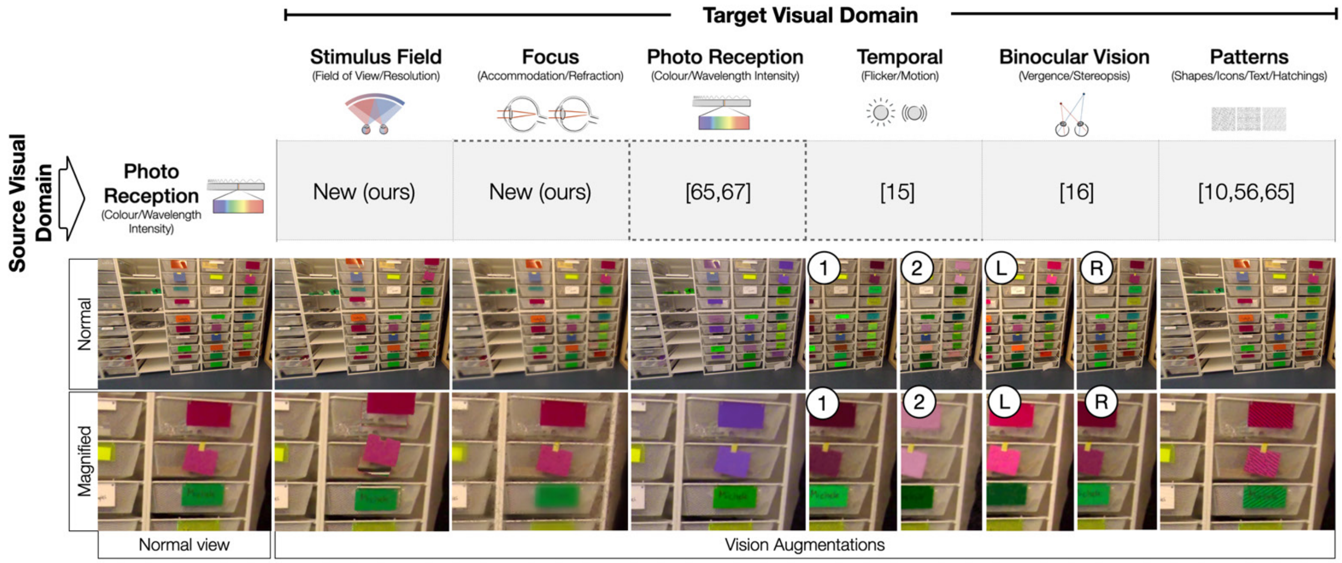

Figure 9: Illustration of using our design space to identify new alternatives for CVD compensation. Focusing on the Photo Reception source domain, we identified and implemented new solutions (marked as New) and reimplemented existing solutions (marked as paper reference) for compensating CVD. The generated example views and magnifications are screenshots from our prototypical implementation using the Varjo XR-3 and run in real time. The views illustrating a transformation to the temporal domain show the two views (1&2) that the system moves back and forward (temporal effect). In contrast, the transformation to binocular vision shows the image for the left (L) and right (R) eye that are used to create a binocular luster effect.

same time, visual field expansion sees application for people with a reduced visual field but also as a technique to extend the human visual system (e.g. superhuman vision [44, 48, 70].

5.1 Generating new Design Alternatives - CVD

Colour Vision Deficiency (CVD) is one of the best-studied examples of Vision Augmentations and multiple directions have been explored [64]. In the following we demonstrate the utilisation of our design space to generate new design alternatives to compensate CVD. As CVD affects our ability to perceive and distinguish frequencies within the visible light, we focus in our demonstration on photo reception as the source sensory domain (see Figure 9). A look into the literature reveals multiple techniques for compensating CVD by modulating photo reception. This includes either representing perceptually similar colours through different light intensities or applying colour shifts that shift selected colours (usually red) more towards the blue spectrum [64, 66], making it easier to distinguish them from e.g. green areas (see Figure 9, modulation Photo Reception to Photo Reception). Similarly, the literature reports on examples that use a transformation into the temporal domain in which the appearance of specific colours changes quickly over time, creating a kind of flicker effect that is highly salient (see Figure 9, transformation Photo Reception to Temporal) and a transformation into the binocular vision domain using a specific form of binocular luster effect (an effect resulting from binocular rivalry) [16] to emphasise specific colours (see Figure 9, transformation Photo Reception to Binocular Vision). Finally, there are multiple examples for the transformation of colour features into geometric patterns [9] (see Figure 9, transformation Photo Reception to Patterns).

