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PERSPECTIVE

The role of the visual field size in artificial vision

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Abstract

Objective. Artificial vision has been and still is the subject of intense research. The ultimate goal is to help blind people in their daily life. Approaches to artificial vision, including visual prostheses and optogenetics, have strongly focused on restoring high visual acuity for object recognition and reading. Consequently, clinical trials were primarily focused on these parameters. *Approach*. Alternatively, enlarging the visual field (VF) size could significantly improve artificial vision. *Main results*. I propose that approaches towards artificial vision address the challenge of creating this rudimental form of sight within a large VF. *Significance*. Enlarging the VF size will enable users to improve their mobility and perform visually-driven search tasks. Eventually, it could make artificial vision more efficient, comfortable and acceptable from the user's point of view.

In sighted individuals, two metrics assess the quality of vision and the presence of visual impairments or blindness [1]. Visual acuity (VA) refers to the capability of discriminating small details. It is measured by identifying small gaps within high-contrast symbols called optotypes. VA depends on several factors, including optical properties and neural functions. The highest VA is in the fovea centralis: the retinal area with the highest cone density. Then, VA drops rapidly as retinal eccentricity increases. The theoretical maximal VA corresponds to a minimum angle of resolution of 1 min of arc or a 5 μm separation on the retina [2], which is 20/20 (or 6/6) in the international system. The International Classification of Diseases 11 (ICD11, The World Health Organisation, 2018) defines blindness as a presenting VA of less than 20/400 (or 6/120) in the better eye with the best possible correction.

The other parameter used to define the quality of vision is the visual field (VF) size. A typical VF for one eye spans approximately 60° nasally to 107° temporally and from 70° above the horizontal meridian to 80° below. The combined VF size from both eyes spans ±107° from the vertical meridian. The central ±60° corresponds to the binocular zone, which is seen by both eyes. The ICD11 defines blindness also when the VF is reduced (tunnel vision) to less than 10° in size. Therefore, the author believes that the VF size is a crucial parameter to consider in artificial vision, which is the rudimental form of vision induced by prosthetic devices or optogenetics [3–5].

1. The VF size in normal vision

Having a large VF is crucial in many aspects of our life.

Visual processing varies strongly across the VF [6]. Vision is dominated by central vision: a small region around the gaze position allowing for high VA and high sensitivity to contrast variations. Peripheral vision provides summarised information about the space around us but lacks the capability to detail individual elements. Central and peripheral vision accomplish two complementary goals, but the visual processing is highly intertwined [7]. In simple terms, saccadic eye movements bring objects of interest from the periphery to the fovea. Continuous repetitions of saccadic eye movements (about 3 per second) allow grasping high-resolution information from multiple points of the VF to build a spatially homogeneous perception across the VF. Similarly, during fixation, an unexpected event in the peripheral field triggers our attention and shifts our gaze. One could wonder about the minimum VF size required for normal behaviour, knowing that involuntary or voluntary eye and head movements permit space exploration.

Peripheral VF loss (PVFL) is a condition leading to the so-called tunnel vision, where only central vision remains functional, as is common in individuals affected by retinitis pigmentosa or glaucoma. Is PVFL affecting eye movements and any related visually-driven exploratory behaviour? Clinical data are not conclusive, probably due to the variability among different diseases leading to PVFL and variability among the various adaptation strategies developed by individuals. For example, while PVFL might impair bottom-up (stimulus-driven) saccadic eye movements, top-down (goal-driven) mechanisms based on space knowledge could emerge in search tasks. Behavioural studies with participants having simulated or real PVFL remarkably showed that only severe PVFL (VF $< 15°$) reduces performance during locomotion and navigation tasks in simple environments [8]. However, subjects under PVFL adapt gaze navigation strategies to compensate for the VF loss [9]. Other studies suggest that the VF size required for efficient navigation is 20° [10, 11]. Variability among reports is probably due to differences in testing conditions, such as the environment complexity, the task difficulty, the luminance level, the contrast in the image etc.

2. Artificial vision

Under the assumption that 20° is sufficient for safe and efficient navigation in PVFL, is this value reasonable also for artificial vision?

Before trying to answer this question, it is important to define artificial vision. Essentially, artificial vision is a rudimentary form of vision caused by the artificial activation of neurons in the visual system by physical forces such as mechanical, chemical or electrical stimuli. For example, visual prostheses electrically stimulate visual neurons upstream to the damaged location, such as the retina, the optic nerve, the lateral geniculate nucleus or the cortex [5, 12–21]. The artificial stimulation of visual neurons induces the perception of bright dots in the visual space (called phosphenes). Phosphenes are the building blocks of artificial vision [22]. Blind people perceive the world by combining multiple phosphenes in a meaningful manner.

