efpsa Journal of European Psychology Students

Muttenthaler, L. (2019). Effective enhancement of attentional functions in the amblyopic brain. *Journal of European Psychology Students, 10*(1), 1-10. Doi: 10.5334/jeps.435

RESEARCH ARTICLE

Effective enhancement of attentional functions in the amblyopic brain

Lukas Muttenthaler[1]

This review endeavoured to investigate whether patients with amblyopia show impairments in attentional functions and whether video games are appropriate to enhance attention. Results revealed that amblyopic patients show deficient performance in tasks which measure spatial or temporal attention. Furthermore, numerous studies highlighted that video games foster the enhancement of visual attention in subjects with normal vision. Accordingly, video games appear to be suitable to treat deficits in high-level visual abilities. High-level visual abilities encompass the entire variety of attentional functions. However, there are only a few studies to date which investigated whether video games advance visual attention in patients with amblyopia. Thus, we cannot draw a thorough, evidence-based conclusion but encourage others to conduct studies which examine the latter.

Keywords: amblyopia; video games; visual attention; high-level vision

Amblyopia is one crucial cause of decreased vision in children and affects approximately two to four percent of the general population (Foss et al., 2013; Levi, Knill, & Bavelier, 2015; Vedamurthy, Nahum, Bavelier, & Levi, 2015). Thus, given this prevalence, it seems reasonable that experimental psychologists foster the advancement of therapeutic methods for amblyopia. Although the eyes of amblyopes look as if they are not affected, the binocular visual pathway from the eyes to the visual cortex is significantly impaired, and causing the decrease in vision (Levi et al., 2015; Tailor, Schwarzkopf, & Dahlmann-Noor, 2017). Hence, amblyopia may be perceived as a neural disorder of the visual cortex rather than a disease of the eye itself (Hussain et al., 2014).

1 Faculty of Psychology, University of Vienna, AUT
Corresponding author: Lukas Muttenthaler (mnd926@alumni.ku.dk)

Amblyopia is the result of abnormal visual inputs (i.e., *neural impairments*) during the early childhood and therefore is categorized as a neuro-developmental disorder (Bavelier, Levi, Li, Dan, & Hensch, 2010; Maurer & Hensch, 2012). Amblyopia usually has its onset during the first three years of life, after the end of the critical period (Levi et al., 2015).

Enhancement of vision in typical development normally continues until the age of seven, when both visual acuity and stereopsis—that is, the perception of depth—finally reach the level of adult vision (Maurer & Hensch, 2012). However, owing to a lack of balanced synaptic inputs, the development of vision in amblyopic patients only continues for the sound eye but stops earlier for the affected eye (Tailor et al., 2017). This lack of binocular synaptic inputs is the quintessential cause of amblyopia (Hess et al., 2014).

Even though earlier studies on animals

suggested that the lateral geniculate nucleus (LGN) is affected by amblyopia (e.g., Hickey, Spear, & Kratz, 1977), studies on the human brain revealed rather ambiguous findings in respect of the impairment of the LGN (e.g., Von Noorden, Crawford, & Levacy, 1983). However, one recent study suggested that the LGN may indeed be affected by amblyopia (Hess, Thompson, Gole, & Mullen, 2009). The latter findings could play a decisive role with regard to rehabilitation, as the treatment tools may also aim at the LGN. However, V1 is the brain region which shows the most significant impairments concerning visual information processing in both humans and animals. Due to a lack of synaptic inputs from both eyes, the striate cortex is not capable of representing the outer world unambiguously. The visual cortex primarily receives visual inputs from the sound eye and barely any from the amblyopic eye. There are only a few cases to date, where both eyes suffer from amblyopia (Hess et al., 2014; Maurer & Hensch, 2012).

To advance unimpaired and highly resolved vision, the visual cortex requires normal visual inputs. That is, inputs which are not affected by strabismus (i.e., the eyes are not properly aligned with each other) or anisometropia (i.e., the eyes have unequal refractive power; Tailor et al., 2017). Hence, amblyopia may be the result of two different neural impairments owing to abnormal vision. Amblyopia may either caused by a misalignment of the two eyes and thus is called *strabismic amblyopia* or results from anisometropia and accordingly is perceived as *anisometropic amblyopia*.

The latter type results from an unequal focus between the two eyes (i.e., different interocular refractive errors), which generates blurry sight in one eye yet both eyes superficially appear the same. Different interocular refractive errors may result from hyperopia in one eye and myopia in the other. In amblyopia, not only visual acuity is impaired, but also stereopsis (i.e., depth perception), contrast sensitivity (CS), and binocular vision are affected as the visual cortex lacks synaptic inputs from the affected eye (Li, Spiegel, et al., 2015). Consequently, the visual cortex essentially develops monocular neurons in the striate area which are only capable of yielding unambiguous representations of the sound eye. There are rare cases, where amblyopia is caused by both strabismus and anisometropia.

