Behavioral techniques and AR technology to systematically control the brain activity outside of the laboratory

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Abstract

This study reviews the behavioral techniques that use the properties of visual stimuli to systematically control the activity of specific regions of an observer's brain and proposes an Augmented Reality (AR) head-mounted display (HMD) that are implemented these techniques as image filters. The camera of the AR HMD captures an image of a real scene out there and the image filter is applied to the captured image. Then, the filtered image is shown to an observer who is wearing the HMD in real-time or near real-time just as if the observer is seeing the scene directly. The AR HMD allows us to use the behavioral techniques to control the brain activity while the observer can move freely in a laboratory or within a field outside of the laboratory. Note also that the AR HMD can be assembled by combining a smartphone and a wearable stereoscope, making it widely available and highly affordable. So, researchers with limited budgets can conduct neuroscience studies and students can learn about these subjects in low-income countries or in underfunded institutions. It can contribute to the democratization of neuroscience and the global equity of scientific research. We developed two AR HMDs with some of the image filters and conducted an observational field study. Applications of the proposed AR HMD are discussed.

Keywords: AR, Augmented reality, VR, Virtual reality, XR, Extended reality, Field study, Brain stimulation

Introduction

There are two major approaches in Neuroscience to test the relationship between the brain activity and the human behavior. One is testing the correlation between the brain activity and the behavior. Several neurophysiological devices have been developed for estimating the brain's activity on the basis of physical signals that are associated with the brain's activity, such as the fMRI, EEG, MRI, NIRS, and single cell recording. The other approach is to control the brain's activity while observing changes of the behavior that was caused by the brain's activity. An advantage inherent in this latter approach is that a causal relationship between the brain activity and the behavior can be tested. Several devices that can directly stimulate the brain and systematically control the brain's activity have been developed. These devices can be used to observe an effect on the behavior caused by the brain's activity that is induced by the devices.

Non-invasive brain stimulation has advanced rapidly in the past two decades and now offers practical tools to modulate cortical excitability and oscillations in humans. Transcranial magnetic stimulation (TMS) can transiently perturb or bias activity in targeted cortical regions, with offline protocols producing effects that outlast stimulation and can be probed during subsequent tasks; transcranial electrical stimulation (tES, including tDCS and tACS) can shift membrane polarization and entrain ongoing rhythms in a frequency-specific manner (Pozdniakov et al., 2021; Feurra et al., 2019; Dayan et al., 2013; Polanía et al., 2018; Thut et al., 2017; Huang et al., 2005). Importantly for out-of-lab research, tES devices are lightweight and have been safely used in portable and home-based, remotely supervised settings, which enables coupling stimulation with naturalistic behavior in the field (Fertonani & Miniussi, 2017; Charvet et al., 2015; Woods et al., 2016). By contrast, TMS remains less amenable to fully mobile deployment because of coil positioning, acoustic output, and safety constraints, but it can still be applied in short offline blocks immediately before field tasks. Together, these approaches provide a causal complement to correlational measures and create a bridge between tightly controlled laboratory studies and ecologically valid testing outside the lab.

Beyond non-invasive methods, invasive brain–computer interfaces provide strong causal leverage in humans by directly recording and stimulating cortex, enabling volitional control and communication in clinical populations, though their use is restricted to surgical settings (Hochberg et al., 2012; Willett et al., 2021). In animals, optogenetics offers unmatched cell-type and timing specificity for activating or silencing defined circuits, setting mechanistic benchmarks for human neuromodulation studies (Deisseroth, 2011). Complementarily, classical lesion studies and modern lesion-network mapping in patients link focal damage to distributed network dysfunction, supplying convergent causal evidence at the systems level that can guide hypotheses tested with non-invasive stimulation such as in AR-enabled, naturalistic contexts (Fox, 2018).

There are also behavioral techniques that use properties of an image to systematically control the activity of specific brain regions when the image is shown to an observer. For example, the visual information of an isoluminant image is mainly processed in the ventral pathway while the dorsal pathway is mostly blind to the isoluminant information (see the section "Isoluminant stimuli and the dorsal pathway"). This allows us to test the role of these pathways in behavioral tasks based on visual information. Note that the isoluminant image can theoretically represent the same amount of visual information as the gray-scale image. So, the visual information and the activity of the dorsal pathway can be independently controlled. Such a behavioral technique is indirect but it is very affordable and they can be incorporated with the physical techniques to test interactions between multiple regions of the brain (Kveraga et al., 2007; Thomas et al., 2012). Also, some of the regions whose activity can be controlled by the behavioral techniques are difficult to be selectively stimulated by the current physical techniques because of the positions of the regions (e.g. superior colliculus, see the subsection "S-cone isolating stimuli and the superior colliculus").

Some of these behavioral techniques can be implemented as computer image filters. This implementation makes the techniques available in the field outside of the laboratory by using an Augmented Reality (AR) head-mounted display (HMD) whose camera captures an image of a real scene out there, and then the captured image is modified, and then the modified image is shown to an observer who is wearing the HMD in real-time or near real-time just as if the observer is seeing the scene directly. AR technology has been used study the behavior of a human observer in a real scene with controlling the visual information of the scene (e.g. Anstis, 1992; Bao & Engel, 2019; Grush et al., 2015; Juan & Calatrava, 2011; Krösl et al., 2020; Velázquez et al., 2015; Tsujita et al., 2023; Sawada et al., 2022; Farshchi et al., 2021). The image filter of the behavioral technique for controlling the specific brain region can be applied to the captured image so that the activity of the region is controlled while the visual system processes the image of the scene. This allows us to test the roles of the brain regions for run-of-the-mill tasks in our everyday life (see Kleinholdermann et al., 2009 for a study using one of the behavioral techniques controlling the brain activity in a virtual reality (VR) set-up).

Most of empirical studies in Neuroscience are conducted in laboratories in which any artifactual factor is minimized so that a specific factor can be tested, but note that it may be difficult to discuss whether or how much the results of such a study can be generalized in the field outside of the laboratory (see Hengartner, 2018). A study can be conducted in the field but there are a lot of limitations on field studies. These limitations can be addressed by the development of technology (e.g. Boto et al., 2018; Maeda et al., 2005; Aoyama et al., 2015). An AR device with image filters that can systematically control the activity of specific brain regions can be also used to extend the limits of the field study.

Another strength of an AR HMD is its affordability. The price of an HMD is much lower than almost any research set-up used in Neuroscience. The HMD can also be assembled by combining a smartphone and a wearable stereoscope (see the section “Observational field study”) and the price of this set-up is even lower. A study using the HMD can be conducted in a small space while many studies in Neuroscience require large laboratory spaces. These properties of the AR HMD allow researchers with limited budgets and space to conduct neuroscience studies and help students learn about these subjects in low-income countries or in underfunded institutions. It can contribute to the democratization of neuroscience and the global equity of scientific research (see Jurcik et al., 2024; Papoutsaki et al., 2016; Valliappan et al., 2020; Bhamla et al., 2017; Wei et al., 2013; Cybulski et al., 2014; Rohof et al., 2020 for studies of research tools with similar motivations).