Artificial vision is spatially and temporally different from natural vision [5]. Phosphenes appear as flickering points of light in the visual space. Their shape can be round or irregular, typically depending on which set of neurons are stimulated. Activation of bipolar cells in the retina usually induces circular phosphenes, while the direct activation of retinal ganglion cells and their axons usually induced oblong perception. Optic nerve and cortical stimulation have also resulted in irregular phosphenes. Phosphene size is also variable as a function of many parameters, from a fraction of degree to even tens of degrees. Colour is typically white or yellow, and brightness can be controlled by the stimulation strength. However, creating a grayscale perception in patients has been a challenge so far. Therefore, artificial vision is at the moment black and white. Spacing among phosphenes is another important parameter, which largely depends on the artificial stimulation resolution. The best performance today in patients has been obtained with a subretinal implant providing a maximal VA of 20/460 and continuous perception above flicker fusion [12]. Still, this is far below natural vision. In all other cases, performance was lower spatially (lower VA) and temporally. Temporal aspects are critical since evoked phosphenes might disappear rapidly, making continuous perception nearly impossible [23–26]. Patients described phosphene perception as exhausting due to constant flickering and requiring high mental effort [27].

Due to these differences, it is reasonable to assume that the capability of using residual central vision under PVFL to safely and efficiently perform navigation tasks might be altered when residual central vision is substituted by artificial vision generated by visual implants or optogenetics.

3. The VF size in artificial vision

Historically, the role of the VF size in artificial vision has been mostly neglected in favour of the resolution. The author believes that in artificial vision, the VF size is equally important as the resolution. Consequently, my laboratory has decided to develop implants leading to a substantial increase in the VF, such as POLYRETINA [28–32]. Other laboratories as well have provided strategies to increase the VF size in retinal prostheses by developing wide-field implants [33–35] or adopting compensatory strategies based on artificial intelligence and image processing [36]. Although most of the research attempting at enlarging the VF size comes from the field of retinal prostheses, it is important to not consider it as a unique problem of this field. Indeed, the author believes that this aspect affects any form of artificial vision, regardless of the methodology used (e.g. retinal prostheses, cortical implants, optogenetics, etc).

Due to the lack of clinical strategies to test quantitative parameters of artificial vision (e.g. number and density of phosphenes, VF size, phosphene fading, etc), researchers have taken the approach of simulating artificial vision [37, 38]. Simulated artificial vision (SAV) uses computer monitors or head-mounted displays to simulate artificial vision in normally sighted volunteers under virtual or augmented reality. Once again, most studies focused on investigating test performance as a function of the number and density of phosphenes, which is artificial vision resolution [38–40]. Studies specifically focusing on the effect of altering the VF size on the ability

of participants to complete some visual tasks are scarce [41–45].

There are two ways to alter the VF size in SAV. The first is by adding phosphenes while maintaining a constant density. The second is to change the pitch between phosphenes, thus affecting at the same time the VF size and the resolution. The author believes that the first approach is scientifically preferable when comparing the VF size. However, it is less suitable for conventional visual prostheses (apart from wireless systems like POLYRETINA) since, in most cases, the number of electrodes is limited by the capacity of the implanted stimulator. Therefore, the only possibility to increase the VF size in these devices is to increase the electrode spacing.

Following the first approach, Cha *et al* evaluated mobility under SAV [41]. The VF size ranged from 2° to 45.5°, and the number of phosphenes was from 100 to 1024. They found that an array of 25 × 25 phosphenes within a 30° of VF size could provide adequate mobility skills. Pelizzone *et al* reported that as few as about 200 phosphenes within a VF size of 33° × 23° allow for mobility in familiar environments. However, more than 1000 phosphenes are needed for safer decision-making in unpredictable environments [42]. Dagnelie *et al* also tested mobility in SAV [43]. The authors used a Gaussian distribution to represent phosphenes and included other factors, such as dynamic background noise and contrast difference between phosphenes and the dark background. However, in this case, only three conditions were tested in which the VF size, the number of phosphenes and the pitch between phosphenes were different among the three conditions. So data on the VF size are not conclusive. Chang *et al* asked participants to identify the faces of people familiar to them under different conditions of SAV [44]. Two aspects were altered: the VF size was either 4.72°, 7.08° or 9.44° (while keeping the pixel density constant), and the image pre-processing was either left unaltered or filtered with both contrast-enhancement and edge-detection algorithms. When altering the VF, the authors found an increase in accuracy and a decrease in the time taken to respond correctly.