For decades, the gold-standard method to treat amblyopia has been occlusion therapy. That is, eye-patching of the sound eye or penalization of the amblyopic eye. However, in neuropsychological research, new treatment approaches have emerged during the past decade. In this review, we will direct attention to video games as one promising approach in respect of the enhancement of decreased vision in patients with amblyopia. Accordingly, we first examined which studies showed that video game-based trainings appear to be effective therapeutic tools to treat decreased vision (e.g., visual acuity, CS, stereopsis). Therefore, we had to comprehensively investigate current literature in regard to the video game-based training approach.

Research Method

We searched through a variety of databases such as PubMed, Web of Science, PSYCINFO, PSYCINDEX, Ovid, Science Direct and Google Scholar. In doing so, we used terms such as "video games treatment", "attentional deficits in amblyopia", "multiple object tracking", "multiple object tracking amblyopia", "video games visual acuity", "high-level vision in amblyopia", "attentional blink", "attentional blink in amblyopia", in order to obtain papers which could adequately meet our research goal. We confined our search to the period 1990 to 2017. However, we primarily aspired to examine very recent papers to summarize the current state of research.

Impaired Low-Level Visual Abilities: Visual Acuity, Binocular Vision and Stereopsis

Our literature research revealed that there are numerous studies to date which displayed that video games enhance low-level visual abilities in patients with amblyopia. However, we suspected that video games may also foster the enhancement of high-level vision in patients with amblyopia. With the term "high-level vision" we referred to visual abilities which involve attentional functions such as spatial or temporal visual attention. Video game training can either be monocular or dichoptic. The latter type of training is a very recent treatment method in basic neuropsychological research, however not yet used in practice. It primarily fosters re-balancing of the inputs from both eyes.

Owing to a lack of synchronized visual inputs in the visual cortex, re-balancing of the inputs appears to be indispensable (Hess & Thompson, 2015). During dichoptic training, patients are required to play video games and while doing so, wear specialized glasses (e.g., shutter glasses). These glasses aim at the separation of the visual impressions generated by both eyes (Eastgate et al., 2005; Foss et al., 2013; Levi et al., 2015). There are currently two types of dichoptic training: One approach presents high-contrast visual stimuli to the amblyopic eye and low-contrast visual stimuli to the sound eye, and the second method aims to present both the background and an enriched foreground to the amblyopic eye but only the background of the frame to the sound eye (Foss, 2017; Guo et al., 2016; Li, Spiegel, et al., 2015). Hence, both eyes perceive independent visual stimuli. In contrast, occlusion therapy, another type of treatment, contributes only to the enhancement of visual acuity and CS in the eye with decreased vision but does not significantly enhance stereopsis and binocular vision nor high-level visual functions such as visual attention. However, rehabilitation therapy in amblyopia should aim to recover higher visual function (Bach, 2016). Furthermore, compliance for occlusion therapy is tremendously low (Hess et al., 2014; Wallace, Stewart, Moseley, Stephens, & Fielder, 2013). Hence, it appears that occlusion therapy may target the associated pathophysiology insufficiently. In contrast, video game-based methods may provide a promising new approach to treat both dichoptic and monocular amblyopia. The latter approaches indeed show significantly higher compliance rates and contribute to the advancement of attentional abilities, whereas occlusion therapy is not capable of enhancing those functions (Foss, 2017; Hussain et al., 2014). In the following paragraphs, the current paper intends to summarize high-level visual abilities, why they are required to be recovered in the amblyopic brain, and how video game-based methods foster their enhancement.

Impaired High-level Visual Abilities: Visual Attention

Li, Spiegel, et al. (2015) propose, that amblyopia primarily is a neural disorder with impaired binocular vision. Thus, to adequately rebalance the visual inputs of the amblyopic eye and its sound eye, simultaneous training of both eyes appears to be indispensable. However, amblyopia apparently is not only a disorder of impaired low-level visual abilities (e.g., visual acuity, stereopsis, CS) but also of high-level visual functions (e.g., visual attention; Green & Bavelier, 2012; Jeon, Maurer, & Lewis, 2012; Li, Ngo, & Levi, 2015). Due to significant impairments in binocular vision, which is crucial to normally develop high-level visual abilities, attentional functions appear to be also affected in the amblyopic brain. Recent studies highlighted that monocular training methods (e.g., video game-based training) yield transfers to other visual abilities which are decisive for binocular vision and attention. Transfers from the amblyopic eye to the sound eye occur more thoroughly for high-level functions than for low-level functions as one recent study depicted (Li, Ngo, et al., 2015).

Since there are only a few studies to date which investigated whether video games indeed foster the enhancement of attentional abilities in patients with amblyopia, we first aim to examine which studies showed that patients with amblyopia suffer from a lack of attentional functions. Even though there is already much evidence supporting the notion of amblyopia being a neural disorder with impaired binocular vision and depth perception, there is no review yet on the lack of attentional functions in patients who suffer from amblyopia. Therefore, the second endeavour of this paper is to investigate which experimental methods were used in recent studies to examine visual attention of patients with amblyopia and how patients with amblyopia performed on these tasks. We deem the latter investigation as indispensable in order to encourage future studies to use those tasks for thorough evaluations of visual attention before (i.e., pre-test) and after (i.e., post-test) a video game-based training period. If future studies provide evidence that amblyopia impairs performance in tasks which measure visual attention, video game-based training might enhance both low-level and high-level visual abilities in patients with amblyopia. Numerous studies already highlighted that playing video games promote an increase in visual and spatial attention in subjects with unimpaired vision (Achtman, Green, & Bavelier, 2008; Bavelier, Achtman, Mani, & Föcker, 2012; Bayliss, Vedamurthy, Nahum, Levi, & Bavelier, 2013; Feng & Spence, 2007; Green & Bavelier, 2006; 2012; Vedamurthy, Nahum, Bavelier et al., 2015; Vedamurthy, Nahum, Huang et al., 2015).

