Effects of in-situ stroboscopic training on visual, visuomotor and reactive agility in youth volleyball players

Michał Zwierko [Corresp., 1], **Wojciech Jedziniak** [2], **Marek Popowczak** [1], **Andrzej Rokita** [1]

[1] Department of Team Sports Games, Wroclaw University of Health and Sport Sciences, Wroclaw, Poland

[2] Institute of Physical Culture Sciences, University of Szczecin, Szczecin, Poland

Corresponding Author: Michał Zwierko
Email address: michal.zwierko@awf.wroc.pl

Background. Stroboscopic training is based on an exercise with intermittent visual stimuli that force a greater demand on the visuomotor processing for improving performance under normal vision. While the stroboscopic effect is used as an effective tool to improve information processing in general perceptual-cognitive tasks, there is still a lack of research focused on identifying training protocols for sport-specific settings. Therefore, we aimed at assessing the effects of in-situ stroboscopic training on visual, visuomotor and reactive agility in young volleyball players. **Methods.** Fifty young volleyball athletes (26 males and 24 females; mean age, 16.5±0.6 years) participated in this study and were each divided randomly into an experimental group and a control group, who then both performed identical volleyball-specific tasks, with the experimental group under stroboscopic influence. The participants were evaluated three times using laboratory based tests for simple and complex reaction speed, sensory sensitivity and saccade dynamics; before the after the six-week-long training (short-term effect) and four weeks later (long-term effect). In addition, a field test investigated the effects of the training on reactive agility. **Results.** A significant TIME vs GROUP effect was observed for (1) simple motor time ($p = 0.020$, $\eta p^2 = 0.08$), with improvement in the stroboscopic group in the post-test and retention test ($p = 0.003$, $d = 0.42$ and $p = 0.027$, $d = 0.35$, respectively); (2) complex reaction speed ($p < 0.001$, $\eta p^2 = 0.22$), with a large post-test effect in the stroboscopic group ($p< 0.001$, $d = 0.87$) and a small effect in the non-stroboscopic group ($p = 0.010$, $d = 0.31$); (3) saccade dynamics ($p = 0.011$, $\eta p^2 = 0.09$), with post-hoc tests in the stroboscopic group not reaching significance ($p = 0.083$, $d = 0.54$); and (4) reactive agility ($p = 0.039$, $\eta p^2 = 0.07$), with a post-test improvement in the stroboscopic group ($p = 0.017$, $d = 0.49$). Neither sensory sensitivity nor simple reaction time was statistically significantly affected as a result of the training ($p > 0.05$). A significant TIME vs GENDER

effect was observed for saccadic dynamics ($p = 0.003$, $\eta p^2 = 0.226$) and reactive agility ($p = 0.004$, $\eta p^2 = 0.213$), with stronger performance gains in the females. **Conclusions.** There was a larger effectiveness from the six-week volleyball-specific training in the stroboscopic group compared to the non-stroboscopic group. The stroboscopic training resulted in significant improvements on most measures (three of five) of visual and visuomotor function with more marked enhancement in visuomotor than in sensory processing. Also, the stroboscopic intervention improved reactive agility, with more pronounced performance gains for short-term compared to the long-term changes. Gender differences in response to the stroboscopic training are inconclusive, therefore our findings do not offer a clear consensus.

Effects of in-situ stroboscopic training on visual, visuomotor and reactive agility in youth volleyball players

Michał Zwierko[1], Wojciech Jedziniak [2], Marek Popowczak[1], Andrzej Rokita[1]

[1] Department of Team Sports Games, Wroclaw University of Health and Sport Sciences, Wroclaw, Poland.
[2] Institute of Physical Culture Sciences, University of Szczecin, Szczecin, Poland

Corresponding Author:
Michał Zwierko[1]
Doctoral School, Wroclaw University of Health and Sport Sciences
al. Ignacego Jana Paderewskiego 35
51-612 Wroclaw
E-mail: michal.zwierko@awf.wroc.pl;

Abstract

Background. Stroboscopic training is based on an exercise with intermittent visual stimuli that force a greater demand on the visuomotor processing for improving performance under normal vision. While the stroboscopic effect is used as an effective tool to improve information processing in general perceptual-cognitive tasks, there is still a lack of research focused on identifying training protocols for sport-specific settings. Therefore, we aimed at assessing the effects of in-situ stroboscopic training on visual, visuomotor and reactive agility in young volleyball players.

Methods. Fifty young volleyball athletes (26 males and 24 females; mean age, 16.5±0.6 years) participated in this study and were each divided randomly into an experimental group and a control group, who then both performed identical volleyball-specific tasks, with the experimental group under stroboscopic influence. The participants were evaluated three times using laboratory based tests for simple and complex reaction speed, sensory sensitivity and saccade dynamics; before the after the six-week-long training (short-term effect) and four weeks later (long-term effect). In addition, a field test investigated the effects of the training on reactive agility.

Results. A significant TIME vs GROUP effect was observed for (1) simple motor time ($p = 0.020$, $\eta p^2 = 0.08$), with improvement in the stroboscopic group in the post-test and retention test ($p = 0.003$, $d = 0.42$ and $p = 0.027$, $d = 0.35$, respectively); (2) complex reaction speed ($p < 0.001$, $\eta p^2 = 0.22$), with a large post-test effect in the stroboscopic group ($p< 0.001$, $d = 0.87$) and a small effect in the non-stroboscopic group ($p = 0.010$, $d = 0.31$); (3) saccade dynamics ($p = 0.011$, $\eta p^2 = 0.09$), with post-hoc tests in the stroboscopic group not reaching significance ($p = 0.083$, $d = 0.54$); and (4) reactive agility ($p = 0.039$, $\eta p^2 = 0.07$), with a post-test improvement in the stroboscopic group ($p = 0.017$, $d = 0.49$). Neither sensory sensitivity nor simple reaction time was statistically significantly affected as a result of the training ($p > 0.05$). A significant TIME vs GENDER effect was observed for saccadic dynamics ($p = 0.003$, $\eta p^2 = 0.226$) and reactive agility ($p = 0.004$, $\eta p^2 = 0.213$), with stronger performance gains in the females. For the other parameters there were no significant differences ($p>0.05$) in the variability of results in response to stroboscopic intervention between genders.

Conclusions. There was a larger effectiveness from the six-week volleyball-specific training in the stroboscopic group compared to the non-stroboscopic group. The stroboscopic training resulted in significant improvements on most measures (three of five) of visual and visuomotor function with more marked enhancement in visuomotor than in sensory processing. Also, the stroboscopic intervention improved reactive agility, with more pronounced performance gains for short-term compared to the long-term changes. Gender differences in response to the stroboscopic training are inconclusive, therefore our findings do not offer a clear consensus.

Keywords: reaction time, visual training, team sports, agility, stroboscopic eyewear

Introduction

In the fast-paced scenario of a volleyball game, players need to rapidly process a considerable amount of information in order to make appropriate motor action responses. In this regard, perceptual-cognitive abilities seem to be a crucial aspect of skilled performance under time pressure. Previous studies have identified several key perceptual-cognitive functions important for skilled player performance. Specifically, compared to non-athletes or novices, experienced volleyball players have an advantage in eye movement dynamics (Fortin-Guichard et al. 2020; Piras et al. 2010), the ability to track multiple moving targets (Zhang et al. 2009),

visuomotor processing (Piras et al. 2014; Zwierko et al. 2010), and also pattern recall, anticipation, and decision making (De Waelle et al. 2021; Fortin-Guichard et al. 2020; Piras et al. 2014).

