Restorative Neurology and Neuroscience xx (20xx) x–xx
DOI 10.3233/RNN-170729
IOS Press

Repetitive dynamic stereo test improved processing time in young athletes

Micha Daniel Schoemann[a,*], Matthias Lochmann[b], Jan Paulus[c] and Georg Michelson[d]
[a]*Friedrich-Alexander-University Erlangen-Nürnberg (FAU), Erlangen, Germany*
[b]*Institute of Sport Science and Sport, Friedrich-Alexander-University Erlangen-Nürnberg (FAU), Germany*
[c]*Pattern Recognition Lab, Institute of Photonic Technologies, Erlangen Graduate School of Advanced Optical Technologies (SAOT), Friedrich-Alexander-University Erlangen-Nürnberg (FAU), Germany*
[d]*Department of Ophthalmology, Interdisciplinary Center of Ophthalmic Preventive Medicine and Imaging, School of Advanced Optical Technologies, Friedrich-Alexander-University Erlangen-Nürnberg (FAU), Germany*

Abstract.
Background: Current studies revealed the importance of perceptual training for the treatment of amblyopia. To improve stereo vision on a higher level, visual tasks have to be completed within a limited time window like in repetitive visual function tests. "Processing time" as the reaction time in which the absence or presence of depth was identified correctly, is of better predictive value for perceiving the depth than the stereo threshold only.
Objective: To examine the long-term effects of repetitive dynamic testing of stereopsis on processing time.
Methods: 15 male soccer athletes (13.3 ± 3.2 years) underwent twelve sessions of a 15 minutes repetitive dynamic stereovision training over a period of six weeks, presented on a polarized 3D-TV in a four-alternative forced choice setup. We measured the response time of correct identified visual tasks of 11, 22, 44, 55, 66, 77 and 88arcsecs disparity before, after six sessions, after twelve sessions and after six month without testing. As response time is the sum of stereo processing time plus the motor reaction time, we defined the difference between the response times at 11 and 88arcsecs as "stereo processing time at 11arcsecs". A Wilcoxon Signed Rank Test was conducted between the testing sessions to evaluate significant changes in response time and stereo processing time.
Results: After six sessions the mean stereo processing time at 11arcsecs decreased significantly from 804.4 ms to 403.7 ms ($Z = -2.499$, $p = 0.012$). Six months after the last training the stereo processing time at 11arcsecs remained at the level of the last session.
Conclusion: Our results suggest that repetitive testing of stereovision is effective in improving processing time of stereoscopic tasks in young male athletes significantly long-term.

Keywords: Binocular vision, depth perception, detection/discrimination, depth, learning, plasticity, stereopsis, stereo acuity

1. Introduction

Perceptual learning is the long-term enhancement of a perceptual ability arising from perceptual experience (Lu, Hua, Huang, Zhou, & Dosher, 2011), which has been explained by the model of cortical plasticity (Polat, 2014) in the visual system based on the variation of interactions between multiple cortical areas (Gilbert, Sigman, & Crist, 2001). It obviously consists of two stages: Firstly, fast learning is accompanied by increased efficacy in intracortical connections through the activation of long-term potentiation (Rioult-Pedotti, 2000), whereas, secondly, slow learning most probably requires gene transcription and protein synthesis (Abel & Lattal, 2001). This includes the necessity of multi-stage

*Corresponding author: Micha Daniel Schoemann, Friedrich-Alexander-University Erlangen-Nürnberg (FAU), Schloßplatz 4, 91054 Erlangen, Germany. Tel.: +49 15225820360; E-mail: micha.schoemann@fau.de.

learning over many days for hippocampus-dependent memory during posttraining sleep (Ribeiro et al., 2002).

In clinical practice perceptual training is gaining more and more importance for treatment of impaired stereopsis in amblyopic or anisometric patients (Levi, 2005; Levi & Li, 2009b, 2009a; Tsirlin, Colpa, Goltz, & Wong, 2015). It could be shown that binocular mechanisms exist in amblyopia, including summation and suppression across the eyes (Hess, Thompson, & Baker, 2014). Thus a paradigm change might be at hand leading from monocular suppression to therapies that balance the information seen by the two eyes. (Hess & Thompson, 2015). Research of the past few years is increasingly changing the focus from pure monocular treatment (Campbell, Hess, Watson, & Banks, 1978) to combination therapy with the fixing eye kept open (Levi, Knill, & Bavelier, 2015) and, finally, binocular therapy based on perceptual training (Hess, 2010; Levi, 2012; Levi & Li, 2009a).