Moreover, if patients with amblyopia significantly lack visual attention, amblyopia may be treated not only as a disorder of visual acuity, binocular vision, and stereopsis but also of attentional functions. The latter approach would most probably foster a more rapid improvement of visual abilities since the lack of attentional capacities can be reduced by various cognitive training approaches (Feng & Spence, 2007; Green & Bavelier, 2012).

Do Patients with Amblyopia suffer from a Lack of Visual Attention?

A notable set of recent studies provide evidence that video game and dichoptic training approaches effectively enhance both binocular vision and stereopsis in the amblyopic brain (Bach, 2016; Bayliss et al., 2013; Eastgate et al., 2005; Green & Bavelier, 2012; Levi et al., 2015; Li, Spiegel, et al., 2015; Vedamurthy, Nahum, Bavelier et al., 2015; Vedamurthy, Nahum, Huang et al., 2015). The vast majority of those studies compared occlusion therapy with video game methods and concluded that the latter approaches are more efficient and show significantly more compliance among patients (Foss, 2017; Hess et al., 2014; Hussain et al., 2014; Levi et al., 2015; Li, Ngo, et al., 2015; Li, Spiegel, et al., 2015; Vedamurthy, Nahum, Bavelier et al., 2015; Vedamurthy, Nahum, Huang et al., 2015). It is hence considered established that dichoptic training approaches, video games, and perceptual learning show more efficacy than patching the sound eye or penalization of the amblyopic eye to foster plasticity in the visual cortex and thus yield recovery of the amblyopic eye (e.g., Li, Spiegel, et al., 2015; Vedamurthy, Nahum, Bavelier et al., 2015; Vedamurthy, Nahum, Huang et al., 2015). One study aimed to combine their video game-based training approach with dichoptic training (see Figure 1; Vedamurthy, Nahum, Huang et al., 2015).

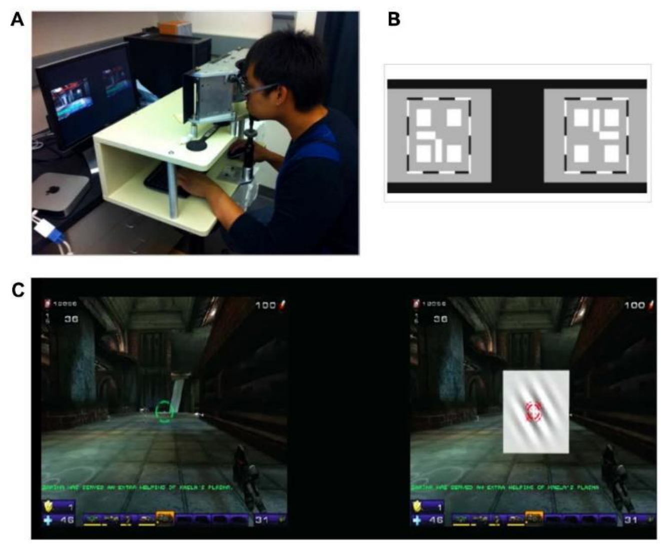

Figure 1. Combination of video game-based and dichoptic training used in the study of Vedamurthy, Nahum, Huang et al. (2015).

Test subjects were therefore required to play the video game through a mirror stereoscope to achieve alignment (A; Figure 1). Nonius lines were shown at the initial phase of each training session to yield fusion of the amblyopic and the fellow sound eye (B; Figure 1). A snapshot of the game was taken while being played by an amblyopic patient (C; Figure 1). The left image displayed in the figure was presented to the sound eye, whereas the right image was shown to the amblyopic eye. The non-amblyopic eye image has lower brightness than the amblyopic eye image. Additionally, a Gabor discrimination task is implemented in the image presented to the amblyopic eye to challenge the amblyopic eye more than its sound eye.

What remains to be answered is whether amblyopia is a disorder only of low-level visual abilities such as visual acuity, binocular vision, and stereopsis or also of impaired high-level visual abilities such as visual attention. An evidence-based response to this question is crucial as amblyopia could then be additionally treated with training methods which foster the enhancement of attentional functions. Indeed, a promising training method to enhance attentional abilities could be the video game approach. Amongst others, this review aims to scrutinize whether the latter method actually is the appropriate approach for amblyopic patients or not. To satisfy this goal, the following sections of the review will draw attention to different paradigms in which amblyopic patients have been studied, specifically within the realms of the attentional blink phenomenon, face perception, Gabor patches and multiple-object tracking.