In open-skill sports, expert players have a superior ability to interact with dynamic environments in real-time (Araújo et al. 2019). Expert-novice differences in the ability to identify relevant stimuli and fast information processing have been identified extensively in team-based sports, including soccer (Klatt & Smeeton 2022), handball (Blecharz et al. 2022), baseball (Müller et al. 2017; Ranganathan & Carlton 2007), basketball (England et al. 2019; Zwierko et al. 2018), and volleyball (Fortin-Guichard et al. 2020; Trecroci et al. 2021). While it is clear that perceptual proficiency enables athletes to produce a faster and more accurate motor response, through enhanced information processing and better perception-action coupling (Farrow & Abernethy 2003; Mann et al. 2007), there is still ongoing research on improving athlete's reactive ability for specific sport environments.

Recently, stroboscopic training has been indicated as an effective tool to enhance cognitive functions and physical performance (Appelbaum & Erickson 201; Hülsdünker et al. 2021a; Hülsdünker et al. 2021b; Wilkins & Appelbaum 2020; Wilkins et al. 2018). In general, the idea of stroboscopic training is based on an exercise with intermittent visual stimuli that force a greater demand on the visuomotor processing, leading to better performance in normal vision conditions (Wilkins & Appelbaum 2020). Scientific evidence has consistently reported beneficial effects of specific stroboscopic intervention in general perceptual-cognitive and motor skills, e.g. information encoding in short-term memory (Appelbaum et al. 2012), central visual field motion sensitivity and anticipatory timing (Appelbaum et al. 2011), visuomotor reaction time (Hülsdünker et al. 2021b), coincidence-anticipation performance (Ballester et al. 2017), hand-eye coordination (Ellison et al. 2020), catching performance (Wilkins & Gray 2015), and postural control in dynamic balance tasks (Lee et al. 2022). While studies have provided valuable information about the role of stroboscopic training on generic adaptation in perceptual-cognitive and motor skill performance in controlled environments, little is known about its role in the complex fast-paced motor tasks that are more specific to open-skill sports. Here, we aim to investigate the impact of stroboscopic intervention on reactive agility, which has been identified as an essential component of performance in team sports (Sheppard et al. 2006).

Recent evidence (Hülsdünker et al. 2021a; Hülsdünker et al. 2021b) has shown in young athletes that stroboscopic training cause improvements in visuomotor reaction time, which was largely associated with visual processing. Specifically, more than 60% of the reduction in reaction time was due to the adaptations in latency of cortical potentials in brain regions for visual processing. Based on this data, it seems that training-induced changes may provide greater efficiency in visual function after training with a stroboscopic protocol. Therefore, we aimed at examining previously unexplored visual parameters following the stroboscopic training, such as: saccadic dynamics (considered as a specific mode of exploratory eye movements that are accompanied by a shift of attention to the selected object, (Kowler 2011), and visual sensitivity identified as a quantitative index of cortical arousal in relation to physical exercise (Davranche & Pichon 2005; Lambourne & Tomporowski 2010).

Also, to the authors' knowledge there are limited studies about the use of in-situ stroboscopic intervention in volleyball training. One of the studies in this area was conducted by Kroll et al. (2020), who demonstrated the effectiveness of stroboscopic training in enhancing jumping performance and its potential as an addition to plyometric training in volleyball. Given that the utilization of stroboscopic protocols in a sport-specific context is a significant advantage (Carroll et al. 2021), research in this field is necessary for a practical application in sport training.

Based on the reported research gaps, the current study aimed at investigating the effect of stroboscopic training on young volleyball players. The six-week program was based on in-situ sport-specific tasks performed either with or without stroboscopic eyewear. In line with previous studies (Appelbaum et al. 2011; Hülsdünker et al. 2021a; Hülsdünker et al. 2021b), it was hypothesized that training with the use of stroboscopic eyewear would be more effective in improving visual and visuomotor performance, and in on-field test results measuring reactive agility, in relation to the same training without the stroboscopic eyewear. The potential impact of stroboscopic training will be also analyzed in relation to gender.

Materials & Methods

Participants

To determine the minimum sample size required for this study, a power analysis was conducted using G*Power 3.1 (Heinrich Heine Universität Düsseldorf, Germany) (Faul et al. 2007). The analysis was based on an effect size of 0.25, an alpha of 0.05, and a power of 0.95 for a mixed-model ANOVA with the between-subject factor of group (stroboscopic, non-stroboscopic) and the within-subject factor of time (pre, post, retention). The power analysis indicated that a minimum of 44 participants were necessary for the desired statistical power, which is consistent with the sample size used in a similar study by Hülsdünker et al. (2021a). Initially, 58 participants were recruited for this study. Due to random factors such as injury or illness, ultimately 50 athletes participated in the study (26 males and 24 females, age range 6 –18 years, mean age ±SD 16.5 ±0.6 years). The inclusion criteria for the study were: (a) volleyball training on a regular basis, at least five days a week, and (b) participating in official volleyball federation competitions during the season. The exclusion criteria included health conditions, such as epilepsy, migraine, or injury that prevented completion of the tests. For each gender, a random selection was made into either the stroboscopic group or the non-stroboscopic group (see **Table 1** for a description of the experimental sample). All the participants, as well as their parent(s) or legal guardian(s), were informed of and consented to the testing procedures, and written informed consent was obtained for the use of the data from this research. The Research Ethics Committee of the University School of Physical Education in Wrocław reviewed and authorized the designed research protocol (No. 8/2021).

Measurements

Laboratory testing

To evaluate perceptual-cognitive functions (simple reaction speed, complex reaction speed, and sensory sensitivity), a computer-assisted Vienna Test System application (Schuhfried, Austria) was used. To this purpose, a computer (CPU 1.6GHz) with a monitor (Dell P1913, diagonal 19”, resolution 1280 × 1024 pixels, refresh rate 85 Hz) and SCHUHFRIED response panel with foot-operated keys were used. Vienna Tests System is a reliable and valid psychometric tool used previously in sports vision training intervention (Krzepota et al. 2015).

Simple reaction speed

153 To assess simple reaction speed, the S1 version of the Reaction Time test was administered.
154 Participants were required to respond to randomly generated light stimuli in the form of a yellow
155 circle appearing at different time intervals (ranging from 2.5 to 6.0 seconds) at the bottom center
156 of the screen. A total of 28 stimuli were presented during the test. To begin the test, participants
157 placed their index finger on the 'waiting key' and in response to the stimulus, the finger was
158 moved from the 'waiting key' to the 'response key'. After the response was made, the finger
159 returned to its initial position. Participants were instructed to respond to the visual stimuli as
160 quickly as possible. Two variables were calculated: simple reaction time [ms], defined as the
161 interval of time between the appearance of the stimulus and lifting the finger from the 'waiting
162 key', and simple motor time [ms], which characterizes the interval of time from lifting the
163 'waiting key' to pressing the 'response key'.