This study will review the behavioral techniques that can systematically control the activity of the brain and will discuss how these techniques can be implemented as image filters. An AR app with some of these image filters was developed and AR HMDs that were installed with the app were used in an observational field study. Four of the authors wore the AR HMD and navigated in real environments.

Behavioral techniques to systematically control brain activity

In this section, behavioral techniques that can control the activity of the brain systematically and that can be implemented as image filters of an AR app without any additional sensors (e.g. eye tracker) will be reviewed.

Isoluminant stimuli and the dorsal pathway

The ventral and dorsal pathways of the cortex are often referred to as the “what” and “where” pathways. The ventral “what” pathway processes the colors, shapes, and sizes of individual objects while and that the dorsal “where” pathway processes the positions and motions, as well as the interaction of an observer with the objects (see Goodale & Milner, 1992; Mishkin, Ungerleider & Macko 1983; Kravitz, Saleem, Baker & Mishkin, 2011; McIntosh & Schenk, 2009 for reviews and discussions). Note that there are some interactions between these pathways (e.g. Schenk, 2012; de Haan & Cowey, 2011; Cardoso-Leite & Gorea, 2010; Schenk & McIntosh, 2010; Doniger, Foxe, Murray, Higgins, & Javitt, 2002; Milner 2017; Borst, Thompson, & Kosslyn, 2011; Ray et al., 2020) but the functions of the pathways are well separated from one another. This difference between the functions of the pathways can be used to selectively study their roles in visual perception.

A retinal image can be decomposed into two 2D distributions of achromatic luminance and isoluminant- (equiluminant-) chromatic information. The luminance information is processed in both ventral and dorsal pathways while the isoluminant chromatic information is processed primarily in the ventral pathway. If the retinal image itself is isoluminant, the image can only stimulate the ventral pathway while the dorsal pathway is only minimally stimulated by this image. This technique using the isoluminant image has been used in many psychophysical studies to examine the roles of the ventral and dorsal pathways and their results are usually consistent with the results of neurophysiological studies that test the ventral and dorsal pathways.

This selectivity of the dorsal pathway is attributed to its input. The input of the dorsal pathway is mainly from the magnocellular pathway, which processes the achromatic luminance information in the retinal image, but also from the parvocellular and koniocellular pathways, which process the chromatic information in the retinal image (Goodale & Millner, 1992). The ventral pathway also receives its input from these three cellular pathways while its main source of input is the parvocellular pathway. Also, the magnocellular cells are not completely blind to isoluminant chromatic change (Schiller & Colby 1983; Logothetis et al. 1990). So, the selective stimulation of the ventral pathway by using isoluminant image is a matter of degree (see Goodale & Millner, 1992; Skottun, 2013).

An isoluminant image is often generated with the red-green isoluminant scale that is based on the red and green channels of an RGB display (Figure 1). This red-green isoluminant scale is represented as a 1D sub-space in a 2D isoluminant color space, which is also a sub-space in a 3D color space. This one-dimensionality makes it easier to control the RGB values of the isoluminant image. Note that the grayscale values of the grayscale image are also represented in a 1D space. This consistency of dimensionality is convenient when the perception of the red-green isoluminant image is compared with the perception of a grayscale image as a control. On the other hand, the number of levels in the red-green scale tends to be smaller than in the grayscale. This discrepancy can be addressed by making the level number in the grayscale. The control image can be generated by removing the red or green channels of the isoluminant image so that the image is represented by the red-black or the green-black scales (Figure 1D, E). The red-black and the green-black scale are also represented as 1D sub-spaces in the 3D color space and they are correlated with the 1D sub-space of the grayscale. The number of isoluminant levels can be larger by using the red-green scale than by using the blue-red or the blue-green scales because the range of luminance within each of the red and green channels is larger than the range of luminance within the blue channel.

It is necessary to calibrate the RGB channels of a display if you want to generate an isoluminant image. The luminance of each pixel is calculated as the sum of the luminance of the RGB channels. The luminance of each channel can be represented as a monotonically-increasing function of the value of the channel. The function is estimated by measuring the luminance for several values of the channel with a photometer and by fitting a gamma curve to the measured luminance (see also Xiao et al., 2011; To et al., 2013 for discussions about non-gamma curves for LCD displays). Once this is done for all channels, the RGB values of the pixel are controlled so that the luminance is constant, or approximately constant, across the image. Note that the luminance is a psychophysical value and the isoluminant scale is slightly different across observers and behavioral measurements are required to more accurately calibrate the display for each observer. Several simple behavioral methods have been proposed for the display calibration when a 1D isoluminance scale is used to generate the isoluminant image (Anstis & Cavanagh, 1983; Chaudhuri & Albright, 1990; Cavanagh et al., 1984; Liu et al., 2024; To et al., 2013; Wagner & Boynton, 1972; see Murray et al., 2022; Zaman et al., 2023 for the calibration of HMDs). Once the display is calibrated, the technique can be implemented as an image filter. The image filter was included in an AR app that was developed in this study.

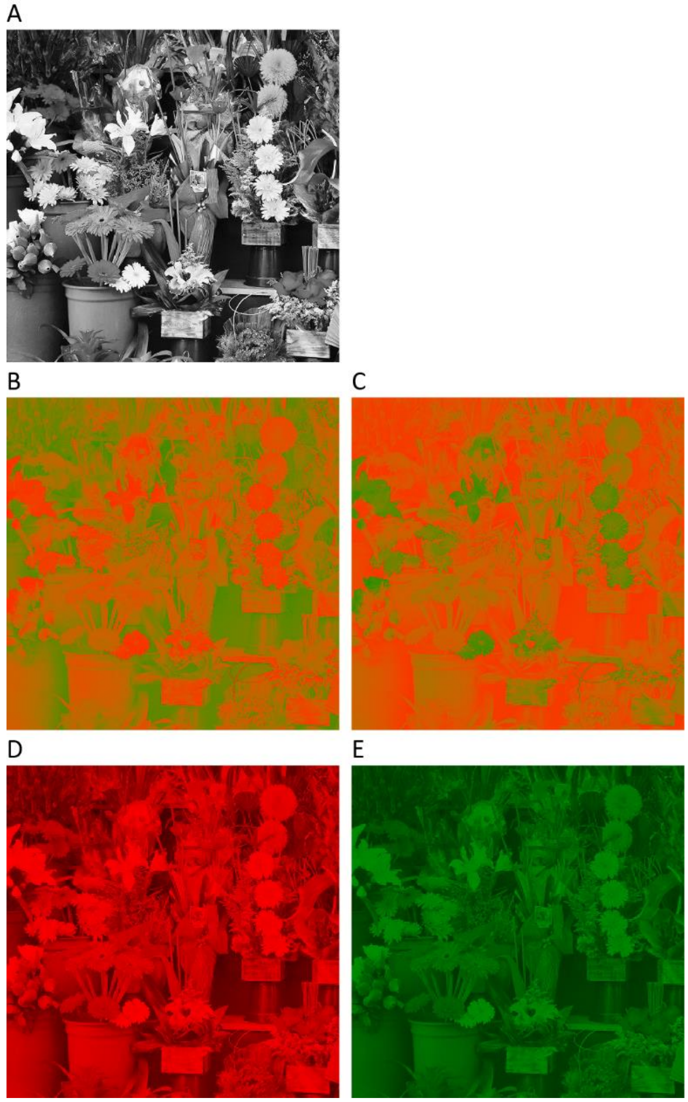

Figure 1. (A) A grayscale image of a real scene and (B, C) its red-green isoluminant images. These isoluminant images were generated on the basis of the calibration of an AR HMD that was used in the observational field study (see the section "Observational field study"). The relationships between the red-green scale and the grayscale in these two isoluminant images are opposite from one another. (D, E). Red-black scale and green-black scale images that were generated by removing the green channel from the isoluminant image (B) and the red channel from the isoluminant image (C).