On the other hand, there are many successful attempts in the literature that have shown the influence of specific visual training on sports performance. The extent of the importance of visual skills may differ between different kinds of sports (Hammami, Behm, Chtara, Ben Othman, & Chaouachi, 2014). The reported results on the difference in stereoscopic performance between athletes and non-athletic subjects may be controversial (Boden, Rosengren, Martin, & Boden, 2009; Laby et al., 1996; Solomon, Zinn, & Vacroux, 1988), but seen as a whole, professional athletes are faster at learning complex dynamic visual tasks (Faubert, 2013). To improve stereo vision at a higher level, certain circumstances have to be given. Firstly, stereo vision can be improved best, when optimal visual acuity is guaranteed (Chang, Liu, Lee, & See, 2015; Saladin, 2005). Secondly, Lev et al. could show that, if a visual task has to be completed within a limited time frame and provides a better stream of visual information for perceptual processing, it even might improve other visual functions apart from the currently trained (Lev et al., 2014). As repetitive identification was already able to improve visual acuity, repeated testing of stereoscopic stimuli seems to be an appropriate method of training (Astle, McGraw, & Webb, 2011; Polat, 2009; Xi, Jia, Feng, Lu, & Huang, 2014).

But there are difficulties in the estimation of stereo vision. Dependent on the way of presentation the results of the measurement of stereo acuity can be very variable (Larson & Faubert, 1992). Dynamic stereopsis tests were able to reveal significant differences between groups with the same results in static stereo tests (Solomon et al., 1988). One attempt to explain poor performance in the common stereovision tests is that some subjects were misled by the wrong cue (Saladin, 2005). Elite athletes in particular often operate at suprathreshold levels, which cannot be determined by classical stereovision tests (Saladin, 2005). Consequently Larson et al. found a parameter of better predictive value for perceiving the depth in everyday life than the stereo threshold only (Larson & Faubert, 1992). Several years ago MacCracken et al. already showed that "stereo latency" decreased after repetitive presentations of static stereo tests. However, this learning effect was not retained over the next few days.

In our study we used the term "processing time" as the reaction time interval in which the absence or presence of depth was identified by the subject (Larson & Faubert, 1992). Our aim was to determine whether repetitive dynamic stereo testing with a limited time frame can induce a significant long-lasting improvement of stereo processing time in a group of young athletes with highly developed stereo acuity.

2. Materials and methods

The study was approved by the local ethical review board of the Friedrich-Alexander University of Erlangen-Nürnberg. After explanation of the nature and possible consequences, written consent was obtained from all participants and from the parents of minors before the study. All tenets of the Declaration of Helsinki have been complied with.

2.1. Subjects

25 subjects from a local amateur soccer club were examined in the context of an alternative training project for young goalkeepers. The ages ranged from 11 to 26 years, with a mean of 13.3 years and a Standard deviation of 3.2 years. All subjects were male goalkeepers that trained at least twice a week. Best corrected visual acuity of all subjects had to be equal or better than 1.0, measured by the "Freiburg Visual Acuity Test". From the 25 participants we included the data of those 15 subjects who completed all trials and whose stereo acuity was at least 11arcsecs, according to the static stereo test we described previously (Paulus, Hornegger, Schmidt, Eskofier, & Michelson, 2012). Eleven participants could be

re-examined in the follow-up testing six months after the last session.