The Attentional Blink in Patients with Amblyopia

We investigated a notable number of studies in respect of their experimental methods to examine attentional functions in patients with amblyopia. The first method, we aim to direct attention to, is the serial visual processing technique (SRVT) or rapid serial visual presentation (RSVP). SRVT is widely used to measure temporal visual attention. During a SRVT task, visual stimuli (e.g., letters) are presented serially in a rapid sequence and in the same location. Accordingly, SRVT or RSVP tasks may be defined as visual search tasks where searching occurs temporally rather than spatially (Shapiro, Arnell, & Raymond, 1997). The attentional blink (AB), first scrutinized by Raymond, Shapiro, and Arnell (1992), refers to the phenomenon of not identifying a second target (T2) that rapidly succeeds a first target (T1) with a delay of 200–500 ms. During SRVT visual stimuli are presented in rapid succession (e.g., T2 is presented 200 ms after T1) within a stream of letters or numbers. The task requires the identification of a white letter or a letter of distinct color except black in a stream of black letters as well as of an "X" in a flow of various other characters. Hence, participants must identify two targets. The correct identification of T1 interferes with the identification of T2 which leads to the non-identification of T2. This phenomenon is called the attentional blink (Raymond et al., 1992; Shapiro et al., 1997). The attentional blink occurs due to an attentional load evoked by T1 and thus, less attention is available for T2 than for T1, which causes the inability to identify T2.

Recent studies revealed that patients with amblyopia require more time to allocate attentional resources after the identification of T1 compared to healthy subjects (Asper, Crewther, & Crewther, 2003). For instance, Popple and Levi (2008) showed that the amblyopic eye of patients with amblyopia responded to T2 as accurate as their sound eye. However, T1 identification was significantly worse for the amblyopic eye. Consequently, amblyopia appears to have a significant impact on the AB which can partially be explained due to impairments in binocular vision and suppression of the amblyopic eye during development (Popple & Levi, 2008).

Li, Ngo, et al. (2015) highlighted that the amblyopic eye is more prone to the attentional blink than its fellow sound eye when T2 is presented with a delay of approximately 200–500 ms. However, after 40 hr of video game training, the amblyopic eye indeed showed a significant enhancement of approximately 40% concerning the AB and thus performed better in the SRVT task than before training. Moreover, the improvement of the amblyopic eye with respect to the AB transferred to the sound eye. As shown above, transfer occurs more thoroughly for high-level visual abilities compared to low-level functions. Notably, post-training results revealed that performance in the SRVT task enhanced not only for the amblyopic eye but also for the sound eye although Li, Ngo, et al. (2015) used a monocular training approach in their study. This finding is in line with results of several studies, which revealed, that video game players (VGPs) perform better in RSVP tasks and recover faster from the AB than non-video game players (NGVPs; Achtman et al., 2008; Green & Bavelier, 2003). Thus, video game play significantly advances performance in SRVT tasks and results in a shorter AB.

In the next section, the paper will focus on the complexity of face perception, the brain areas that are involved in that task and to what extent it is impaired in the amblyopic brain.

Impaired Face Perception

Faces are non-trivial objects for the human brain—a face does not appear as a single object but rather as an arrangement of multiple details and most often expresses an emotion—and are unique on their own—there are no two faces that entirely resemble each other. Thus, face perception is a complex task that requires attentional functions. As already highlighted, visual attention is impaired in patients with amblyopia. Hence, one might assume that the perception of faces is affected in the amblyopic brain at least to some extent. Results of recent studies displayed that patients with amblyopia indeed perform worse in tasks where they were required to process and identify upright and inverted faces compared to subjects with normal vision (Jeon et al., 2012). Furthermore, Lerner et al. (2003) showed that neural connections between the amblyopic eye and face-related areas (e.g., fusiform face area) in the extrastriate ventral pathway are disrupted. Thus, both the processing and recognition of faces is impaired in the amblyopic brain. These findings may reflect the notion of abnormal visual inputs in childhood affecting the development of circuitries in visual brain areas, particularly in high-order areas.

However, there are only a few studies to date which investigated the performance of patients with amblyopia in face perception tasks. Bailey and West (2013) highlighted that video games have negative effects on the processing of social information. Thus, video games that have been used in recent studies appear not to contribute to the enhancement of deficient face recognition. However, future studies are required to further investigate the latter claim. It may be the case that there are indeed video games which could support the advancement of normal face perception in patients with amblyopia.

Underestimation During the Enumeration of Gabor patches

Enumeration of quickly presented Gabor patches is another experimental method to measure high-level visual abilities (e.g., visual attention). A Gabor patch is a circular low-contrast greyish visual stimulus. Within the inner space of a Gabor patch vertical or horizontal lines are arranged. Sharma, Levi, and Klein (2000) investigated how patients who suffer from amblyopia perform in tasks which require to enumerate the number of Gabor patches presented beforehand. However, the researchers not only examined whether amblyopia impairs the capability to enumerate patches. They further investigated whether deficient performance results from decreased low-level vision or from reduced high-level visual abilities.