164

165 *Complex reaction speed*
166 To assess complex reaction speed, the Determination Test version S1 was used. The
167 Determination Test is a comprehensive and multifaceted reaction test that includes the
168 presentation of both visual stimuli, such as colored stimuli and auditory signals, and is used in
169 sports diagnostics (Ong 2015). The test is designed to measure the ability to tolerate reactive
170 stress, attention and complex reaction speed. Participants were to react to programmed randomly
171 generated visual stimuli (in red, yellow, white, blue, and green colors) and auditory stimuli
172 (high-pitch and low-pitch sounds) by pressing the appropriate button for the stimulus on the
173 reaction panel. Also, white lights which appeared on a black background on the screen required
174 pressing one of the two reaction pedals with a foot. The visual stimuli randomly appear in
175 different locations on the screen. The rate at which the stimuli are presented was based on the
176 participant's pace of work. The exercise length was approximately 6 minutes, including the
177 practice phase. An analysis of the uncorrected total complex reaction speed [ms] was conducted.
178 Additionally, incorrect responses in the complex task were monitored.

179

180 *Sensory sensitivity*
181 The flicker-fusion frequency test is a widely used and objective measure of central nervous
182 system function capacity, including cortical arousal and visual sensory sensitivity threshold
183 (Davranche & Pichon 2005; Fuentes et al. 2018; Mankowska et al. 2021). In this study the

Flicker Frequency test was used to calculate the sensory sensitivity threshold. The test was performed under stable conditions by placing a light source in a darkened tube with backlighting background and held up to the participant's eyes. Inside the tube, a red point was placed in the center of vision. Initially, the participant recognized the light as steady (non-flickering), then the frequency of the red point gradually decreased until the subjective sensation of flickering. The participant should recognize the frequency change of the light source (steady to flickering) by pressing the button. The mean value of the measurements taken during the decreasing mode corresponded to the frequency [Hz] at which the light appeared to transition from a constant to a flickering state, as perceived subjectively. The decision to use only the descending series, instead of alternating descending and ascending, which is a more common method to avoid anticipation, was made due to time constraints related to the study procedure (Balestra et al. 2018).

Saccade dynamics

To initiate a saccadic response, a free-viewing visual search activity was conducted, without any design specific to sports, where participants were instructed to identify a target (a red letter 'E') from a field of 47 distractors, including an inverted red letter 'E' ('Ǝ'), a red letter 'F', and a blue letter 'E'. (Zwierko et al. 2019). Visual stimuli were displayed on a 55-inch television monitor (LG, 55UK6470, Korea) at a distance of 1 m. Participants completed a total of 16 trials, with half of them being target-present trials and the other half being target-absent trials, and which were displayed in a random order. Participants were not informed about the type of trial they were in or the location of the target, ensuring an unbiased outcome. Participants were instructed to use one button to confirm the detection of the target (target-present trials) and another button to indicate the absence of the target (target-absent trials) as quickly as possible. During the visual search task, the saccadic movements of the eyes were recorded and analyzed. The average saccade velocity [°/s] was used to evaluate the saccade dynamics. Binocular gaze data was collected at a rate of 60 Hz (SMI ETG 2w, Germany) using a portable eye-tracking system while participants performed the visual search task. A standard one-point calibration procedure was conducted binocularly, and the gaze data was subsequently analyzed using SMI BeGaze 3.5.101 software.

Field test

Reactive agility

Following the testing procedure by Popowczak et al. (2020), a five-repetition shuttle run to test gates was conducted using a Fusion Smart Speed System (Fusion Sport, Coopers Plains, QLD, Australia). The system included an RFID reader to identify the athlete's tag, electronic gates with a photocell, an infrared transmitter, and light reflector, a smart jump mat integrated with a photocell, and computer software. The timing of movement during repeated stop-and-go directional adjustments in response to a random light signal at the gate was measured. Each participant performed five runs from the beginning mat to each of the designated gates (each 1 m long and positioned between photocells with reflectors). The distance from the mat to the gate was 4.5 meters. Prior to beginning the measurements, the participants underwent a standardized warm-up procedure of 15 minutes. Each participant performed the test twice with a 3-minute rest period interval. The shortest run time [s] was used for the analysis. **Figure 1** presents a schematic of the reactive agility test.

Experimental procedure

The experiment involved a six-week training period. The experiment was performed three times per week during the initial part of regular trainings. The pre-tests, post-tests and four-week retention tests included both a laboratory test (perceptual-cognitive function) and a field test (reactive agility). The total duration of the testing session for one person did not exceed 60 minutes, with the experimental time for the laboratory sub-tests approximately 40 minutes, and for the field test 20 minutes (including warm-up). To minimize potential bias and ensure that the observed effects were truly due to the stroboscopic protocol, and also for logistical reasons, the participants were divided into four groups: a female stroboscopic group, a male stroboscopic group, a female non-stroboscopic group, and a male non-stroboscopic group. Each group was tested on a separate day. Each testing session took place under the same conditions, starting at 9am. The participants were familiarized with the tests (lab and field) prior to data acquisition using familiarization sessions to avoid any potential learning effects. Furthermore, a standard procedure, including an instruction and practice phase, was carried out in the Vienna Test System prior to each measurement. A method of randomizing the order of tests was used to control for potential order effects. Both, the stroboscopic and non-stroboscopic groups completed identical sport-specific exercises, under either stroboscopic or normal visual conditions,

respectively. Each group trained on a separate court. Three volleyball-specific training protocols were undertaken. Protocol I 'wall passing drills' consisted of 3 tasks with the ball, including forms of reaction time exercise (e.g. visual search, time pressure, second balls). Protocol II 'partner passing drills' consisted of 5 tasks in the frontal position, including forms of reaction time exercise by using external light stimuli, tennis balls, or time pressure. Protocol III 'passing rotation drill' consisted of 2 forms of passing (overhead and forearm passes) with changes of direction by forced time pressure. **Figure 2** presents a graphical illustration of the study protocols, along with examples of the exercises. Protocols lasted 25 and 30 minutes. During the training period, the experimental group wore stroboscopic eyewear (Senaptec Strobe, Beaverton, USA) with both lenses strobing. The eyewear was programmed and controlled via bluetooth using the Senaptec Strobe App installed on a smartphone. Following Hülsdünker et al. (2021a), stroboscopic protocols were restricted to 2.5 minutes with a 2.5-minute break interval. The flicker speed of the stroboscopic glasses was modulated for frequency (Hz) and duty cycle (%) (proportion of time the strobe light is on compared to the time it is off) to avoid adaptation effects, with the task difficulty increasing gradually (week 1: 15 Hz, 50%; week 2: 13 Hz, 50%; week 3: 11 Hz, 50%; week 4: 10 Hz, 50%; week 5: 9 Hz, 60%; week 6: 9 Hz, 70%).

Statistical analyses

Descriptive statistics were presented as means and standard deviations. Normality of the data was examined using a Shapiro-Wilk test, and the homogeneity of variances was confirmed using a Levene test ($p > 0.05$). A mixed model ANOVA was performed, with inter-subject factor GROUP (stroboscopic, non-stroboscopic) and the intra-subject factor TIME (pre, post, retention). To investigate gender differences in response to the stroboscopic training, another mixed-model ANOVA was conducted with the inter-subject factor GROUP (female vs. male) and intra-subject factor TIME (pre, post, retention). Post-hoc comparisons were adjusted using the Holm-Bonferroni procedure, and statistical significance was set at $p < 0.05$. The magnitude of the differences (effect sizes) was reported using Cohen's d and partial eta squared (ηp^2) for t- and F-tests, respectively. The criteria for interpreting the magnitude of the effect sizes were: small (0.2), medium (0.5), and large (0.8) for the Cohen d and small (0.01), medium (0.06), and large (0.14) for partial eta squared (Cohen 1988). JASP statistical software (version 16.1) was used for all analyses.