2.2. Stimulus and input

We previously described the c-DIGITAL VISION TRAINER® as simulating realistic sports impressions for precise evaluation and training of distance stereopsis (Paulus et al., 2012). The c-DIGITAL VISION TRAINER® test provides a combined analysis of stereo acuity and recognition speed. All tests were presented on a polarized 3D-TV (Philips 55PUS7809) with a diagonal of 55inches with 60 Hz frame rate at a 4K resolution of 3840 × 1080 pixels. The test was implemented as a four-alternative forced choice (4AFC) test. The dynamic stereo test provides a moving stereoscopic stimulus on a background with the appearance of grass (Fig. 1). The visual targets consist of four spheres looking like soccer balls. Four virtual soccer balls were located in the screen plane with one, on a defined disparity difference to the other balls, appearing to be in front of the rest. In this configuration, the balls move out of the screen towards the observer by continuously enlarging, their disparities remaining constant. All the balls move with the same velocity. However, the observer perceives the leading ball always in the same depth difference to the other balls. All four balls have the same size when observed monocularly. It continuously increases during the movement to enable a realistic impression of approaching objects. However, as the 2D size of all balls is the same at the beginning of the movement and increases in the same velocity during the movement, the 2D sizes of all balls relative to each other remain the same. This is intended to avoid an identification of the leading ball by monocular size differences. Additionally to the axial movement, each ball is equally rotating around its x-axis. The subject's task is to detect the leading ball as fast as possible (Paulus et al., 2014). The disparity difference between the front ball and the other balls, defined the stereo threshold for stereo acuity, depends mainly on relative depth differences between objects rather than on their absolute distance in depth from an observer (Neri, Bridge, & Heeger, 2004).

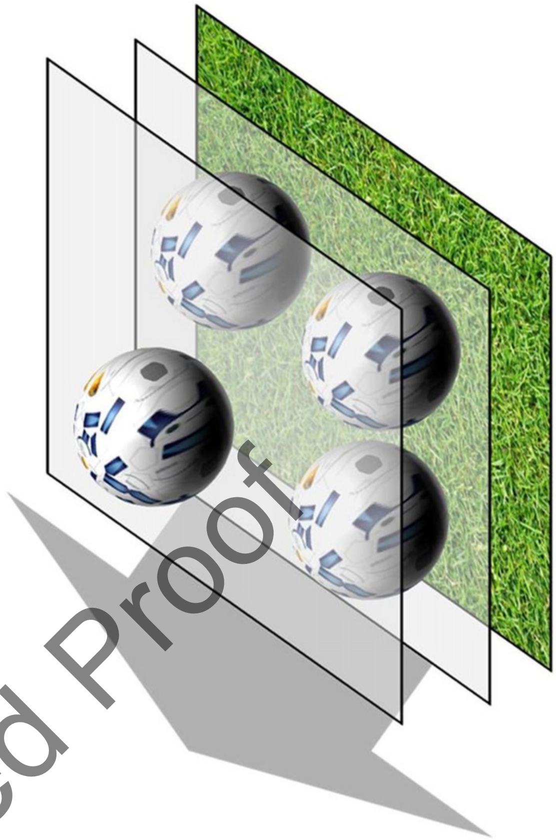

Fig. 1. Illustration in 3D of the dynamic stereoscopic stimulus: the target objects are constantly moving towards the observer.

2.3. Test procedure

The subject's task was to identify the front ball as quickly as possible. For a simple and intuitive gesture driven interface we used the Microsoft's Kinect sensor and its underlying pose estimation (Shotton et al.; Shotton, 2011). The subject selected the ball by pointing in its direction.

The timer of the CPU was automatically started on stimulus presentation and stopped as soon as the subject moved one of his hands more than 30 cm away from his shoulder to indicate the target selection via gesture control. This allowed a more reliable and precise measurement of speed than in previously described settings (Larson & Faubert, 1992). Each subject tested the training process for one session before measuring to make sure that everyone had completely understood the task.

We measured the time from the beginning of the stimulus presentation until the subject moved one of his hands more than 30 cm away from the shoulder indicating a ball selection. This time we defined as response time.

The individual improvement of the subjects were recorded and rewarded with certificates and little gifts to support attention during the training (Singer, 1982).

2.4. Performance data

The distance to the screen was 5 m. We obtained eight disparity differences ranging from 11 to 88arcsecs in 11arcsecs steps. We performed training sessions and testing sessions.

We performed twelve training sessions over 15 minutes within six weeks. One training session consisted of 400 trials leading to 4800 trials overall. Figure 2 shows a representative result of one single training session of one single subject as an output of the c-DIGITAL VISION TRAINER®.

As testing sessions we measured response times from 11 to 88arcsecs disparity difference in 11arsces steps before, after six sessions and after twelve sessions. To evaluate the long-term stability, we measured the response time six months after cessation of training. In the testing sessions each disparity consisted of 16 trails whereby the first one was not used for the estimation of performance. The first trial was intended to familiarize the subjects with the stereovision test. The predefined disparity differences were presented in randomized order. The disparity threshold was defined when at least 10 out of 16 balls with a defined disparity difference were correctly recognized. This resulted in a guessing probability for a disparity range of lower than 0.01.