Spatial frequencies and the magnocellular and parvocellular pathways

Neurons of the magnocellular pathway in the lateral geniculate nucleus (LGN) are more sensitive to the low spatial and high temporal frequencies of a retinal image, whereas neurons of the parvocellular pathway in LGN are more sensitive to the high spatial and low temporal frequencies (Derrington & Lennie, 1984; Livingstone & Hubel, 1987, 1988; Denison et al., 2014; Wen et al., 2021, see Skottun, 2015 for a review). This difference in spatial frequency tuning between the pathways may be used to stimulate one pathway more than the other pathway (see Skottun, 2015 for a discussion).

The low and high spatial frequency components can be extracted from a grayscale image of a real scene from a camera by applying low-pass and high-pass filters in the 2D Fourier domain of the image (Figure 2). To apply these filters, the 2D Fourier transform of the image is first computed. To generate the low-pass filter, the magnitudes of high spatial frequency components are set to zero in the Fourier domain and the inverse Fourier transform is computed. To generate the high-pass filtered image, the magnitudes of low spatial frequency components are set to zero in the Fourier domain and the inverse Fourier transform is computed. The transformed image should be shown on a calibrated display.

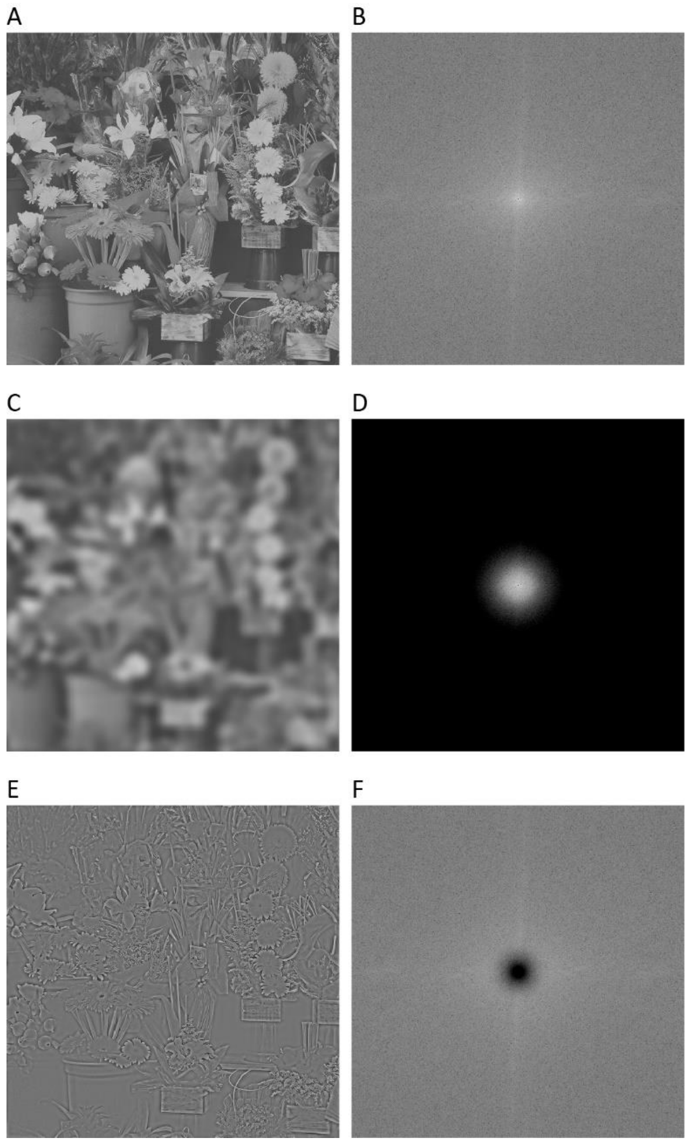

Figure 2. (A) A grayscale image of a real scene, its (C) low-pass and (E) high-pass filtered images, and (B, D, F) their 2D Fourier transforms (amplitude spectrums). The grayscale image (A) was generated by reducing the contrast of the image in Figure 1A so that the grayscale values of the filtered images (C, E) do not overflow (>255) or underflow (<0). The low-pass and high-pass filters are 2D Butterworth filters (Butterworth, 1930).

Note that it is not clear how much the processing of a retinal image in the pathways can be suppressed by the low-pass and high-pass image filters alone because the difference in spatial frequency turning between the magnocellular and parvocellular pathway is small (Skottun, 2015). The distinction between the pathways may be enhanced by introducing dynamic changes to the image and controlling its temporal frequency (Gao et al., 2025; Zhou et al., 2025). The activity of the magnocellular pathway can be suppressed by replacing the grayscale of the image with the isoluminant chromatic scale (see the subsection "Isoluminant stimuli and the dorsal pathway").

These image filters can be used in an AR app (e.g. Gao et al., 2025; Zhou et al., 2025) but the image filters use the Fourier and inverse Fourier transforms, which are computationally expensive. It can be difficult to apply the filters to an image of a real scene from a camera in real time or near-real time using a smartphone. The AR app needs a good processor to run on.

S-cone isolating stimuli and the superior colliculus

The superior colliculus is a part of the mammalian midbrain and its activity can be controlled by calibrating the channels of an RGB display. The superior colliculus is involved in visual detection, spatial attention, and eye movements (Krauzlis et al., 2013; Kato et al., 2011; Bell et al., 2006; Dorris et al., 1997; Kustov et al., 1996; Spering & Carrasco, 2015; Mizzi & Michael, 2014; Anderson & Carpenter, 2008), as well as body movements (Gandhi & Katnani, 2011; Prabhu & Himmelbach, 2023). The superior colliculus is especially sensitive to negatively-affective visual information (Almeida et al., 2015; Wang et al., 2020; Ajina, Pollard, & Bridge, 2020, see also Carretié et al., 2021; Méndez et al., 2022). It is also suggested that the superior colliculus plays a role in integration of visual information from the left and right halves of the visual field (Savazzi & Marzi, 2004; Leh et al., 2010; van Koningsbruggen et al., 2017) and in integration of multisensory spatial information (Leo et al., 2008; Maravita et al., 2008). These results suggest that the superior colliculus is important for preconscious rapid detection and reaction to potential threats.