Results

The control analyses revealed no differences between the groups in anthropometric measures, gender, average training time per week, and training exposure time (as shown in **Table 1**). Pre-test performance scores between the stroboscopic and non-stroboscopic groups met the criteria for comparability in the control analysis, as all p-values were not significant ($p > 0.05$) for the following measures: simple motor time $p = 0.761$, simple reaction time $p = 0.842$, complex reaction speed $p = 0.351$, sensory sensitivity $p = 0.054$, saccade dynamics $p = 0.055$, reactive agility $p = 0.197$.

We used the mixed model ANOVA (main effects of TIME and GROUP) to analyze the variability of the perceptual-motor test results of the groups using stroboscopic glasses and without. The descriptive statistics of the sample in pre, post, and retention conditions for stroboscopic and non-stroboscopic groups are presented in **Table 2**. The interactions between the two-factor variables (TIME x GROUP) are displayed in **Figure 3**.

Simple reaction speed

The ANOVA on the motor time component of the simple reaction speed test revealed a significant main effect for TIME ($F_{2,96} = 4.59$, $p = 0.013$, $\eta p^2 = 0.09$) and no effect for GROUP ($F_{1,48} = 0.38$, $p = 0.542$, $\eta p^2 = 0.01$). Further, an interaction between the factors TIME and GROUP ($F_{2,96} = 4.06$, $p = 0.020$, $\eta p^2 = 0.08$) was observed. In the stroboscopic group, post-hoc tests showed significant differences between the pre-test and post-test (133.40 ± 36.75 vs 118.80 ± 37.39 ms, $p = 0.003$, $d = 0.42$) as well as between the pre-test and retention test (133.40 ± 36.75 ms vs 121.20 ± 40.49 ms, $p = 0.027$, $d = 0.35$), indicating a significantly faster motor time dependent on the stroboscopic training. The reaction time showed no significant main effect of TIME ($F_{2,96} = 1.61$, $p = 0.206$, $\eta p^2 = 0.03$), nor of GROUP ($F_{1,48} = 0.14$, $p = 0.709$, $\eta p^2 < 0.01$) nor interaction terms TIME x GROUP ($F_{2,96} = 0.96$, $p = 0.386$, $\eta p^2 = 0.02$).

Complex reaction speed

Regarding complex reaction speed, we observed a statistically significant effect of TIME ($F_{2,96} = 81.54$, $p < 0.001$, $\eta p^2 = 0.63$) and the interaction TIME x GROUP ($F_{2,96} = 13.21$, $p < 0.001$, $\eta p^2 = 0.22$), however, the inter-subject effect - GROUP - was insignificant ($F_{1,48} = 0.21$, $p = 0.649$, $\eta p^2 < 0.01$). Post-hoc analysis showed that both groups, stroboscopic and non-stroboscopic, achieved

better results ($p < 0.05$) in the post-test and retention test compared to the pre-test, and the stroboscopic training yielded a higher magnitude of effect for the compared tests. In particular, pre-test vs post-test differences for the stroboscopic group showed a large effect (737.20 ± 62.48 ms vs 674.40 ± 61.58 ms, $p < 0.001$, $d = 0.87$) and small effect for the non-stroboscopic group (719.60 ± 69.49ms vs 697.20 ± 77.81 ms, $p = 0.010$, $d = 0.31$). Similarly, the pre-test vs retention test differences with a large effect were observed in the stroboscopic group (737.20 ± 62.49 ms vs 662.80 ± 81.27 ms, $p < 0.001$, $d = 1.03$) and differences with small effect for the non-stroboscopic group (719.60 ± 69.49 ms vs 684.80 ± 78.91ms, $p < 0.001$, $d = 0.48$). The control analysis of complex reaction incorrect responses showed no significant main effect for TIME ($F_{2,96} = 0.91$, $p = 0.405$, $\eta p^2 = 0.02$) or GROUP ($F_{1,48} = 1.99$, $p = 0.164$, $\eta p^2 = 0.04$) factors. The interaction between the factors also had no significant effect ($F_{2,96} = 1.31$, $p = 0.276$, $\eta p^2 = 0.03$).

Sensory sensitivity

The analyses of sensory sensitivity (flicker frequency) did not reveal a significant main effect either for TIME ($F_{2,96} = 1.34$, $p = 0.267$, $\eta p^2 = 0.03$) or for GROUP ($F_{1,48} = 1.68$, $p = 0.201$, $\eta p^2 = 0.03$) factors. The interaction between factors did not exert significant effects ($F_{2,96} = 1.88$, $p = 0.158$, $\eta p^2 = 0.04$).

Saccade dynamics

Regarding saccade dynamics, the analyses revealed a significant effect of TIME ($F_{2,96} = 5.23$, $p = 0.007$, $\eta p^2 = 0.098$) and the interaction TIME x GROUP ($F_{2,96} = 4.73$, $p = 0.011$, $\eta p^2 = 0.09$). The factor GROUP did not reach statistical significance ($F_{1,48} = 0.43$, $p = 0.514$, $\eta p^2 = 0.01$). Post-hoc analysis in the stroboscopic group showed a trend toward significance when comparing the pre-test vs post-test results (94.30 ± 9.73°/s vs 99.25 ± 9.08°/s, $p = 0.083$, $d = 0.54$) and significance when comparing pre-test vs retention test results (94.30 ± 9.73°/s vs 101.38 ± 6.89°/s, $p = 0.002$, $d = 0.77$).

Reactive agility

The analyses of reactive agility revealed a significant main effect of TIME ($F_{2,96} = 8.24$, $p < 0.001$, $\eta p^2 = 0.15$) and the interaction TIME x GROUP ($F_{2,96} = 3.35$, $p = 0.039$, $\eta p^2 = 0.07$). The

factor GROUP was not significant ($F_{1,48} = 2.41$, $p = 0.127$, $\eta p^2 = 0.05$). In the stroboscopic group post hoc tests showed a statistically significant difference between the pre-test and post-test results (18.18 ± 1.23 s vs 17.62 ± 0.88 s, $p = 0.017$, $d = 0.49$), whereas in the non-stroboscopic group a significant difference between the pre-test and retention test results was observed (18.61 ± 1.09 s vs 18.04 ± 1.15 s, $p = 0.014$, $d = 0.50$).

Gender differences in response to stroboscopic training

Table 3 presents the differences in the test results between male and female players within the stroboscopic group over time of the experimental procedure. A significant TIME vs GENDER effect was observed for saccadic dynamics ($F_{2,46} = 6.72$, $p = 0.003$, $\eta p^2 = 0.23$) and reactive agility ($F_{2,46} = 6.21$, $p = 0.004$, $\eta p^2 = 0.21$). Post-hoc analysis indicated that in both cases, a significant improvement in post-test results compared to pre-test results occurred in the female group (95.65 ± 8.61°/s vs 87.08 ± 5.18 °/s, $p = 0.018$, $d = 1.14$ for saccadic dynamics and 18.26 ± 0.64 s vs 19.23 s, $p < 0.001$, $d = 1.46$ for reactive agility, respectively), with no significant changes in the male group ($p > 0.05$). No significant gender differences ($p > 0.05$) were found in the course of variability of other test results.