The “response time” we measured is the sum of the time interval for the perception of the depth plus the time interval from perceiving the stimulus to the registration of the completely executed arm movement by the Kinect sensor. The “response time at 11arcsecs” was the time from showing the stimulus of 11arcsecs disparity difference to the successful gesture performed by moving the hand in the correct direction. The “response time at 88arcsecs” was the time from showing the stimulus of 88arcsecs disparity difference to the successful gesture performed by moving the hand in the correct direction.

The time difference of “response time” at 11 and 88arcsecs was used as a surrogate parameter for stereo processing time, acknowledging the possibility that a difference of the “response time at 88arcsecs” could arise from a change of the motor processing time. This time difference we defined as “Stereo processing time at 11arcsecs”.

We also performed a questionnaire on the subjective effect of the test in a Likert-type scale asking about the following items:

- “Do you think your estimation of distances improved during the training?”
- “Do you think your soccer performance improved during the training?”
- “Do you think the training had a benefit for visual tasks of everyday life? If yes, for which ones?”

2.5. Statistical data analysis

The response times were analyzed for each disparity difference. Only response times for correct decisions were included in calculations, to exclude the bias of faster selection when the subjects were just guessing right ball. The mean of all correct response times for one disparity difference was calculated as a representation of response speed for the respective disparity difference. As no fixation target or any gaze control was provided, the response times included eye movements, perception and execution of the hand movement.

To identify potential significant changes of “stereo processing time at 11arcsecs” a Wilcoxon Signed Rank Test was conducted between the test before, the test after six sessions, the test after twelve sessions and the test six months after the training had been finished.

A Wilcoxon Signed Rank Test of mean “response time at 11arcsecs” was conducted between every testing session in order to evaluate the effect of training duration as well as the minimum required duration.

Considering the data of the testing six months after the training had been finished, we define the retention coefficient of “stereo processing time at 11arcsecs” as

$$\frac{\text{Mean stereo processing time (retested)} - \text{Mean stereo processing time (pre} - \text{training)}}{\text{Mean stereo processing time (post} - \text{retested)} - \text{Mean stereo processing time (pre} - \text{training)} \times 100\%}$$

following Zhou et al. (2006) (Zhou et al., 2006). A retention coefficient of 100% indicates a full retention of the effects of training, while a retention coefficient of less than 100% indicates decline after cessation of the training.

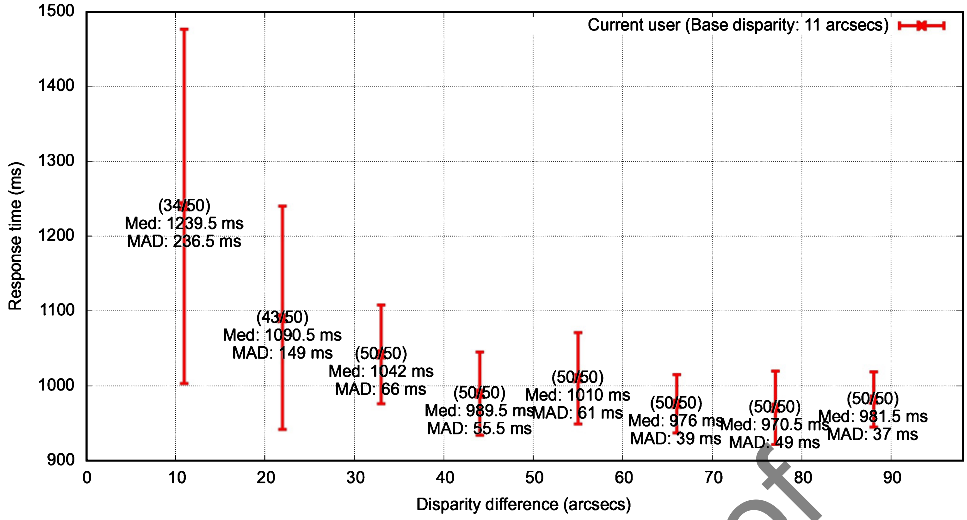

Fig. 2. Example of response times of subject in the first training session by disparity difference as measured with the c-DIGITAL VISION TRAINER® test. ("Med" = Medium response time illustrated by the red bar, "MAD" = Standard deviation of mean response time illustrated by the red bar, "(50/50)" = 50 out of 50 trials have been identified correctly by the red cross).