Deficits in low-level vision would predict an overestimation of the number of presented Gabor patches, whereas limitations of high-level visual abilities would predict that patients with amblyopia underestimate the number of patches. First, participants were required to count Gabor patches which were randomly presented on a high-contrast grey background. Second, participants had to enumerate the number of missing patches which were presented in a 7 x 7 square matrix. Results revealed, that patients who suffer from amblyopia consistently underestimate both the number of patches and the number of missing patches. A significant difference between the performance of patients with amblyopia and participants with normal vision was reported such that patients with amblyopia underestimated the number of patches and missing patches to a far greater extent than observers with normal vision. Furthermore, patients with amblyopia underestimated the number of patches and missing patches to a significantly greater extent with their amblyopic eyes compared with their fellow sound eyes. When estimating the numbers of patches with their sound eyes, patients with amblyopia performed as accurate as observers with normal vision but only when the number of patches did not exceed five (Sharma et al., 2000). The study of Sharma et al. (2000) depicted, that patients with amblyopia do not only suffer from impairments in low-level vision but also lack high-level visual abilities. Notably the amblyopic eye is affected by impaired attentional functions. Their results could reflect the notion, that binocular synaptic inputs may not only be affected in the visual cortex but perhaps also in the parietal cortex—which is associated with enumerating and attentional functions. Unfortunately, there is no study to date which investigated whether video games enhance the enumeration of Gabor patches in patients who suffer from amblyopia.

Poor Multiple Object Tracking

As shown above, patients with amblyopia suffer from a lack of various attentional functions (e.g., face perception, temporal attention, enumeration). However, we have not yet addressed the issue whether distributive spatial attention, as measured by multiple object tracking, is also impaired in amblyopic patients. An evidence-based response to the latter issue is particularly important since the number of hours a person is playing video games appears to be a crucial factor on the performance in tasks which measure spatial attention (Green & Bavelier, 2003; Spence & Feng, 2010). Thus, if patients with amblyopia indeed show poor tracking performance this would highly support the notion that video games are appropriate to enhance distributive attention in the amblyopic brain.

A notable number of recently conducted studies showed that performance in multiple object tracking (MOT) tasks appears to be an adequate measurement of how a person can effectively distribute its attention on multiple moving objects simultaneously (Cavanagh & Alvarez, 2005). In MOT tasks, subjects are required to focus their visual attention on several moving objects simultaneously while ignoring others. As the number of moving targets and distractors increases, the task becomes more difficult due to an increased attentional load. In addition to MOT tasks, several studies used multiple trajectory tracking. Whereas in MOT tasks test subjects are required to focus their attention on moving circles, in trajectory tracking tasks, subjects must allocate attentional functions to not lose track of specific trajectories. Tripathy and Levi (2008) showed that performance of patients with amblyopia in trajectory tracking tasks was almost as preserved as in subjects with normal vision, whereas in MOT tasks, patients with amblyopia showed deficient performance. In the study of Secen, Culham, Ho, and Giaschi (2011) amblyopic patients showed significant impairments in attentive tracking and performed significantly worse than a control group with normal vision.

Another study conducted by Ho et al. (2006) revealed that patients with amblyopia show systematic deficits in spatial attention and tracking. Subjects were required to perform a single-object tracking task during the first experiment of the study and an MOT task during the second experiment. Results revealed that patients who suffer from amblyopia performed significantly worse than a control group in respect of both their amblyopic eye and their fellow sound eye in tracking single and multiple objects. These deficits in high-level motion processing may result from impairments in the posterior parietal cortex which, as an indispensable part of the dorsal visual stream, is involved in various attentional functions, particularly in the processing of moving objects (Ho et al., 2006; Secen et al., 2011). The posterior parietal cortex is also impaired in patients suffering from spatial neglect, a neurological condition that affects primarily spatial attention. Accordingly, amblyopia should be treated not only as a disorder of low-level visual functions but also as a disorder of high-level attentional abilities such as neglect.

There is one recent study which used video game-based training to enhance performance on multiple object tracking tasks in visually impaired patients (Nyquist, Lappin, Zhang, & Tadin, 2016). Results suggested that such a training approach may indeed advance distributive attention. Although the participants in that study did not suffer from amblyopia, the study serves as a striking example for video game-based training as being appropriate to enhance attentional functions in patients with impaired vision.

Unimpaired endogenous visual attention

Endogenous visual attention, that is, voluntary and goal-driven visual attention, appears to be unimpaired in amblyopic patients as one recent study has highlighted (Roberts, Cymerman, Smith, Kiorpes, & Carrasco, 2016). In contrast to exogenous visual attention, which is stimulus-driven and accordingly a bottom-up effect, endogenous attention is the result of top-down processes (Carrasco, 2011; 2014). The study particularly examined covert spatial attention. Covert spatial attention is one type of endogenous visual attention which refers to the selective processing of both visual and spatial information without moving the eyes (Posner, 1980). The study showed that endogenous, goal-driven attention contrary to exogenous, stimulus-driven attention is unaffected by amblyopia (Roberts et al., 2016). As shown by numerous other studies and thoroughly depicted in our current review, exogenous attention is significantly impaired in patients with amblyopia compared to healthy observers (e.g., Asper et al., 2003; Sharma et al., 2000). However, Roberts et al. (2016) showed that covert spatial attention does not significantly differ between amblyopic patients and subjects with normal vision. As there is only one study to date, which examined endogenous visual attention in the amblyopic brain, further studies are required to investigate why goal-driven attention appears to be unaffected but stimulus-driven attention indeed is impaired.