Discussion

Our study evaluated the effects of stroboscopic intervention on visual, visuomotor and reactive agility in youth volleyball players. The results indicated that stroboscopic training were more effective than regular training, with the stroboscopic group showing significant short and long-term improvements in simple motor reaction time and saccade velocity, as well as larger gains in complex reaction speed and reactive agility (in the short-term). Additionally, gender differences in response to the stroboscopic intervention were identified in two out of six variables.

Our findings add further support to the suggestions (Carroll et al. 2021; Wilkins & Appelbaum 2020) that stroboscopic training may be an effective tool for improving visual and visuomotor abilities in sports training. Previous behaviors and neurophysiological evidence (Hülsdünker et al. 2021a; Hülsdünker et al. 2021b) showed that visuomotor reaction times after stroboscopic protocols in young elite badminton athletes were largely associated with visual processing rather than motor processes. Similarly, Poltavski et al. (2021) used

electrophysiological indexes of EEG and visual evoked potentials to monitor visual training effects and progress in the performance of youth ice hockey players. Training-induced changes in the electrophysiological indexes reflected greater efficiency in visual information processing and cognitive resource allocation following visual training with a stroboscopic protocol. However, the present study results cannot fully confirm the cited data. The laboratory parameters analyzed in our study, i.e. a visual sensory sensitivity measured by flicker frequency and simple reaction time, did not show significant variations after the reactive training in either the stroboscopic or non-stroboscopic group. On one hand, volleyball is a very visuomotor-demanding sport and may yield beneficial neuroadaptation to visual sensory processing in earlier stages of sports training. In a study using electrophysiological recordings (visual evoked potentials, VEP) in young athletes practicing volleyball for 2 years, Zwierko et al. (2014) observed a decrease in VEP latencies (P100 and N75), suggesting that the effects of regular sports training cause improvements in the sensory stage of information processing. On the other hand, it is also possible that the maturation of the visual system may influence training effects in different ways between athletes aged 13 (Hülsdünker et al. 2021b) and 16-18 (current study). Following Kovács et al. (1999) the maturation of the visual system is not homogeneous, and the development in visual spatial integration may extend between 5 and 14 years. That is why stroboscopic training may bring more noticeable effects in younger athletes. It is also possible that the sensory processing measurement used in this study (reaction time to a yellow light appearing on a computer screen, flashing light in a sensory sensitivity test) primarily activated processing in the ventral visual stream, which is responsible for processing visual information such as object recognition and color perception (Ungerleider & Mishkin 1982), while the environment of the volleyball players mainly requires the use of the dorsal visual stream, which processes more coarse visual information such as motion, depth and spatial location. The results indicate that athletes required to quickly respond to moving stimuli rely more on their dorsal stream (Sasada et al. 2015). However, research suggests that there is an interaction between the dorsal and ventral pathways in action contexts (van Polanen & Davare 2015), so stroboscopic excitation of the dorsal pathway may influence the ventral pathway. It is important to note that this is just a possible explanation and that further research would be needed to determine the specific mechanisms behind the observed effects.

It appears that stroboscopic protocols may have specific effects on certain types of tasks, as demonstrated in our study, where it improved simple motor time (the speed of a simple reaction involving hand movement) in the stroboscopic group but not in the non-stroboscopic group. The adaptation to stroboscopic training used in sport-specific exercises, by better processing and integrating visual information for efficient movement execution, led to improved coordination and an increase in movement speed. This aligns with previous studies, which have found that stroboscopic protocols are effective in enhancing eye-hand coordination in dynamic and complex coordination tasks (Ellison et al. 2020; Jones et al. 2016).

This study gives partly supporting evidence to the claim that stroboscopic protocols improve the speed of cognitive and information processes created by the action of multiple stimuli on the player sensory system. We observed a significant effect of the 'TIME' factor in the complex reaction speed, which suggests that both groups improved their reaction speed in complex tasks, with more pronounced gains in the stroboscopic group. The main focus of the protocols (especially protocol 2) was to perform specific volleyball exercises that involved complex reaction tasks (e.g. as shown in the Figure 2b). It is also possible that the results of the complex reaction tests may have been influenced by a learning effect, despite the participants having prior familiarity with the tests (both in the lab and field). This is an issue that has been observed in previous studies using a stroboscopic protocol (Wilkins et al., 2018). A number of previous studies have shown that the stroboscopic training leads to improvements in some aspects of visual cognition, in particular central visual field motion sensitivity and transient attention abilities (Appelbaum et al. 2011), some aspects of visual memory (Appelbaum et al. 2012), anticipatory timing (Ballester et al. 2017; Smith & Mitroff 2012) and Go/ No-Go reaction time (Appelbaum et al. 2016). There is also some evidence which does not confirm the positive effect of stroboscopic training on visual and perceptual-cognitive skills in elite athletes (Wilkins et al. 2018). It is possible that these conflicting results may be caused by differences in sporting experience and individual adaptability to stroboscopic conditions.

To our best knowledge, this is the first study where the positive impact of stroboscopic training on saccadic dynamics was reported. In stroboscopic conditions, a player is forced to utilize the limited visual samples, which may cause increased efficiency in the oculomotor system. In consequence, the temporal integration of information during stroboscopic protocols becomes more efficient (Wilkins & Appelbaum 2020), leading to a saccadic dynamics advantage

later. This finding corresponds to the study results by Poltavski et al. (2021), who observed that training of information processing skills based on visuomotor integration and information processing skills (visual software training) in ice hockey players, indirectly trained their oculomotor system (eye quickness variables, i.e. near-far quickness and target capture tasks). It should be noted that in the current study the baseline level between the stroboscopic and non-stroboscopic groups was close to achieving significance (p=0.055), which may to some extent affect the performance gains in the stroboscopic group being attributed to a lower starting level. The issue of oculomotor processes when performing tasks with a repeated interruption of visual input is worth further investigation. Future research should try to evaluate the eye movements that lead to the successful tracking of moving objects in stroboscopic conditions.

Reactive agility improvements in the post (stroboscopic group) and retention test (non-stroboscopic group) were further observed in the field test; however, final training effects did not differ between groups. While both groups showed improvement in reactive agility, the study results indicate a clear positive impact of stroboscopic intervention on reactive agility. However, it is important to note that reactive agility is also closely associated with motor and biomechanical components, such as running speed and technique, balance, strength and muscle power of the lower limbs (Condello et al. 2016; Freitas et al. 2022; Koźlenia et al. 2020; Spiteri et al. 2015; Spiteri et al. 2014). It appears that these observations support the idea that the gains seen in the present study, apart from the perceptual-cognitive factor, may be mainly linked to improvements in strength, power, or other factors, as similar findings have been observed in previous research on reactive agility in male and female volleyball players. In particular, our own previous studies (Zwierko et al. 2022) have found that factors such as lower body explosive strength, complex reaction time, selective attention, and sensory sensitivity play significant roles in determining reactive agility, with adjusted coefficients of determination (R^2) of 23.6% (explosive strength and complex reaction time) and 34.5% (explosive strength, selective attention, and sensory sensitivity). Furthermore, other studies (Horníková et al. 2021) have found that perceptual-cognitive factors contribute to 23.6% of determining reactive agility in team sport players. The contribution of perceptual-cognitive factors in reactive agility seems to be significant.