The superior colliculus receives visual information from the cortex and also from the retinotectal pathway that bypasses the lateral geniculate nucleus (LGN) and the cortex (see May, 2006; Liu et al., 2022 for reviews). Neurophysiological studies in monkeys suggest that the information from the cortex to the superior colliculus depends primarily upon the magnocellular pathway (Schiller et al., 1979). Neither the magnocellular nor retinotectal pathways process chromatic information (Schiller & Malpeli 1977; Schiller et al. 1979; Marrocco & Li 1977) and they receive no input from short-wavelength sensitive cones (S-cones; de Monasterio 1978; Tailby et al., 2012). Both the retinotectal and magnocellular pathways receive input from medium- and long-wavelength sensitive cones (M-cones, L-cones) but they cannot process the chromatic information because these pathways do not process the input from the M-cones and the L-cones in an opponent manner. Note that the retinotectal and magnocellular pathways are based on different neurophysiological mechanisms in the retina and these pathways can have different spectrum sensitivity functions.

It is possible to design visual stimuli based on these properties of the superior colliculus so that the superior colliculus is minimally stimulated. The chromatic information contained in the stimulus is represented in the temporal variation and spatial distribution of S-cone responses while M-cone and L-cone responses are kept constant (Hall & Colby, 2013; Leh et al., 2009; Smithson, 2014). The S-cone isolating stimulus is processed in the LGN and in the visual cortex via the koniocellular pathway (Hendry et al., 2000; Xu et al., 2001) but the superior colliculus is minimally stimulated by this stimulus. The S-cone isolating stimulus is also isoluminant because the luminance is based on the M-cone and L-cone responses and because their responses are kept constant. Note that the chromatic information can also be represented by the balance between the M-cone and L-cone responses while keeping the isoluminance of the stimulus (see the subsection "The ventral pathway and the dorsal pathway"). But, keeping the M-cone and L-cone responses is usually preferred to minimize the stimulation of the superior colliculus because the spectrum sensitivity functions of the retinotectal and magnocellular pathways can be different from one another. So, the M-cone and L-cone responses can change so that one of these two pathways cannot detect the change (like a metamer) but the other pathway can still detect it. The S-cone isolating stimulus, which only represents chromatic information by the S-cone responses should be used to minimally stimulate the superior colliculus is minimized.

Note well that the superior colliculus is not totally blind to the chromatic information in a visual stimulus. It has been shown that neurons in the superior colliculus respond to the chromatic information but with a delay when compared to the response to the achromatic information (White et al., 2009; Zhang et al., 2025, see also Ottes et al., 1987; Herman & Krauzlis, 2017). Hall and Colby (2014, 2016) also showed that neurons in the macaque superior colliculus can respond to input from the S-cones as fast as they can respond to the achromatic information if the S-cones are sufficiently stimulated (see also Coubard, 2017 for a commentary on this study). These results are also consistent with human neuroimaging studies. The human superior colliculus is not blind to the chromatic information in a stimulus (Chang et al., 2016) but its activity can still be reduced if there is no achromatic information in the stimulus (Leh et al., 2009). So, the S-cone isolating stimulus can reduce or delay stimulation of the superior colliculus, but it is a matter of degree. To further minimize any effect of the S-cone input, luminance noise can be added to the stimulus to mask the input (Birch et al., 1992).

It is possible to make an image filter for an AR app that can generate an S-cone isolating stimulus from a grayscale image of a real scene out there. The filter replaces the luminance gradient of the image with the S-cone response gradient that subtends between blue and yellow. Luminance noise can be added to mask the S-cone input so that any effect of the S-cone input on the superior colliculus is minimized. With this image filter, it is possible to test human behavior while minimizing the visual input to the superior colliculus. Note that S-cone isolating stimuli that were used in the past studies to minimize the stimulation of the superior colliculus were very simple. It can be interesting to test how the superior colliculus responds to S-cone isolating stimuli with complex patterns.

A spectroradiometer is necessary to calibrate the RGB channels of a display for S-cone isolation. Stimulation of the S-cone should be controlled while the stimulation of the M-cone and L-cone should be kept individually constant for the S-cone isolation. Note that the spectrum energy distributions of the RGB channels are usually so wide that they individually stimulate multiple types of cones. For example, stimulation of the S-cone is mostly controlled by the blue channel but the blue channel usually also stimulates the M-cone and the L-cone to some extent. Each channel stimulates the three types of cones while maintaining the proportion of their stimulation and the stimulation of each type of cone is a sum of the stimulations from the RGB channels. Then, the RGB channels can be represented as three vectors in the LMS color space. This allows us to derive how the intensity of the RGB channels should be controlled to change the S-cone stimulation while the M-cone and L-cone are constantly stimulated. From the derived intensity of the RGB channels, the RGB values (usually eight bit for each channel) can be computed. The relationship between the intensity of the RGB channels and the RGB values is not usually linear. Note that the spectroradiometer can be a limitation of this technique because spectroradiometer is often expensive.

The range of luminance within the blue channel is smaller than the range of luminance within each of the red and green channels. This property of the blue channel limits the number of levels in the scale of the S-cone isolation stimulus. This problem could be addressed by a physical color filter that reduces the intensity of the red and green channels, but not the blue channel as much. The filter would be installed between the screen of a HMD and an observer's eyes to balance the intensity of the channels.

First-order and second-order noise stimuli and the primary visual cortex (V1)

Many neurons in the primary visual cortex (V1) are sensitive to a change in luminance amplitude and they systematically respond to spatial or temporal patterns of the luminance amplitude (Carandini et al. 2005; Hubel & Wiesel, 1977; Sawada & Petrov, 2017). This type of visual information is referred to as the first-order information while the second-order information is represented by spatial or temporal patterns of a larger-scale image feature that is represented by a change in luminance amplitude, such as luminance contrast, orientation, scale, and motion (Figure 3). There are several different types of the second-order visual information but the most common type is that a spatial pattern is represented by a change of contrast of a random noise pattern or of a regular pattern. It has been considered that the neurons in V1 could not detect the second-order information and that the second-order information could be used to control spatial or temporal patterns without systematically stimulating the V1 neurons. But, neurophysiological studies in monkeys showed that some of the V1 neurons are also sensitive to the second-order information while the proportion of cells sensitive to the second-order information depends on the studies (Lamme et al., 1993; Marcar et al., 2000; O'keefe & Movshon, 1998; von der Heydt, 1989; Zhou & Baker, 1993; Baker & Mareschal, 2001; Ju et al., 2022; An et al., 2014). This diversity can be partially attributed to the types of second-order information, but it is still observed across studies using the same type of second-order information (luminance contrast, Zhou & Baker, 1993; Baker & Mareschal, 2001; Ju et al., 2022; O'keefe & Movshon, 1998; An et al., 2014). The neurons are tuned to the spatial properties of second-order patterns that are close to the spatial properties of first-order patterns to which they are also tuned but this does not mean that V1 and the visual system equally processes the first-order and second-order information.