However, our design space for vision augmentations also revealed other methods that so far have not been identified. For example, with the help of our design space, we discovered that a transformation of colour information into the focus domain was never considered, despite focus being a strong visual cue. A possible solution would be a transformation in which selected target colours are blurred, creating a visible effect that can be picked up relatively easily. Figure 9, transformation Photo Reception to Focus, demonstrates a prototypical implementation of this idea implemented on a video-see through HMD (Varjo XR-3). Additional, as per our design space, we also discovered the potential to transform Photo Reception into the Stimulus Field by applying a spatial 2D manipulation that differs depending on the colour (see Figure 9, transformation Photo Reception to Stimulus Field). It is important to emphasise here that a design space does not necessarily provide solutions that are all equally good at solving the problem. Instead, the design space is to identify theoretically possible solutions, and their fitness to solve the actual problem has to be evaluated through prototyping the solutions and empirical studies, which is not a part of this work.

5.2 Generating new Design Alternatives - Visual Field Extension

We also demonstrate the generation of new design alternatives using another commonly proposed use-case: enhancing the visual field beyond physiological limits [44, 46, 48, 70]. According to the literature, enhancing the visual field (stimulus field) can increase

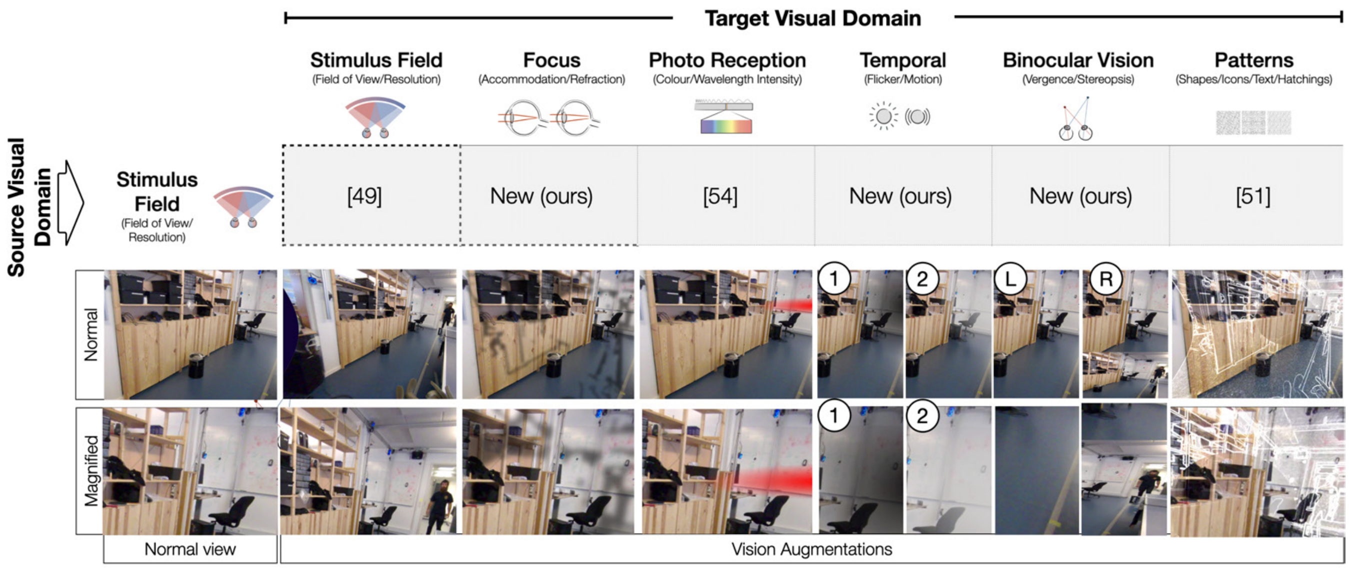

Figure 10: Illustration of using our design space to map existing techniques and identify new alternatives to expand the visual field. Focusing on the Stimulus Field source domain, we identified and implemented new solutions (marked as New) and reimplemented existing solutions (marked as paper reference) for expanding the visual field. The generated example views and magnifications are screenshots from the view through the Varjo XR-3 and run in real time. The views illustrating a transformation to the temporal domain show the two views (1&2) that the system moves back and forward (temporal effect). In contrast, the transformation to binocular vision shows the image for the left (L) and right (R) eye.