We found significant gender differences in relation to test result variability only for two of the six analyzed parameters, i.e. saccade dynamics and reactive agility, when the females

460 received improvements with large effect sizes, while the males did not. It is possible that the
461 stronger performance gains in the female group may be attributable to a lower baseline
462 performance level (pre-test value in Table 3). Our previous study (Zwierko et al. 2022) on a
463 cohort of 135 participants indicated that male volleyball players highly outperformed female
464 volleyball players in reactive agility test and saccade dynamics, whereas, perceptual and
465 cognitive factors (selective attention, simple reaction speed, complex reaction speed, sensory
466 sensitivity) presented non-significant or small to moderate differences in relation to gender.
467 Shaqiri et al. (2018) reported that the gender-related differences in visual and perceptual function
468 are heterogeneous. Using fifteen different visual tasks, they found that males had significantly
469 better performances than females in simple reaction time, visual acuity, visual backward
470 masking, motion direction detection, biological motion, and the Ponzo illusion. In our view, the
471 observed gender differences in response to stroboscopic intervention are not straightforward or
472 easy to interpret, as there is no clear consensus in previous research. It appears that certain types
473 of tasks are more impacted by stroboscopic training than others. The effects may be specific to
474 the task being performed and may also vary based on gender. In a future study we will try to
475 identify the best parameter or parameter combination to distinguish responders from non-
476 responders in response to stroboscopic intervention, and gender will be considered an
477 independent variable.

478 The present study provides novel insights into the relationship between stroboscopic
479 training and visual and visuomotor performance in young volleyball players. However, this study
480 is not free of limitations. First, in our study, there is a lack of specific volleyball skill tests that
481 should be designed to transfer standardized laboratory tasks (near transfer) to more sport-specific
482 conditions (far transfer). Achieving far transfer after different kinds of perceptual and cognitive
483 training is so far poorly investigated in research studies (Fleddermann et al. 2019; Palmer et al.
484 2022; Sala et al. 2019). It would be interesting for a future study to evaluate the effects of
485 stroboscopic training on specific sporting performance. Second, the experimental sample was
486 limited to young athletes, and it has recently been reported that stroboscopic vision may be used
487 to stimulate larger training effects in more skilled players (Beavan et al. 2021). Therefore, the
488 generalizability of the present results to other athlete age categories needs to be tested in future
489 studies. Third, the findings of this study should be evaluated in the context of the limitations in
490 the study design. In traditional controlled designs, such as drug trials, it is possible to establish a

placebo protocol to balance the experience, expectancy and motivation of the participants. However, in the case of stroboscopic protocols, it is not possible to create a placebo or conceal the experience of the stroboscope from the participants (Ellison et al. 2020; Wilkins & Appelbaum 2020). To minimize potential bias, we divided the participants into four separate groups and trained them on different courts. Additionally, the training protocols were conducted by one instructor to ensure consistency. Our study design did not include measures of motivation and expectancy, which can be considered a limitation of the study.

Conclusion

The present results demonstrate a significantly greater effectiveness of six-week volleyball-specific training in the group using stroboscopic eyewear compared to those who trained using regular methods. Stroboscopic intervention resulted in significant improvements in most measures (three of five) of visual and visuomotor function, with greater enhancement in visuomotor than in sensory processing. Additionally, the stroboscopic training improved reactive agility, with more pronounced performance gains in short-term changes compared to long-term changes. Gender differences in response to the stroboscopic training are inconclusive, and our findings do not offer a clear consensus on this issue.

References

Appelbaum LG, Cain MS, Schroeder JE, Darling EF, and Mitroff SR. 2012. Stroboscopic visual training improves information encoding in short-term memory. *Atten Percept Psychophys* 74:1681-1691. 10.3758/s13414-012-0344-6

Appelbaum LG, Lu Y, Khanna R, and Detwiler K. 2016. The Effects of Sports Vision Training on Sensorimotor Abilities in Collegiate Softball Athletes. *Athletic Training & Sports Health Care* 8:154-163. 10.3928/19425864-20160314-01

Appelbaum LG, Schroeder JE, Cain MS, and Mitroff SR. 2011. Improved Visual Cognition through Stroboscopic Training. *Front Psychol* 2:276. 10.3389/fpsyg.2011.00276

Araújo D, Hristovski R, Seifert L, Carvalho J, and Davids K. 2019. Ecological cognition: expert decision-making behaviour in sport. *International Review of Sport and Exercise Psychology* 12:1-25. 10.1080/1750984X.2017.1349826

Balestra C, Machado ML, Theunissen S, Balestra A, Cialoni D, Clot C, Besnard S, Kammacher L, Delzenne J, Germonpre P, and Lafere P. 2018. Critical Flicker Fusion Frequency: A Marker of Cerebral Arousal During Modified Gravitational Conditions Related to Parabolic Flights. *Front Physiol* 9:1403. 10.3389/fphys.2018.01403

Ballester R, Huertas F, Uji M, and Bennett SJ. 2017. Stroboscopic vision and sustained attention during coincidence-anticipation. *Sci Rep* 7:17898. 10.1038/s41598-017-18092-5

Beavan A, Hanke L, Spielmann J, Skorski S, Mayer J, Meyer T, and Fransen J. 2021. The effect of stroboscopic vision on performance in a football specific assessment. *Sci Med Footb* 5:317-322. 10.1080/24733938.2020.1862420

Blecharz J, Wrześniewski K, Siekańska M, Ambroży T, and Spieszny M. 2022. Cognitive Factors in Elite Handball: Do Players' Positions Determine Their Cognitive Processes? *J Hum Kinet* 82:213-221. 10.2478/hukin-2022-0063

Carroll W, Fuller S, Lawrence J, Osborne S, Stallcup R, Burch R, Freeman C, Chander H, Strawderman L, Crane C, Younger T, Duvall A, Mock S, Petway A, Burgos B, and Piroli A. 2021. Stroboscopic Visual Training for Coaching Practitioners: A Comprehensive Literature Review *International Journal of Kinesiology and Sports Science* 9:49-59. 10.7575/aiac.ijkss.v.9n.4p.49

Cohen J. 1988. *Statistical Power Analysis for the Behavioral Sciences*. New York, NY: Routledge Academic.