Discussion and Conclusions

We can conclude from a comprehensive analysis of the available literature on amblyopia that amblyopic patients suffer from impaired high-level visual abilities. Patients with amblyopia show deficient performance in different tasks which examine visual attention in comparison with normal observers. Their AB occurs longer than normal observer's AB (Li; Ngo, et al., 2015; Popple & Levi, 2008). Accordingly, they show inferior performance in RSVP tasks due to poor attentional capacities. Patients with amblyopia have impairments in the processing and recognition of faces (Jeon et al., 2012; Lerner et al., 2003).

Patients with amblyopia systemically underestimate the number of Gabor patches when they are required to enumerate them (Sharma et al., 2000). Moreover, patients with amblyopia show tremendous deficits with tracking multiple moving objects (Ho et al., 2006; Secen et al., 2011). The latter refers to a significant lack of distributive spatial attention (Cavanagh & Alvarez, 2005). Hence, we can conclude that patients who suffer from amblyopia do not exclusively show impairments in low-level vision but also lack attentional functions. In addition, we intended to investigate whether video games are appropriate to treat amblyopia. Numerous studies have shown that video games, irrespective of whether the study was conducted monocularly or dichoptically, improve low-level visual abilities (e.g., visual acuity, CS, stereopsis, binocular vision) in amblyopic patients (Bach, 2016; Bayliss et al., 2013; Eastgate et al., 2005; Green & Bavelier, 2012; Levi et al., 2015; Li, Spiegel, et al., 2015; Vedamurthy, Nahum, Bavelier et al., 2015; Vedamurthy, Nahum, Huang et al., 2015).

Unfortunately, there is only one study to date which investigated whether video games foster the enhancement of attentional functions in amblyopia (Li; Ngo, et al., 2015). However, the results were promising. Moreover, a notable number of recent studies highlighted that video games foster the advancement of various attentional abilities, spatial and distributive attention in particular, which are significantly impaired in the amblyopic brain (Achtman et al., 2008; Bavelier et al., 2012; Bayliss et al., 2013; Feng & Spence, 2007; Green & Bavelier, 2006, 2012; Vedamurthy, Nahum, Bavelier et al., 2015; Vedamurthy, Nahum, Huang et al., 2015).

Furthermore, there is substantial evidence that video games, in contrast to occlusion therapy and perceptual learning, show high compliance in patients (Levi et al., 2015; Li, Ngo, et al., 2015; Li, Spiegel, et al., 2015; Vedamurthy, Nahum, Bavelier et al., 2015; Vedamurthy, Nahum, Huang et al., 2015). Results displayed that patients are highly motivated to play video games not only in the laboratory under controlled conditions, but also during their recreational time.

However, the efficacy of video games appears to be limited to the enhancement of low-level visual abilities such as CS, visual acuity, stereopsis and binocular vision, and of high-level functions such as distributive visual attention, yet the advancement of high-level functions was scarcely investigated in patients with amblyopia. Video games were only used to foster the enhancement of the AB (e.g., Li, Ngo, et al., 2015), whereas no study to date has examined whether video games may help the amblyopic brain to enhance its performance on multiple object tracking or the enumeration of Gabor patches. Future studies are required to investigate whether video games may indeed help patients with amblyopia to enhance their performance on the latter set of tasks. One recent study has shown that video games do not appear to adequately improve the perception of facial expressions (Bailey & West, 2013).

However, further studies are required to thoroughly test the latter. In doing so, we recommend using a variety of video games. As there are only few studies to date which investigated the correlation between video games and the enhancement of high-level visual abilities in patients who suffer from attentional impairments, this review should serve as an encouragement for further research and not only as a summary of past research. Nevertheless, we can conclude that video games may serve as a promising approach to foster the enhancement of various high-level visual abilities in patients with amblyopia though further studies need to investigate whether video games significantly enhance the enumeration of patches, performance in MOT tasks, motion perception as well as performance in RSVP tasks in patients with amblyopia. We also encourage others to scrutinize whether monocular or binocular treatment approaches are more efficient to treat visual impairments as the current state of research lacks evidence regarding that issue.

In investigating these aforementioned issues, we recommend that future research also direct attention to the underlying neural mechanisms of attentional functions which appear to be impaired in the amblyopic brain.

Conflicts of Interest

The author has no conflicts of interest to declare.