3. Results

3.1. Number of trials and response time

After the first 2400 trials of training we found a statistically significant decrease of "response time at 11arcsecs" from 2615 ms (SD = 1625 ms) to 1120 ms (SD = 330.0 ms) ($Z = -3.223$, $p = 0.001$). Trial 2400 to 4800 did effectuate a significant change to 1063 ms (SD = 209.5 ms) ($Z = -4.853$, $p = 0.000$).

Figure 3 displays the mean "response time at 11arcsecs" of all subjects over the time course. For the first four sessions consisting of 400 trials each the mean response time decreased significantly ($Z = -3.170$ (Session 1), $Z = -5.239$ (Session 2), $Z = -5.224$ (Session 3) and $Z = -3.611$ (Session 4), each $p < 0.005$), after the fourth session further trials no longer produced a statistically significant change of response time ($Z = -0.826$ (Session 5), $p = 0.409$).

Figure 4 displays the individual "response time at 11arcsecs" of all subjects within the first 1600 trails. Except one participant all subjects improved within the first session. Four subjects initially showed response times of less than 2000 ms.

To display the data of the first session, Fig. 5 shows the data of the improvement within the first session trial by trial to give a better resolution of the improvement during the first session.

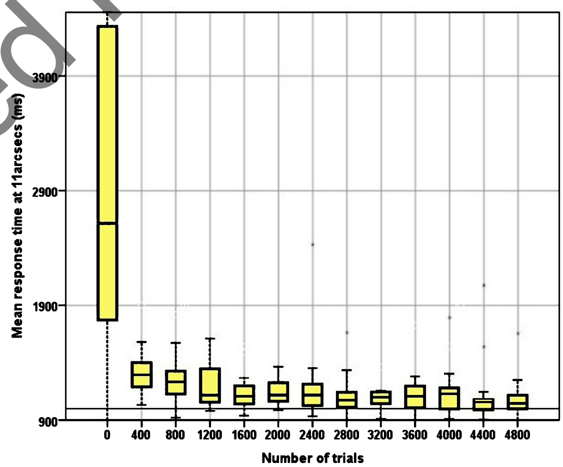

Fig. 3. Mean response time at 11arcsecs disparity of all 15 subjects by number of trials as measured with the c-DIGITAL VISION TRAINER® test.

3.2. Number of trials and stereo processing time

After the first 2400 trials of training we found a statistically significant decrease of "stereo processing time at 11arcsecs" (mean difference of "response time at 11arcsecs" and "response time at 88arcsecs") from 804.4 ms (SD = 1895 ms) to 403.7 ms (SD = 305.7 ms) ($Z = -2.499$, $p = 0.012$). Trial 2400 to 4800 effectuated a significant change to 350.7 ms (SD = 222.1 ms) ($Z = -2.442$, $p = 0.015$). After six months without training, mean "stereo processing

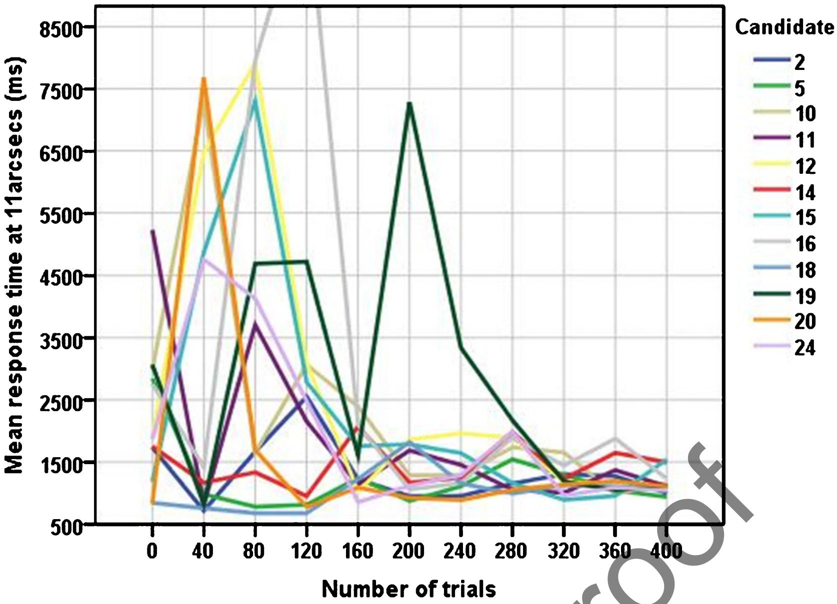

Fig. 4. Response time at 11arcsecs disparity of all 15 subjects individually by number of trials within the first training session as measured with the c-DIGITAL VISION TRAINER® test.