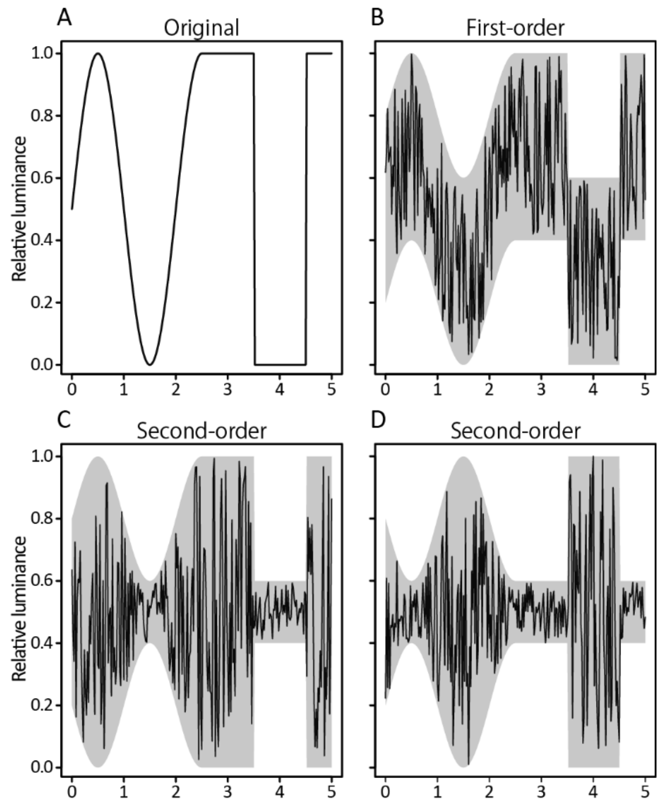

Figure 3. (A) A 1D pattern of signal and (B) first-order and (C, D) second-order (C, D) noise patterns that represent the signal (A). The distribution of the noise is uniform (white noise) within a range of gray areas in (B-D). (B) The center of the noise range is proportional to the signal. (C) The width of the noise range is proportional to the signal. (D) The width of the noise range is negatively proportional to the signal.

V1 neurons are often modeled as a combination of (i) a process that characterizes 2D patterns to which the neurons are tuned to and (ii) a divisive normalization that represents suppression (or facilitation) from LGN, from intracortical connections within V1, and from top-down feedback (see Carandini et al. 2005; Carandini & Heeger, 2012; Heeger, 1992; Sawada & Petrov, 2017 for reviews). The first process is formulated as a 2D linear filter to a retinal image that is followed by a nonlinear transformation. This process characterizes sensitivity of the V1 neurons to the first-order visual information while the process cannot detect the second-order information. Physiological studies suggest that the sensitivity of the V1 neurons to the second-order visual information can be attributed to the process that is formulated as the divisive normalization (Tanaka & Ohzawa, 2009; Hallum & Movshon, 2014, see also Ju et al., 2022). So, the difference in responses to first- and second-order visual stimuli can be attributed to two components of V1 neurons rather than to V1 and subsequent visual cortices.

Psychophysical studies suggest that the human visual system is sensitive to the second-order information (Baker & Mareschal, 2001; Chubb & Sperling, 1988; Chubb et al., 2001; Schofield et al., 2010) but note that the first- and second-order information are processed in separate mechanisms of the visual system (see also Cavanagh & Mather, 1989). Nishida et al. (1997) showed that the effect of motion adaptation only weakly transfers between the first- and second-order motion information (see also Nishida, 2011 for a review). The detection of the first- and second-order visual information is facilitated by additional visual information of the same type but not by additional information of a different type (Schofield & Georgeson, 1999). These results show that the first- and second-order information are processed differently in the visual system.

A grayscale image can be transformed to the first- and second-order visual stimuli (Figure 4). The stimuli are generated from a dynamic pattern of a 2D white noise by controlling the range of the white noise to represent the information in the grayscale image. The luminance of the noise pattern needs to be calibrated. For the first-order stimulus, the center of the noise range at each position in the pattern is proportional to the grayscale value at the same position in the image while the width of the range is constant across the pattern. The information in the grayscale image is represented by the 2D distribution of local mean luminance in the pattern. For the second-order visual stimulus, the width of the noise range is proportional to the grayscale value either positively or negatively while the center of the range is constant. The information in the grayscale image is represented by the 2D distribution of the local variance of luminance in the pattern. These transformations of the grayscale image can be implemented as image filters for an AR app.

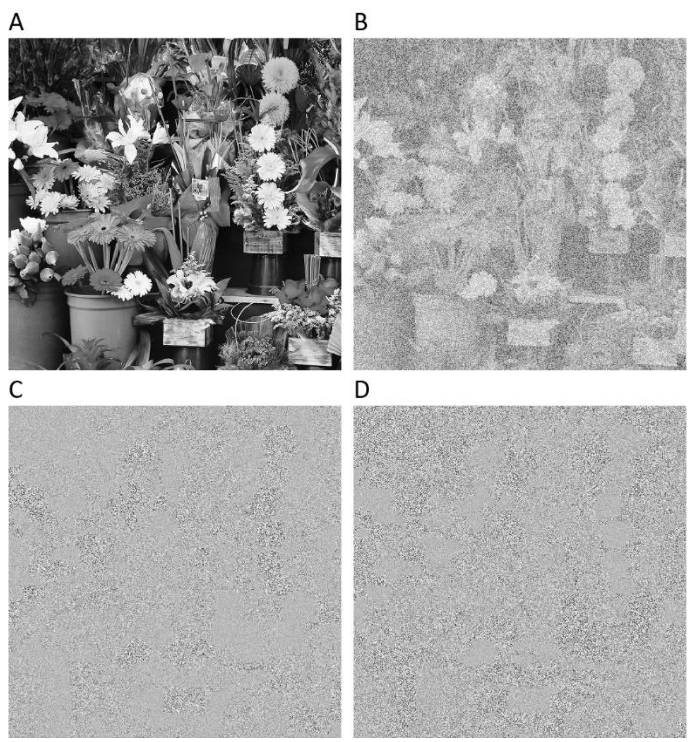

Figure 4. (A) A grayscale image of a real scene and (B) first-order and (C, D) second-order noise patterns that were generated from the grayscale image (A). These noise patterns were generated on the basis of the calibration of an AR HMD that was used in the observational field study (see the section "Observational field study"). (B) The noise in the pattern is white noise and the center of its range is proportional to the grayscale value. (C, D) The width of the white noise range is (C) proportional and (D) negatively proportional to the grayscale value.

The power-law and the efficient coding in V1

Photo images of real scenes almost always have a common property in their spatial Fourier spectrums. The logarithm of their spatial-frequency spectrum is correlated linearly to the logarithm of the spatial frequency with a coefficient of around −1.2 (Figure 5, Field, 1987; Tolhurst, 1992). This property is referred to as a power law.