References

Achtman, R. L., Green, C. S., & Bavelier, D. (2008). Video games as a tool to train visual skills. *Restorative Neurology and Neuroscience*, *26*(4–5), 435–446. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2884279/

Asper, L. J., Crewther, D. P., & Crewther, S. (2003). Do different amblyopes have different attentional blinks? *Investigative Ophthalmology & Visual Science*, *44*, 4094. Retrieved from https://iovs.arvojournals.org/article.aspx?articleid=2415897

Bach, M. (2016). Dichoptisches training bei amblyopie. *Der Ophthalmologe*, *113*(4), 304–308. DOI:10.1007/s00347-016-0238-4

Bailey, K., & West, R. (2013). The effects of an action video game on visual and affective information processing. *Brain Research*, *1504*, 35–46. DOI:10.1016/j.brainres.2013.02.019

Bavelier, D., Achtman, R., Mani, M., & Föcker, J. (2012). Neural bases of selective attention in action video game players. *Vision Research*, *61*, 132–143. DOI:10.1016/j.visres.2011.08.007

Bavelier, D., Levi, D. M., Li, R. W., Dan, Y., & Hensch, T. K. (2010). Removing brakes on adult brain plasticity: From molecular to behavioral interventions. *Journal of Neuroscience*, *30*(45), 14964–14971. DOI:10.1523/JNEUROSCI.4812-10.2010

Bayliss, J. D., Vedamurthy, I., Nahum, M., Levi, D., & Bavelier, D. (2013). Lazy eye shooter: Making a game therapy for visual recovery in adult amblyopia usable. In A. Marcus (Ed.), *Design, user experience, and usability: Health, learning, playing, cultural, and cross-cultural user experience* (pp. 352–360). Berlin, Heidelberg: Springer.

Cavanagh, P., & Alvarez, G. A. (2005). Tracking multiple targets with multifocal attention. *Trends in Cognitive Sciences*, *9*(7), 349–354. DOI:10.1016/j.tics.2005.05.009

Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research*, *51*(13), 1484–1525, DOI:10.1016/j.visres.2011.04.012.

Carrasco, M. (2014). Spatial covert attention: Perceptual modulation. In Nobre K. & Kastner S. (Eds.), *The Oxford Handbook of Attention* (pp. 183–230). Oxford, UK: Oxford University Press.

Eastgate, R. M., Griffiths, G. D., Waddingham, P. E., Moody, A. D., Butler, T. K. H., Cobb, S. V., … Brown, S. M. (2005). Modified virtual reality technology for treatment of amblyopia. *Eye*, *20*(3), 370–374. DOI:10.1038/sj.eye.6701882

Feng, J., & Spence, I. (2007). Effects of Cognitive Training on Individual Differences in Attention. In D. Harris (Ed.), *Engineering Psychology and Cognitive Ergonomics: 7th International Conference* (pp. 279–287). Berlin, Heidelberg: Springer Berlin Heidelberg.

Foss, A. J. (2017). Use of video games for the treatment of amblyopia. *Current Opinion in Ophthalmology*, *28*(3), 276–281. DOI:10.1097/ICU.0000000000000358

Foss, A. J., Gregson, R. M., MacKeith, D., Herbison, N., Ash, I. M., Cobb, S. V., … Haworth, S. M. (2013). Evaluation and development of a novel binocular treatment (i-BiT) system using video clips and interactive games to improve vision in children with amblyopia ('lazy eye'): Study protocol for a randomised controlled trial. *Trials*, *14*, 145. DOI:10.1186/1745-6215-14-145

Green, C. S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature*, *423*, 534–537. DOI:10.1038/nature01647

Green, C. S., & Bavelier, D. (2006). Enumeration versus multiple object tracking: The case of action video game players. *Cognition*, *101*(1), 217–245. DOI:10.1016/j.cognition.2005.10.004

Green, C. S., & Bavelier, D. (2012). Learning, attentional control, and action video games. *Current Biology*, *22*(6), 198–206. DOI:10.1016/j.cub.2012.02.012

Guo, C. X., Babu, R. J., Black, J. M., Bobier, W. R., Lam, C. S. Y., Dai, S., … Thompson, B. (2016). Binocular treatment of amblyopia using videogames (BRAVO): Study protocol for a randomised controlled trial. *Trials*, *17*, 504. DOI:10.1186/s13063-016-1635-3

Hess, R. F., Babu, R. J., Clavagnier, S., Black, J., Bobier, W., & Thompson, B. (2014). The iPod binocular home-based treatment for amblyopia in adults: Efficacy and compliance. *Clinical and Experimental Optometry*, *97*(5), 389–398. DOI:10.1111/cxo.12192

Hess, R. F., & Thompson, B. (2015). Amblyopia and the binocular approach to its therapy. *Vision Research*, *114*, 4–16. DOI:10.1016/j.visres.2015.02.009

Hess, R. F., Thompson, B., Gole, G. and Mullen, K. T. (2009), Deficient responses from the lateral geniculate nucleus in humans with amblyopia. *European Journal of Neuroscience*, *29*(5), 1064–070. DOI:10.1111/j.1460-9568.2009.06650.x

Hickey, T. L., Spear, P. D., & Kratz, K. E. (1977), Quantitative studies of cell size in the cat's dorsal lateral geniculate nucleus following visual deprivation. *Journal of Comparative Neurology*, *172*(2), 265–281. DOI:10.1002/cne.901720206

Ho, C., Paul, P., Asirvatham, A., Cavanagh, P., Cline, R., & Giaschi, D. (2006). Abnormal spatial selection and tracking in children with amblyopia. *Vision Research*, *46*(19), 3274–3283. DOI:10.1016/j.visres.2006.03.029