situational awareness by indicating things that generally would fall outside our visual field. For example, some animals have a visual field almost reaching 360°. Similar techniques are also used to assist people with age-related vision impairments that cause a reduced visual field (e.g. [39]. In both cases, the challenge is to identify novel ideas for how vision augmentations can be used to indicate in our actual stimulus field what happens in our surroundings but is outside of our stimulus field.

Exploring design ideas for extending the visual field requires us to look at the stimulus field as the source domain and brainstorm techniques that modulate, or transform this domain into another target domain (see Figure 10. We already know from the literature of existing approaches that show the user a wider view by modulating the stimulus field [44, 46, 70], and here specifically the compression of a wide-field of view into the existing smaller field of view (see Figure 10, modulation Stimulus Field to Stimulus Field) and our brain is usually able to adapt to the different perspective over time. There are also approaches that indicate the presence of objects of relevance outside the visual field using lights and photo reception [44] (see Figure 10, transformation Stimulus Field to Photo Reception) transforming information from the wider stimulus field into different target visual domain. Finally, there have been prior approaches, initially to compensate for tunnel vision, that enhanced the visual field by transforming a wider visual field into a pattern representation. Specifically, they overlayed patterns (edges extracted from the wide field of view) as an overlay in AR [51] (see Figure 10, transforming Stimulus Field to the Pattern domain).

However, with the help of our design space, we also discovered new design alternatives that extend the visual field. The morphological analysis in our design space shows that focus as target domain was so far not considered. A solution could present a larger visual field by transforming into the focus target domain. Specifically, an unfocused representation (protoypically implemented as an unfocused black outline) could be blended with the actual view and provides a spatial understanding of objects, their size and movements) out of the visual field as a blurred, unfocused overlay (see Figure 10, transformation from Stimulus Field to the Focus domain). This identified solution using an unfocused view has the potential to visually separate both views (actual and extended visual field) while also being less salient than transforming into some of the other domains. We also identified a possible approach that transforms to the Temporal domain and here flicker. While flicker has already been used for guiding towards visible objects [34, 68], one can easily imagine flicker at the border of the visible stimulus field to indicate objects outside of the current view (Figure 10, transformation Stimulus Field to Temporal domain) thus increasing spatial awareness.

Finally, using our design space, we also identified a solution space for extending the visual field that utilises the Binocular vision target domain that was so far not considered. Possible solutions could take inspiration from binocular effects in traditional optics for assisting degraded peripheral vision [52]. For example, we prototypically create a solution for this approach that presents an extended visual field as an overlay to one eye (see Figure 10, transformation Stimulus Field to Binocular Vision). Presenting it only to the lower segment will potentially interfere less with central vision, which has proven beneficial [52] while presenting it to only one eye has potential positive effects as the general impact to the perceived environment is less as the process of visual summation (the combination of visual information from both eyes to create a single, detailed image). At the same time, the use of head-mounted display technology would also allow disabling the view, something that is not possible with traditional glasses or view expanders.

Overall, we demonstrated the use of our developed design space to identify new design alternatives for given problems in vision augmentations and as such promote the systematic exploration of this important area. We support our conceptual exploration with the prototypical implementation of identified design options and the re-implementation of existing approaches on a VSTHMD (Varjo XR-3) driven by a desktop computer with an RTX 3080 GPU and a Ryzen 5800x CPU. For capturing the environment we used the integrated world cameras of the Varjo XR-3. The image operations (e.g. image tresholding, colours space segmentation) were performed as shaders in Unity 2023 which was also used for the final rendering on the Varjo XR-3. The pipeline was not optimised but running at framerates of 30fps. An overview of all techniques can be seen in Figure 9 and 10. The latter uses visual field extension to either indicate a larger field of view or indicate the presence of objects of interest (e.g. here a person in the door) outside of the current field of view. We again emphasise that the aim here was not to create the best techniques, but create new design ideas that later can be evaluated to identify strengths and weaknesses.