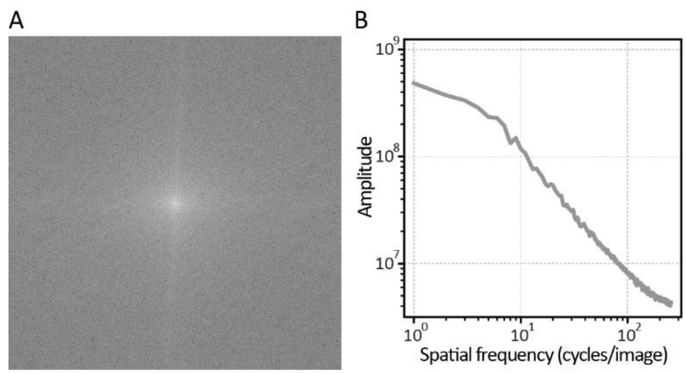

Figure 5. (A) The 2D Fourier transform (amplitude spectrum) of the image in Figures 1A and 4A and (B) the 1D amplitude spectrum that was generated by averaging the 2D distribution (A) across all orientations. (A) In the 2D pattern of the Fourier transform, a Fourier component is represented as a point in the pattern. The pattern is organized and a polar coordinate system is set with its origin at the center of the pattern so that the orientation and the spatial frequency of the component are represented by the radius and orientation of the position of the point representing the component in the pattern. The grayscale level at the point represents the log amplitude of the component.

The power law with the coefficient of −1.2 is important for the visual system. Neurophysiological studies in monkeys and mice suggest that V1 can process a retinal image more "efficiently" when the image satisfies the power law than when the image violates the law (Simoncelli & Olshausen, 2001; Baudot et al., 2013; Froudarakis et al., 2014; Rikhye & Sur, 2015; Yoshida & Ohki, 2020). A smaller number of neurons in V1 respond to the image satisfying the power law, spike rates of the individual neurons are smaller, and the timing of the spikes is more consistent across trials in which the same image is shown (Baudot et al., 2013; Rikhye & Sur, 2015; Yoshida & Ohki, 2020). Namely, the visual system can process the retinal image satisfying the power law with a small number of signals and a retinal image frequently satisfy the power law in a real environment. This allows the visual system to process more information with its finite resources (Attneave, 1954; Barlow, 1961; Simoncelli & Olshausen, 2001, see also Shannon, 1949). This efficient coding may not be intuitive because neuroimaging studies often interpret that a region of the brain is tuned to a property of stimuli when the region is activated more to stimuli with the property than to stimuli without the property.

Consider a grayscale image is given. To control whether the image violates (or satisfies) the power law, the Fourier transform of the image is computed and the magnitude of Fourier components at each frequency is scaled so that the power law is violated (or satisfied). Once this is done, the inverse Fourier transform is computed to generate a transformed image that violates (or satisfies) the power law (Figure 6). The transformed image should be shown on a calibrated display. This transformation can be implemented as an image filter for an AR app but it is more computationally expensive than the filters previously discussed in this study because the Fourier and inverse Fourier transforms are involved. It can be difficult to apply the transformation to an image of a real scene from a camera in real time or near-real time unless the AR app is running on a good processor.

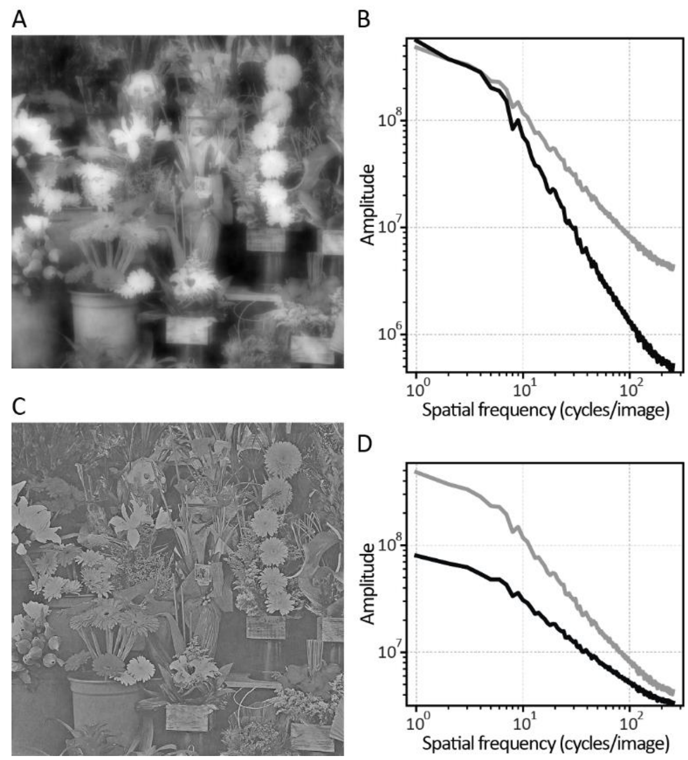

Figure 6. (A, C) Images that were generated by modifying the 1D amplitude spectrum (Figure 5B) of the image in Figure 1A so that the modified spectrums have (B) a steeper slope and (D) a shallower slope. The amplitude spectrum was raised to the power of (B) 1.5 for the image (A) and to the power of (D) 1/1.5 for the image (C). The vertical positions of the spectra were adjusted so that the resulting images (A, C) have grayscale values between 0 and 255.

It is possible to transform an image of a real scene so that the transformed image violates or satisfies the power law by superimposing a noise pattern (Rikhye & Sur, 2015). Note that the original image of the real scene is expected to satisfy the power law. When the noise pattern violates the power law (e.g. white noise, Figure 7A), the image with the noise pattern also violates the law and the degree of the violation depends on the intensity of the noise pattern. When the noise pattern satisfies the power law (pink noise with its exponent is around 1.2, Figure 7B), the image with the noise pattern also satisfies the law and it does not depend on the intensity of the noise pattern. This transformation can be also implemented as an image filter for an AR app and its computational cost is low if the noise patterns are pre-rendered.

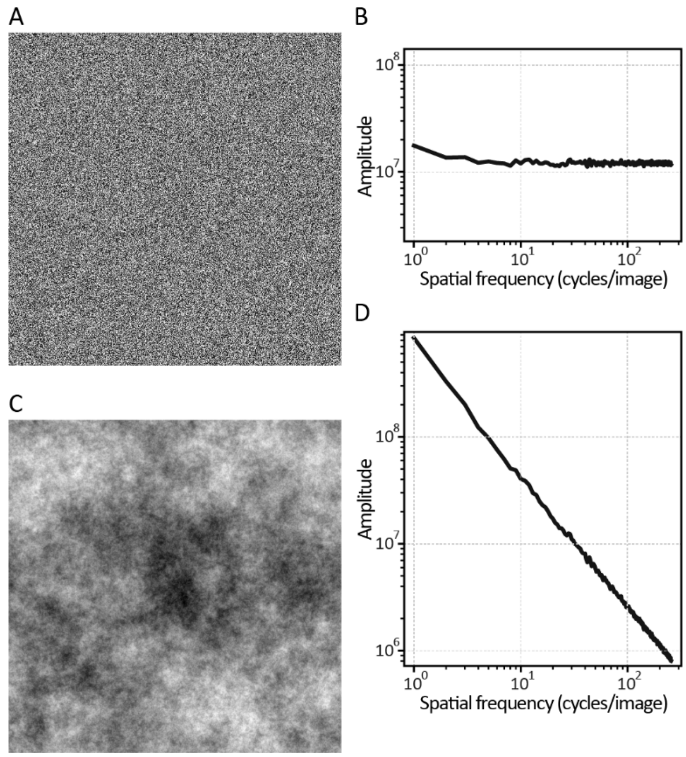

Figure 7. (A) A white noise image, (B) its 1D amplitude spectrum, (C) a pink noise image, and (D) its 1D amplitude spectrum. The amplitude spectrum (B) of the white noise image (A) is close to be flat. The pink noise image (C) was generated from the white noise image (A) so that the 1D amplitude spectrum (D) has a slope of approximately −1.2. Each amplitude of the spectrum of the white noise image was divided by a factor of its spatial frequency raised to the power of 1.2 to generate the spectrum of the pink noise image. The vertical position of the resulting spectrum (D) was adjusted so that the resulting image (C) has grayscale values between 0 and 255.