Hussain, Z., Astle, A. T., Webb, B. S., & McGraw, P. V. (2014). The challenges of developing a contrast-based video game for treatment of amblyopia. *Frontiers in Psychology*, *5*, 1210 DOI:10.3389/fpsyg.2014.01210

Jeon, S. T., Maurer, D., & Lewis, T. L. (2012). The effect of video game training on the vision of adults with bilateral deprivation amblyopia. *Seeing and Perceiving*, *25*(5), 493–520. DOI:10.1163/18784763-00002391

Lerner, Y., Pianka, P., Azmon, B., Leiba, H., Stolovitch, C., Loewenstein, A., … Malach, R. (2003). Area-specific amblyopic effects in human occipitotemporal object representations. *Neuron*, *40*(5), 1023–1029. DOI:10.1016/S0896-6273(03)00720-7

Levi, D. M., Knill, D. C., & Bavelier, D. (2015). Stereopsis and amblyopia: A mini-review. *Vision Research*, *114*, 17–30. DOI:10.1016/j.visres.2015.01.002

Li, R. W., Ngo, C. V., & Levi, D. M. (2015). Relieving the attentional blink in the amblyopic brain with video games. *Scientific Reports*, *5*(1), 1–7. DOI:10.1038/srep08483

Li, J., Spiegel, D. P., Hess, R. F., Chen, Z., Chan, L. Y., Deng, D., … Thompson, B. (2015). Dichoptic training improves contrast sensitivity in adults with amblyopia. *Vision Research*, *114*, 161–172. DOI:10.1016/j.visres.2015.01.017

Maurer, D., & Hensch, T. K. (2012). Amblyopia: Background to the special issue on stroke recovery. *Developmental Psychobiology*, *54*(3), 224–238. DOI:10.1002/dev.21022

Nyquist, J. B., Lappin, J. S., Zhang, R., & Tadin, D. (2016). Perceptual training yields rapid improvements in visually impaired youth. *Scientific Reports*, *6*, 37431. DOI:10.1038/srep37431

Popple, A. V., & Levi, D. M. (2008). The attentional blink in amblyopia. *Journal of Vision*, *8*(13), 1–9. DOI:10.1167/8.13.12

Posner, M. I. (1980). Orienting of attention. *The Quarterly Journal of Experimental Psychology*, *32*(1), 3–25, DOI:10.1080/00335558008248231.

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an rsvp task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance*, *18*(3), 849–860. DOI:10.1037/0096-1523.18.3.849

Roberts, M., Cymerman, R., Smith, R. T., Kiorpes, L., & Carrasco, M. (2016). Covert spatial attention is functionally intact in amblyopic human adults. *Journal of Vision*, *16*(15), 30. DOI:10.1167/16.15.30.

Secen, J., Culham, J., Ho, C., & Giaschi, D. (2011). Neural correlates of the multiple-object tracking deficit in amblyopia. *Vision Research*, *51*(23–24), 2517–2527. DOI:10.1016/j.visres.2011.10.011

Shapiro, K. L., Arnell, K. M., & Raymond, J. E. (1997). The attentional blink. *Trends in Cognitive Science*, *1*(8), 291–296. DOI:10.1016/S1364-6613(97)01094-2

Sharma, V., Levi, D. M., & Klein, S. A. (2000). Undercounting features and missing features: Evidence for a high-level deficit in strabismic amblyopia. *Nature Neuroscience*, *3*(5), 496–501. DOI:10.1038/74872s

Spence, I., & Feng, J. (2010). Video games and spatial cognition. *Review of General Psychology*, *14*(2), 92–104. DOI:10.1037/a0019491

Tailor, V. K., Schwarzkopf, D. S., & Dahlmann-Noor, A. H. (2017). Neuroplasticity and amblyopia. *Current Opinion in Neurology*, *30*(1), 74–83. DOI:10.1097/WCO.0000000000000413

Tripathy, S. P., & Levi, D. M. (2008). On the effective number of tracked trajectories in amblyopic human vision. *Journal of Vision*, *8*(4), 1–22. DOI:10.1167/8.4.8

Vedamurthy, I., Nahum, M., Bavelier, D., & Levi, D. M. (2015). Mechanisms of recovery of visual function in adult amblyopia through a tailored action video game. *Scientific Reports*, *5*, 8482. DOI:10.1038/srep08482

Vedamurthy, I., Nahum, M., Huang, S. J., Zheng, F., Bayliss, J., Bavelier, D., & Levi, D. M. (2015). A dichoptic custom-made action video game as a treatment for adult amblyopia. *Vision Research*, *114*, 173–187. DOI:10.1016/j.visres.2015.04.008

Von Noorden, G. K., Crawford, M. L., & Levacy, R. A. (1983). The lateral geniculate nucleus in human anisometropic amblyopia. *Investigative Ophthalmology & Visual Science*, *24*(6), 788–790. Retrieved from https://iovs.arvojournals.org/article.aspx?articleid=2176853

Wallace, M. P., Stewart, C. E., Moseley, M. J., Stephens, D. A., & Fielder, A. R. (2013). Compliance with occlusion therapy for childhood amblyopia. Investigative *Opthalmology & Visual Science*, *54*, 6158–6166. DOI:10.1167/iovs.13-1