Condello G, Kernozek TW, Tessitore A, and Foster C. 2016. Biomechanical Analysis of a Change-of-Direction Task in Collegiate Soccer Players. *Int J Sports Physiol Perform* 11:96-101. 10.1123/ijspp.2014-0458

Davranche K, and Pichon A. 2005. Critical Flicker Frequency Threshold Increment after an Exhausting Exercise. *Journal of Sport and Exercise Psychology* 27:515-520. 10.1123/jsep.27.4.515

De Waelle S, Warlop G, Lenoir M, Bennett SJ, and Deconinck FJA. 2021. The development of perceptual-cognitive skills in youth volleyball players. *J Sports Sci* 39:1911-1925. 10.1080/02640414.2021.1907903

Ellison P, Jones C, Sparks SA, Murphy PN, Page RM, Carnegie E, and Marchant DC. 2020. The effect of stroboscopic visual training on eye–hand coordination. *Sport Sciences for Health*:1-10. 10.1007/s11332-019-00615-4

England A, Brusseau T, Burns R, Koester D, Newton M, and Thiese M. 2019. The Cognitive Structure of the Basketball Free Throw in Adolescent Physical Education Students. *Motor Control*:1-13. 10.1123/mc.2018-0035

Farrow D, and Abernethy B. 2003. Do expertise and the degree of perception-action coupling affect natural anticipatory performance? *Perception* 32:1127-1139. 10.1068/p3323

Faul F, Erdfelder E, Lang AG, and Buchner A. 2007. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods* 39:175-191.

Fleddermann MT, Heppe H, and Zentgraf K. 2019. Off-Court Generic Perceptual-Cognitive Training in Elite Volleyball Athletes: Task-Specific Effects and Levels of Transfer. *Front Psychol* 10:1599. 10.3389/fpsyg.2019.01599

Fortin-Guichard D, Laflamme V, Julien A-S, Trottier C, and Grondin S. 2020. Decision-making and dynamics of eye movements in volleyball experts. *Scientific Reports* 10:17288. 10.1038/s41598-020-74487-x

Freitas TT, Pereira LA, Alcaraz PE, Comyns TM, Azevedo P, and Loturco I. 2022. Change-of-Direction Ability, Linear Sprint Speed, and Sprint Momentum in Elite Female Athletes: Differences Between Three Different Team Sports. *J Strength Cond Res* 36:262-267. 10.1519/jsc.0000000000003857

570 Fuentes JP, Villafaina S, Collado-Mateo D, de la Vega R, Gusi N, and Clemente-Suárez VJ.
571 2018. Use of Biotechnological Devices in the Quantification of Psychophysiological
572 Workload of Professional Chess Players. *J Med Syst* 42:40. 10.1007/s10916-018-0890-0
573 Horníková H, Jeleň M, and Zemková E. 2021. Determinants of Reactive Agility in Tests with
574 Different Demands on Sensory and Motor Components in Handball Players. *Applied*
575 *Sciences* 11:6531. 10.3390/app11146531
576 Hülsdünker T, Gunasekara N, and Mierau A. 2021a. Short- and Long-Term Stroboscopic
577 Training Effects on Visuomotor Performance in Elite Youth Sports. Part 1: Reaction and
578 Behavior. *Med Sci Sports Exerc* 53:960-972. 10.1249/mss.0000000000002541
579 Hülsdünker T, Gunasekara N, and Mierau A. 2021b. Short- and Long-Term Stroboscopic
580 Training Effects on Visuomotor Performance in Elite Youth Sports. Part 2: Brain-
581 Behavior Mechanisms. *Med Sci Sports Exerc* 53:973-985.
582 10.1249/mss.0000000000002543
583 Jones C, Carnegie E, and Ellison P. 2016. The effect of stroboscopic vision training on eye-hand
584 coordination. British Psychological Society (BPS) Division of Sport & Exercise Science
585 Conference.
586 Klatt S, and Smeeton NJ. 2022. Processing visual information in elite junior soccer players:
587 Effects of chronological age and training experience on visual perception, attention, and
588 decision making. *European Journal of Sport Science* 22:600-609.
589 10.1080/17461391.2021.1887366
590 Kovács I, Kozma P, Fehér A, and Benedek G. 1999. Late maturation of visual spatial integration
591 in humans. *Proc Natl Acad Sci U S A* 96:12204-12209. 10.1073/pnas.96.21.12204
592 Kowler E. 2011. Eye movements: The past 25years. *Vision Research* 51:1457-1483.
593 10.1016/j.visres.2010.12.014
594 Koźlenia D, Domaradzki J, Trojanowska I, and Czermak P. 2020. Association between speed
595 and agility abilities with movement patterns quality in team sports players. *Medicina*
596 *dello Sport* 73:176-186. 10.23736/S0025-7826.20.03662-5
597 Kroll M, Preuss J, Ness BM, Dolny M, and Louder T. 2020. Effect of stroboscopic vision on
598 depth jump performance in female NCAA Division I volleyball athletes. *Sports*
599 *Biomechanics*:1-11. 10.1080/14763141.2020.1773917
600 Krzepota J, Zwierko T, Puchalska-Niedbal L, Markiewicz M, Florkiewicz B, and Lubinski W.
601 2015. The Efficiency of a Visual Skills Training Program on Visual Search Performance.
602 *J Hum Kinet* 46:231-240. 10.1515/hukin-2015-0051
603 Lambourne K, and Tomporowski P. 2010. The effect of exercise-induced arousal on cognitive
604 task performance: a meta-regression analysis. *Brain Res* 1341:12-24.
605 10.1016/j.brainres.2010.03.091
606 Lee H, Han S, Page G, Bruening DA, Seeley MK, and Hopkins JT. 2022. Effects of balance
607 training with stroboscopic glasses on postural control in chronic ankle instability patients.
608 *Scand J Med Sci Sports* 32:576-587. 10.1111/sms.14098
609 Mankowska ND, Marcinkowska AB, Waskow M, Sharma RI, Kot J, and Winklewski PJ. 2021.
610 Critical Flicker Fusion Frequency: A Narrative Review. *Medicina (Kaunas)* 57.
611 10.3390/medicina57101096
612 Mann DT, Williams AM, Ward P, and Janelle CM. 2007. Perceptual-cognitive expertise in sport:
613 a meta-analysis. *J Sport Exerc Psychol* 29:457-478. 10.1123/jsep.29.4.457
614 Müller S, Fadde PJ, and Harbaugh AG. 2017. Adaptability of expert visual anticipation in
615 baseball batting. *J Sports Sci* 35:1682-1690. 10.1080/02640414.2016.1230225

Ong NCH. 2015. The use of the Vienna Test System in sport psychology research: A review. *International Review of Sport and Exercise Psychology* 8:204-223. 10.1080/1750984X.2015.1061581

Palmer T, Coutts AJ, and Fransen J. 2022. An exploratory study on the effect of a four-week stroboscopic vision training program on soccer dribbling performance. *Brazilian Journal of Motor Behavior* 16:254-265. 10.20338/bjmb.v16i3.310

Piras A, Lobietti R, and Squatrito S. 2010. A study of saccadic eye movement dynamics in volleyball: comparison between athletes and non-athletes. *J Sports Med Phys Fitness* 50:99-108.

Piras A, Lobietti R, and Squatrito S. 2014. Response time, visual search strategy, and anticipatory skills in volleyball players. *J Ophthalmol* 2014:189268. 10.1155/2014/189268

Poltavski D, Biberdorf D, and Praus Poltavski C. 2021. Which Comes First in Sports Vision Training: The Software or the Hardware Update? Utility of Electrophysiological Measures in Monitoring Specialized Visual Training in Youth Athletes. *Frontiers in Human Neuroscience* 15. 10.3389/fnhum.2021.732303

Popowczak M, Domaradzki J, Rokita A, Zwierko M, and Zwierko T. 2020. Predicting Visual-Motor Performance in a Reactive Agility Task from Selected Demographic, Training, Anthropometric, and Functional Variables in Adolescents. *International Journal of Environmental Research and Public Health* 17:5322.