Other behavioral methods

Four behavioral techniques that can control the activity of the brain systematically and that can be implemented as image filters of an AR app were reviewed in this section. These behavioral techniques use the camera of the AR device but they do not use any additional sensors.

If the HMD is installed with an eye tracker and an image on the HMD's screen can be rendered in real time depending on an observer's eye movement, the retinal images of the observer could be fully controlled and other behavioral techniques could also be implemented for the AR app. Note that the projection from the retina to V1 is systematically characterized by a 2D-to-2D log-polar transformation (Tootell et al., 1982). Systematic relationships with the retinae are also observed in V2, V3, and V4 (see Wandell & Winawer, 2011; Winawer & Witthoft, 2015 for reviews). Namely, a specific region of the early visual cortex can be stimulated by stimulating its corresponding region of the retina. For example, the left and right cerebral hemispheres can be stimulated separately to some extent by controlling visual stimuli in the right and left visual fields individually (divided visual field paradigm, Bourne, 2006; Ivry & Robertson, 1998). The initial processing of visual information from the left and right visual fields takes place in the left and right hemispheres, respectively. This technique needs the oculomotor information from an observer because the borderlines between the left and right visual fields in the screens of the AR device change depending on the orientations of the left and right eyes of the observer, including their cyclotorsions, relative to the observer's head.

Another example is the distinction between the central and peripheral regions of the retinae. These two regions of the retinae have different physiological properties, they are processed differently in the brain, and these differences are also reflected in the perception (Rozhkova et al., 2019; Belokopytov et al., 2022; Freeman & Simoncelli, 2011; Hadjikhani & Tootell, 2000; Ziemba & Simoncelli, 2021, see also Barton & Brewer, 2015; Wallis et al., 2019). It has also been shown that the lower and upper visual fields are processed differently within the visual system (Previc, 1990; Kravitz et al., 2013). Note that there are HMDs with eye trackers but it is still difficult to render images on their screens in real time depending on the eye movement with sufficiently short delay and with sufficient precision for studying the visual system.

Observational field study

In this section, an AR app with some of the image filters of the behavioral techniques was developed and it was installed to AR HMDs. The AR HMDs were tested in an observational field study to show an example of how the device can be used. The field study was conducted in Yerevan, Armenia and Moscow, Russia.

Method

Some of the behavioral techniques that can systematically control the activity of the brain were implemented as image filters of an AR app. The app was installed in two AR HMDs and they were used in an observational field study (Figure 8). The image filters transformed a grayscale image into (i) a red-green isoluminant image (see the subsection “Isoluminant stimuli and the dorsal pathway”) and (ii) first- and (iii) second-order noise images (see the subsection “The first-order and second-order noise stimuli and the primary visual cortex (V1)”). The image filters (ii) and (iii) were tested only in Yerevan. The AR HMDs could show the grayscale image and filtered images that were generated by applying these image filters. There were two types of (i) the isoluminant filters that transformed the grayscale into a red-green isoluminant scale and into a green-red isoluminant scale. As controls, image filters that generated monochrome-red and monochrome-green images were also used. These monochrome images were generated by removing the green channel from the red-green isoluminant image and the red channel from the green-red isoluminant image. There were two types of (ii) the second-order filter where the larger variance of the noise image represented the larger and smaller grayscale levels.

Figure 8. One of the AR head-mounted displays (AR HMD) that were used in this observational field study.

The AR HMD used in the field study was composed primarily of a smartphone (Redmi 9A in Yerevan and Lenovo Phab 2 Pro in Moscow), a small wide-angle lens, and a wearable stereoscope (Figure 8). A camera of the smartphone located on the back of the screen was used to capture an image of a real scene in front of an observer wearing the AR HMD. The wide-angle lens was attached to the camera to widen the camera’s field of view. The image filter was applied to the captured image. Note that the screen of the smartphone was divided into two halves that were seen individually by the two eyes of an observer through the lenses of the stereoscope. These halves of the screen show two segments of the filtered image. The whole process of capturing the image of the real scene, applying the image filter to the captured image, and displaying the segments of the filtered image on the screen was carried out using the smartphone alone.

Although no stimulation was applied in the field study, the set-up is compatible with pre-registered protocols in which brief offline TMS or short tES blocks precede AR navigation. This enables clean pre/post comparisons while keeping the wearable load minimal and within routine safety guidance (Huang et al., 2005; Woods et al., 2016).

The positions of the segments in the filtered image were adjusted so that the observer could easily fuse their retinal mages. Binocular depth cues (binocular disparity and vergence) from the retinal images of the image segments represented a frontoparallel plane with this set up but this depth information seemed to little deteriorate the immersive experience with the AR HMD (Wijntjes et al., 2016).

The luminance of one of the AR HMDs was calibrated using the behavioral method ("Isoluminant stimuli and the dorsal pathway"). The gamma curves of the red and green channels were individually estimated and the ratio of luminance between the channels was estimated using a minimum motion technique (Anstis & Cavanaugh, 1983). The calibration of this AR HMD was conducted by one of the authors (MD) and she used this AR HMD in a session of the observational field study. The luminance calibration of the other AR HMD was done using a photometer. This AR HMD was used by three of the authors (TS, AZ, and AT).

Five of the authors (TS, AZ, and AT in Yerevan and MD and VS in Moscow) conducted the observational field study in total. All of them had normal-trichromatic color vision. They wore the AR HMDs and dynamically navigated in forests, parks, urban areas, and inside buildings. The observers wore the AR HMD only intermittently while they navigated to make it possible to change the image filters and for safety reasons.

Results

Navigating in all types of real scenes was easy with the full-color image and grayscale image as well as with the monochrome-red and -green images while the navigation with the isoluminant images was difficult in general. Note that the isoluminant image was composed of the red and green channels while the monochrome image was generated by removing one of these channels. So, the amount of visual information in the monochrome image was less than the amount of visual information in the isoluminant image but the navigation became difficult with the other channel of the isoluminant image. This suggests that the amount of visual information in the common channel of the isoluminant and monochrome images was sufficient for the navigation but the human visual system became less sensitive to the information of the common channel when the other channel of the isoluminant image was superimposed to cancel the luminance information of each other.