6 DISCUSSION AND CONCLUSION

In this work we present a first design space for vision augmentations that is based on a morphological analysis. The key design idea of our design space was to be able to express all possibilities for changing visual cues by either modulating them (maintaining the visual source domain by changing its expression) or transforming them into a different visual target domain. We later showed how our space can be used to categorise existing approaches in vision augmentations as well as how our design space can be used to generate new ideas and approaches for vision augmentations.

Specifically, we showed that our design space supports different views of the space that can be used to categorise the area of vision augmentation based on multiple criteria (e.g. technical views, application view, etc.) and we demonstrated the generation of overall five new design alternatives for vision augmentation for CVD and visual field expansion. We highlight here that those examples were chosen because both, CVD and visual field expansion, have attracted a fair amount of prior research that already explored different visual target domains. Still, with the use of our developed design space, we demonstrated how we identified new design alternatives and revealed new opportunities for both use cases which can similarly expanded to other areas of vision augmentations.

Overall, we firmly believe that our design space is beneficial and might even become necessary to develop the field of vision augmentations further. Our design space for vision augmentations does not only help to gain insights (e.g. through categorisation or mapping of prior work) or help in identifying new opportunities previously not considered (e.g. identifying new solutions or identifying existing solutions that are applied in contexts), but also provides a joint vocabulary that is currently missing (e.g. transformation vs. modulation, key visual domains that can be utilised). This is even more important given the interdisciplinary of the field and the different areas that contribute to the area of vision augmentations with each using different terminologies (e.g. Accessibility, Optometry, Optics, Augmented Human, Augmented Reality, Human-Computer Interaction, Psychology). As vision augmentations encompass techniques ranging from legally blind and low vision users to non-impaired users, this joint vocabulary and our design space could help to better align research agendas across different communities. Finally, our design space clearly indicates key visual cues that can be used and shows technologies and their abilities to utilise these cues. This knowledge does not always exist in the different research communities but is contributed as part of this work."

However, our work still has limitations. Foremost, we followed recent works that categorised human augmentations into three distinct areas summarised as (1) Augmented physical capabilities, (2) Augmented intellectual capacities, and (3) Augmented social skills [14, 67]. However, when looking at the human visual system especially the separation between (1) and (2) is more fluent. As an example, grapheme–colour synesthesia, is one of the more common forms of synesthesia (an interaction of normally distinct cognitive pathways caused by anomalous connectivity between brain areas) in which certain letters or shapes (intellectual capabilities) are perceived in different colours (physical or sensory capability) [2]. Grapheme–colour synesthesia is connected to improved memory and there are already the first approaches that considered a technology-induced grapheme–colour synesthesia using wearable display [53] which is just one example that crosses the separation between (1) and (2). Similarly, recent works discuss the idea of changing the visual appearance of the physical world to decrease social anxiety [56], which would be an example of a complex interaction between categories (1) and (3). That said, our design space would still be able to express this using an application-centred view of the space (cp. Figure 8).

Furthermore, we also point out that besides vision, other sensory augmentations are researched as part of works on human augmentations and accessibility [6, 43, 58] but are not the focus of this. While we believe that our design space could be extended by adding other cues apart from vision (e.g. touch, smell, etc.) this would also add additional challenges such as making the trade-off between a fine granularity of cues while still maintaining the overall overview and might result in showing the different opportunities that vision might offer which was the goal of this work.

Finally, we have not evaluated our developed design alternatives. We are aware, that some design space research also integrates evaluations of identified design alternatives, but many others do not and we think it would distract from the core message of this paper which was not to propose new solutions for specific problems but rather propose a design space that can be of help for identifying solutions for a wide range of problems.

AUTHOR CONTRIBUTIONS

Tobias Langlotz performed writing - original draft, conceptualisation, project administration and funding acquisition, Jonathan

Sutton performed writing - review & editing and conceptualisation, Holger Regenbrecht provided conceptualisation.

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