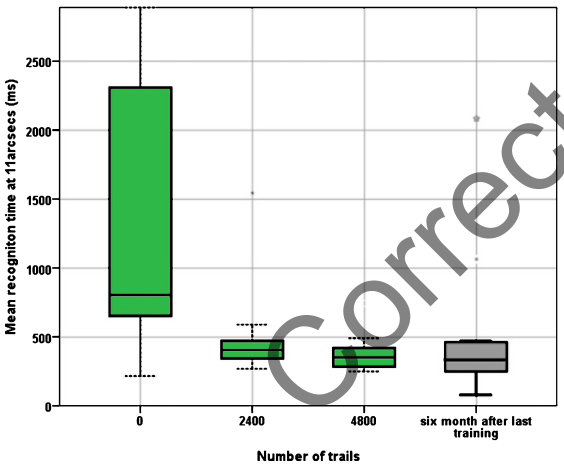

Fig. 5. Mean stereo processing time at 11arcsecs disparity difference of all 15 subjects by number of trials and six months after the last training as measured with the c-DIGITAL VISION TRAINER® test.

time at 11arcsecs" did not change significantly (334.3 ms, SD = 575.0 ms) (Z = –0.622, p = 0.534) (Fig. 6).

3.3. Retention

The retention of training effects on stereo processing time was evaluated for 11 subjects 6 months after the last trail. The mean retention coefficient was 103.6%. Thus the individual improvements were more or less fully retained within the limits of accuracy of the measurements. There was no significant difference between the group of subjects who did the test six months after the last trail and the group, who were not able to perform the final test, neither in "stereo processing time at 11arcsecs" (p = 0.345), nor in the improvement in "stereo processing time at 11arcsecs" (p = 0.715).

In the questionnaire 17 of 23 (73.9%) subjects reported a subjective improvement on the estimation of distances, 16 of 23 (69.6%) reported an improvement in global soccer performance and also a subjective improvement in daily life. 16 of 23 (69.6%) stated an additional helpful effect in the visual challenges of everyday life (e.g. traffic).

4. Discussion

In the current study, we evaluated the effect of repetitive measurement of response time at 11, 22, 33, 44, 55, 66, 77 and 88arcsecs by a forced four-choice stereoscopic test.

During the study of "response time at 11arcsecs" we found a steady improvement up to session four. This corresponds to the findings of Li et al. (Li, Provost, & Levi, 2007), which revealed that improvements in perceptional learning reached a plateau after a certain time of testing. The analysis of the first

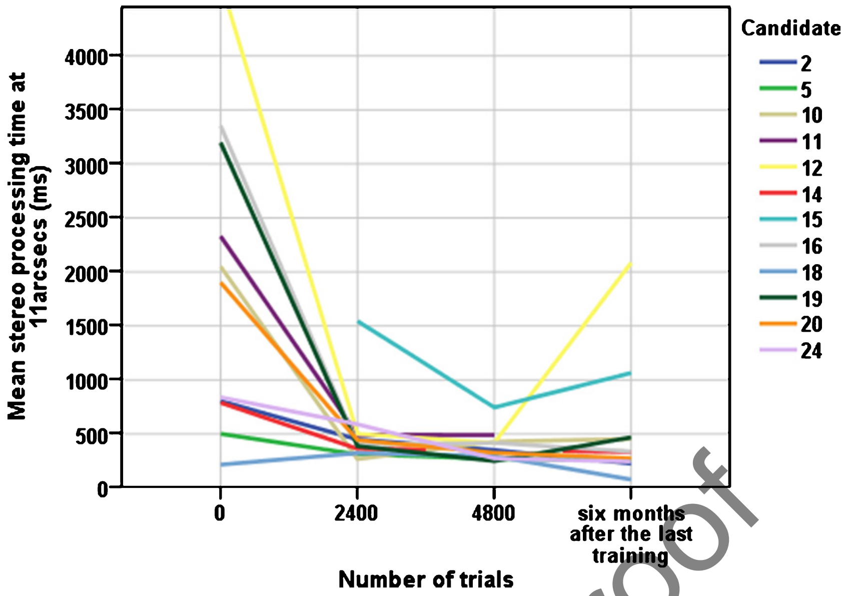

Fig. 6. Mean stereo processing time at 11arcsecs disparity difference of all 15 subject individually by number of trials and six months after the last training as measured with the c-DIGITAL VISION TRAINER® test.