The edges in an isoluminant image were not clearly visible unless there was a high color contrast between the two sides of the edges. Such edges were useful for navigating along the sidewalks and the hallways when they represented the curbs of the side-walk and the edges between the floor and walls of the hallways. The navigation with an isoluminant image was difficult without these clearly-visible edges. The clearly-visible edges were also helpful for recognizing man-made objects in urban environments.

The isoluminant gradient was not effective for perceiving depth. Detecting the bumps, dents, steps, and the slopes of the ground were difficult with an isoluminant image but were easy with grayscale or monochrome images. This observation is consistent with the results of psychophysical experiments testing depth perception from isoluminant shading (Kingdom, 2003; Sunaga et al., 1995; see also Cavanagh & Leclerc, 1989; Kunsberg et al., 2018 for relevant studies).

Depth perception from textures in an isoluminant image depended on the type of texture. The orientation of a regular grid pattern, such as a paved ground, could be perceived even from the isoluminant image. It was difficult to perceive any depth from other types of textures, such as a grass field and a dirt ground.

The observational field study using an isoluminant image suggested that texture gradients work differently as depth cues depending on the type of texture. Note that results of psychophysical experiments testing depth perception from isoluminant texture are not consistent across studies (e.g. Livingstone & Hubel, 1987; Troscianko et al., 1991; Cavanagh, 1987). This inconsistency could be attributed to different types of texture used in these experiments.

The navigation with the first-order image in all types of real scenes and the recognition of objects were mostly possible but it was difficult to see details of their visual information because of the random dynamic noise added to the filtered image. The navigation and the recognition were almost impossible with the second-order image. Regions of low luminance contrast in the second-order image might be perceived as semi-transparent figures over a noisy background with high luminance contrast but this figure-ground segmentation of the second-order image was inconsistent with the veridical figure-ground segmentation of the grayscale image from which the second-order image was generated.

The second-order image could be more helpful for the navigation and for the recognition if the image was generated not to represent the luminance distribution of the grayscale image but to represent the figure-ground segmentation of the image. Note that good processors are necessary to compute the figure-ground segmentation of an image of a real scene from a camera in real time or near-real time. The processors of the AR HMDs that were used in this study were too slow for figure-ground segmentation.

General discussion

This study reviewed behavioral techniques that can control brain activity systematically and discussed their implementation as image filters for an AR HMD. This AR HMD allows us to use the behavioral techniques while an observer can move freely in a laboratory or within a field outside of the laboratory. We developed the AR HMDs with some of the image filters and conducted an observational field study in which four of the authors navigated in real scenes while wearing the AR HMDs.

The AR HMD that was used in the observational field study was composed of a smartphone, a small wide-angle lens, and a wearable stereoscope. This set-up is widely available and highly affordable, but the weakness of this set-up is its a little sluggish temporal property: the refresh rate (~ 10 Hz) of the smartphone's display and the delay (~ 300 msec) between changes in the real scene and their reflection on the display. This temporal property of the AR HMD was acceptable for the observational field study in which the observers slowly navigated in real scenes. For any faster actions, the AR HMD should be set-up with a sufficiently high refresh rate and short delay.

The study discussed AR but the image filters used for the behavioral techniques controlling brain activity can be also used in a Virtual Reality (VR). In a VR, a 2D image that is shown on the screen of an HMD is generated by rendering a virtual scene. The image filters can be applied to the image on the screen after an image is rendered and before it is displayed on the screen ("post-processing" in computer graphics). Note that VR requires data of the virtual 3D scene and the rendering process from the 3D scene to its 2D image while AR uses an image of a real scene captured by a camera. This allows us to deform the 3D scene and to distort geometry in the rendering process in VR to study the visual and cognitive systems (e.g. Chan et al., 2023; Szirmay-Kalos & Magdics, 2022; Hart et al., 2017; Pisani et al., 2019). AR and VR can be used depending on the purpose and control of the experiment.

A pragmatic next step is a hybrid protocol of AR/VR and non-invasive brain stimulation. Short, portable tES sessions can be paired with specific image filters of AR/VR to probe hypothesized pathways, for example testing whether occipito-parietal stimulation modulates performance costs under isoluminance, or whether motor-area tACS (Pozdniakov et al., 2021; Feurra et al., 20919) influences visually guided locomotion. This design maintains causal leverage while preserving ecological validity and low cost (Charvet et al., 2015; Fertonani & Miniussi, 2017; Polanía et al., 2018).

An AR/VR HMD with the image filters controlling the activity of specific brain regions allows us to study the roles of these regions in visual perception under dynamic conditions and in the interaction between perceptual and motor processes on human behavior, such as motor control with visual feedback. When an observer sees a 3D scene with moving the observer's head, the retinal image of the scene changes. The visual system perceives depth from the relationship between the head movements and the image changes (motion parallax). The image changes can also be important for the perception of materials (Anstis, 1992; Blake & Bülthoff, 1990). Depth perception from motion parallax has been studied with restricting the directions and ranges of the head movements because of the technical limitation of head tracking as well as the control of their experiments. This technical limitation can be resolved by using the AR/VR HMD. With the HMD, it is also possible to test the effect of the dynamic head movements on more complex cognitive tasks, such as face recognition and finding a familiar face in a crowd. An interesting example is visual search and foraging. Gilchrist et al. (2001) reported that an observer uses different strategies for visual search and foraging where the observer can freely move around. The AR/VR HMD may be also useful in more industry-oriented applications, like the evaluation of outdoor advertisement and the urban environment.

An AR HMD with the image filter of S-cone isolating stimuli can be useful in studying the roles of the superior colliculus in people's social behavior. The superior colliculus processes an emotional signal in visual information (Carretié et al., 2021; Méndez et al., 2022), which is important for the social behavior, including interaction with others. Note that some of experiments in social psychology that involve this interaction are conducted in real environments. The wearable AR HMD can be useful to study how the brain regions affect the social behavior in these experiments (most AR HMDs are bulky so they are likely limited to use in interactions with experimenters or confederates at the current stage). The superior colliculus is especially sensitive to negatively-affective visual information (Almeida et al., 2015; Wang et al., 2020; Ajina, Pollard, & Bridge, 2020). Then, the filter of the S-cone isolating stimuli may be used to control the intensity of exposure therapy for post-traumatic stress disorder (PTSD) and phobias. Some other clinical issues are associated with brain regions whose activity can be controlled using the image filters discussed in this study: e.g. the superior colliculus with autism (Jure, 2019, 2022), the magnocellular- or dorsal-pathways with dyslexia (Quercia et al., 2013; Gori & Facoetti, 2015) and schizophrenia (Whitford et al., 2018; Kody & Diwadkar, 2022), and the parvocellular pathway with amblyopia (Wen et al., 2021, see Gao et al., 2025; Zhou et al., 2025 for examples).

The behavioral techniques that were discussed in this study only indirectly control the brain activity, and their relationship with the controlled regions of the brain is based on the results of neurophysiological studies. So, the relationship may be revised in the future, which could affect the neurophysiological inferences drawn from the results of the experiments that used the techniques. Besides, it has been shown that the techniques clearly affect visual perception, which is the outcome of the process in the brain. Therefore, the functional properties of the process can still be discussed in terms of which aspects of perception are or are not affected by the techniques.

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