Finally, Thorn *et al* carried out a series of virtual reality experiments using SAV to understand further the impact of the VF size on task performance [45]. Unlike previous studies, phosphenes were modelled according to mathematical models extrapolated from the user's experience [46]. The model accounts for elongated phosphenes due to the activation of retinal ganglion cell axons. The increase of the VF size (from 5° to 45°) consistently resulted in higher performance when identifying a series of common objects, reading words, understanding depth, and making visually-driven decisions. More importantly, manipulating the phosphene pitch from 150 to 60 μm showed that resolution has little influence if the VF size is sufficiently large (e.g. 45°).

4. The interplay between VF size and resolution in artificial vision

Although putting all these data together is challenging, it is still possible to draw some qualitative conclusions.

1. Subjects with PVFL adapt to the lack of peripheral vision and behave normally unless the VF size drops below approximately 10–20°. This result can be explained by two factors: the adaptation in scanning behaviour and the quality of the residual central vision.
2. Totally blind subjects with artificial vision require a larger VF size to perform behavioural tasks, particularly locomotion.
3. Thorn *et al* concluded that a VF size of about 45° is adequate for mobility tests involving visually-driven decisions. This value is in agreement with previous studies. The author's hypothesis is that a small VF is ineffective due to the low quality of artificial vision.
4. It is reasonable to assume that an improvement in artificial vision quality might compensate for the need for a large VF. Better artificial vision could facilitate top-down mechanisms during search tasks.
5. The relation between the VF size and the quality of artificial vision is still elusive since it depends on multiple factors, including spatial and temporal resolution, perception persistence, etc.

These conclusions are drawn based on evidence collected mostly under SAV. Studies detailing the effects of manipulating the VF size in patients under artificial vision are still missing. Therefore, these conclusions might be inaccurate. In particular, SAV represents an optimistic scenario, while artificial vision in patients is typically worse. For this reason, it might be possible that the VF size plays an even more significant role. Last, we should not forget that resolution also plays an important role. While the VF size is important for general orientation, space mapping, and mobility, resolution is crucial for object recognition and tasks requiring precision.

5. Final remarks

The author believes that VF size is a key parameter in artificial vision. Every approach aiming at improving artificial vision should focus on this aspect and evaluate functional improvements in mobility and quality of life, not only on resolution and VA.

However, increasing the VF size is a technological challenge difficult to achieve.

Among retinal prostheses, only epiretinal [28, 35] and suprachoroidal [47, 48] devices could cover a significant portion of the retina, corresponding to a large

VF size. In subretinal position, the device size is limited by the risks of retinal detachment. Consequently, subretinal prosthesis have a maximum restored visual angle of about 10°, making them more indicated for central retina diseases, such as age-related macular degeneration [12]. Suprachoroidal devices allow for simpler and minimally invasive surgeries. The surgery does not require intravitreal manipulation and the procedure can be easily repeated for device replacement [49]. However, subretinal and suprachoroidal haemorrhage has been reported during preclinical and clinical trials [47, 50, 51]. Epiretinal devices follow a surgical approach familiar to vitreoretinal surgeons, but they are attached to the retina using one or more retinal tacks. Retinal tacks lose mechanical stability over time, increasing the distance to the retina and reducing the stimulation efficacy [52]. Subretinal and suprachoroidal prostheses have higher mechanical stability [1, 53].

Retinal optogenetics is also impacted by the limited VF size [54], requiring multiple injections to express the construct in a wide area. Also, approaches like photovoltaic prostheses and optogenetics require image projection from wearable glasses. Image projection with a wide angle through the pupil is technically challenging and might pose safety concerns about thermal heating [29].

It is still unclear how to increase the VF size for cortical approaches. A large portion of V1 is difficult to access surgically, like the interhemispheric area and the calcarine sulcus. Combining activation of different visual areas (e.g. V1, V2 and V3) might be a solution [55, 56], but it still needs to be determined how phosphene induced by these areas will combine into artificial vision. Technologically, increasing the VF size implies developing scalable electrode arrays with a substantially higher number of channels than what is available today [15, 57].

Nevertheless, enlarging the VF size could make artificial vision more efficient, comfortable and acceptable from the user's point of view.

Data availability statement

No new data were created or analysed in this study.

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