sessions shows that the main part of the improvement was limited to the first 1600 trails within two weeks. This finding is supported by the results of previous studies of occlusion therapy that already reached a limit after a certain time (Keech, Ottar, & Zhang, 2002), even if the treatment was passive and monocular whereas our training was active and binocular. This might also explain the reported fact that the occlusion therapy reached its limit after 150–200 hours (Stewart, Moseley, Stephens, & Fielder, 2004). Our and the data of Tsirlin et al. suggest that adult participants can already benefit from a much shorter duration of perceptual training (Tsirlin et al., 2015). There is not much evidence in literature about minimum training duration in stereopsis training, yet. Levi & Li even assumed that there is little relationship between the duration of the training and the improvement (Levi & Li, 2009a).

Our results suggests that the observed shortening of stereo processing time is mainly contributed to fast learning through the activation of long-term potentiation (Rioult-Pedotti, 2000) and not to slow learning on the basis of gene transcription (Ribeiro et al., 2002).

By subtracting the response times of the smallest incremental disparity from the longest incremental disparity, and by assuming a constant motor component (Castel, Pratt, & Drummond, 2005; Griffith, Voloschin, Gibb, & Bailey, 1983), we estimated the stereo processing time at the smallest disparity increment. We were able to demonstrate clearly that the "stereo processing time at 11arcsecs" decreased with the number of trials.

4.1. Retention

We found that the "stereo processing time at 11arcsecs" was retained over a period of 6 months after completion of repetitive testing. This finding is controversial to a previous paper showing a decline in latency of depth perception (MacCracken & Hayes, 1976). However, it corresponds to the findings of Polat et al. and Zhou et al., who reported little deterioration in visual acuity following perceptual learning over periods of 3 to 18 months (Polat, Ma-Naim, Belkin, & Sagi, 2004; Zhou et al., 2006).

4.2. Limitations

Our viewing conditions were confined by a minimum stereo disparity of 11arcsecs and a viewing distance of 5 m. We also cannot determine whether the observation of shortened stereo processing time after training might be due to low level factors such as learning eye convergence or high level factors. Thus it remains open as to whether subjects might be able to learn to see depth faster without perceptual learning. The shortened stereo processing time could be due to oculomotor factors or other sensory factors. To check for the causes of the learning effect and to tease oculomotor factors or sensory factors apart we also plan to measure reaction and stereo processing time in different gaze directions.

By subtracting the response times of the smallest incremental disparity from the longest incremental disparity we excluded the bias of "motor reaction time". This way of calculating the "stereo processing times at 11arcsecs" is limited as we use the "response time at 88arcsecs" as base motor response time, although we are aware that the response time at 88arcsecs includes the base motor response time plus the stereo processing time at 88arcsec. Thus we underestimated "stereo processing times at 11arcsecs".

In the questionnaire we did not further investigate on the influence of the training on other categories of everyday life. The questionnaire determined the subjective improvement without considering gaming statistics. We can only say that the subjects documented a transfer of the learning effect to other visual challenges they experienced.

In summary our data suggests that repetitive tests of stereoscopic stimuli twice a week over six weeks significantly decreased the "stereo processing time at 11arcsecs" in young male athletes. These results, together with others (Su, Chen, He, & Fang, 2012), might indicate that the stereo processing time can be shortened through training. The improvement of stereo processing time as well as the observed retention after finishing the training suggests that repetitive dynamic stereovision tests could improve stereovision in young athletes with highly developed stereo acuity over at least six months.

Acknowledgments

The authors gratefully acknowledge funding of the Erlangen Graduate School of Advanced Optical Technologies (SAOT) by the German National Science Foundation (DFG) within the framework of the excellence initiative. Furthermore, the authors thank the players of the soccer club SG Quelle Fürth for participating in this study. The present work was performed in fulfillment of the requirements for obtaining the degree "Dr. med."

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