Ranganathan R, and Carlton LG. 2007. Perception-action coupling and anticipatory performance in baseball batting. *J Mot Behav* 39:369-380. 10.3200/jmbr.39.5.369-380

Sala G, Aksayli ND, Tatlidil KS, Tatsumi T, Gondo Y, and Gobet F. 2019. Near and Far Transfer in Cognitive Training: A Second-Order Meta-Analysis. *Collabra: Psychology* 5. 10.1525/collabra.203

Sasada M, Nakamoto H, Ikudome S, Unenaka S, and Mori S. 2015. Color perception is impaired in baseball batters while performing an interceptive action. *Attention, Perception, & Psychophysics* 77:2074-2081. 10.3758/s13414-015-0906-5

Shaqiri A, Roinishvili M, Grzeczkowski L, Chkonia E, Pilz K, Mohr C, Brand A, Kunchulia M, and Herzog MH. 2018. Sex-related differences in vision are heterogeneous. *Sci Rep* 8:7521. 10.1038/s41598-018-25298-8

Sheppard JM, Young WB, Doyle TL, Sheppard TA, and Newton RU. 2006. An evaluation of a new test of reactive agility and its relationship to sprint speed and change of direction speed. *J Sci Med Sport* 9:342-349. 10.1016/j.jsams.2006.05.019

Smith TQ, and Mitroff SR. 2012. Stroboscopic Training Enhances Anticipatory Timing. *Int J Exerc Sci* 5:344-353.

Spiteri T, Newton RU, and Nimphius S. 2015. Neuromuscular strategies contributing to faster multidirectional agility performance. *J Electromyogr Kinesiol* 25:629-636. 10.1016/j.jelekin.2015.04.009

Spiteri T, Nimphius S, Hart NH, Specos C, Sheppard JM, and Newton RU. 2014. Contribution of strength characteristics to change of direction and agility performance in female basketball athletes. *J Strength Cond Res* 28:2415-2423. 10.1519/JSC.0000000000000547

Trecroci A, Duca M, Cavaggioni L, Rossi A, Scurati R, Longo S, Merati G, Alberti G, and Formenti D. 2021. Relationship between Cognitive Functions and Sport-Specific Physical Performance in Youth Volleyball Players. *Brain Sci* 11. 10.3390/brainsci11020227

662 Ungerleider LG, and Mishkin M. 1982. Two cortical visual systems. In: Goodale MA, Ingle DJ,
663 and Mansfield RJW, eds. *Analysis of visual behavior*. Cambridge: MIT Press, 549-586.
664 van Polanen V, and Davare M. 2015. Interactions between dorsal and ventral streams for
665 controlling skilled grasp. *Neuropsychologia* 79:186-191.
666 10.1016/j.neuropsychologia.2015.07.010
667 Wilkins L, and Appelbaum LG. 2020. An early review of stroboscopic visual training: insights,
668 challenges and accomplishments to guide future studies. *International Review of Sport*
669 *and Exercise Psychology* 13:65-80. 10.1080/1750984X.2019.1582081
670 Wilkins L, and Gray R. 2015. Effects of stroboscopic visual training on visual attention, motion
671 perception, and catching performance. *Percept Mot Skills* 121:57-79.
672 10.2466/22.25.PMS.121c11x0
673 Wilkins L, Nelson C, and Tweddle S. 2018. Stroboscopic Visual Training: a Pilot Study with
674 Three Elite Youth Football Goalkeepers. *Journal of Cognitive Enhancement* 2:3-11.
675 Zhang X, Yan M, and Yangang L. 2009. Differential performance of Chinese volleyball athletes
676 and nonathletes on a multiple-object tracking task. *Percept Mot Skills* 109:747-756.
677 10.2466/pms.109.3.747-756
678 Zwierko M, Jedziniak W, Popowczak M, and Rokita A. 2022. Reactive Agility in Competitive
679 Young Volleyball Players: A Gender Comparison of Perceptual-Cognitive and Motor
680 Determinants. *J Hum Kinet* 85:87-96. 10.2478/hukin-2022-0112
681 Zwierko T, Jedziniak W, Florkiewicz B, Stępiński M, Buryta R, Kostrzewa-Nowak D, Nowak R,
682 Popowczak M, and Woźniak J. 2019. Oculomotor dynamics in skilled soccer players:
683 The effects of sport expertise and strenuous physical effort. *Eur J Sport Sci* 19:612-620.
684 10.1080/17461391.2018.1538391
685 Zwierko T, Lubinski W, Lesiakowski P, Steciuk H, Piasecki L, and Krzepota J. 2014. Does
686 athletic training in volleyball modulate the components of visual evoked potentials? A
687 preliminary investigation. *J Sports Sci* 32:1519-1528. 10.1080/02640414.2014.903334
688 Zwierko T, Osiński W, Lubiński W, Czepita D, and Florkiewicz B. 2010. Speed of visual
689 sensorimotor processes and conductivity in visual pathway in volleyball players. *Journal*
690 *of Human Kinetics* 23:21-27.
691 Zwierko T, Popowczak M, Woźniak J, and Rokita A. 2018. Visual control in basketball shooting
692 under exertion conditions. *J Sports Med Phys Fitness* 58:1544-1553. 10.23736/s0022-
693 4707.17.07522-3

694
695
696
697
698
699
700

701

702

703

704

705

706 **Figure legends**

707 **Figure 1**. A schematic of the reactive agility test.

708 **Figure 2.** A graphical illustration of the study protocols with examples of the exercises; (A)
709 Protocol I: "Wall Passing Drills": The player stands in front of a wall on which numbers are
710 placed as optotypes. They bounce the ball off the wall, make an overhead pass above themselves,
711 and then touch the designated number before returning to the starting position for the next
712 bounce. (B) Protocol II: "Partner Passing Drills": The player makes an overhead shot above
713 themselves, and on the second touch, passes the ball to their partner. During the first pass, the
714 partner signals one of four colors (blue, green, red, yellow). After the pass, the player must touch
715 the designated color marker and return to the defensive position, and be ready for the next pass.
716 (C) Protocol III: "Passing Rotation Drill": The players are arranged in two pairs and positioned
717 facing each other. They make overhead or forearm passes to their partner, then simultaneously
718 switch positions according to a rotation scheme to keep the ball in play. The graphic illustrations
719 were prepared using Easy Sports-Graphics software.

720 **Figure 3**. Interaction plots of visual and visuomotor parameters by TIME and GROUP: stroboscopic
721 (black dots) vs. non-stroboscopic (white dots) groups in a pre-post-retention design. Pre-test, post-test,
722 and retention test values are presented as means and 95% CIs. Significant changes ($p < 0.05$) in
723 visual and visuomotor parameters are denoted by an asterisk (*) for the stroboscopic group and a
724 pound sign (#) for the non-stroboscopic group, with accompanying effect sizes (d).

Table 1(on next page)

Descriptive (mean ± standard deviation) characteristics of the experimental sample.

Note. The 'p' column corresponded to the t-test, except for one instance marked with '#' where it represented the chi-square statistic with Yates correction.

Table 1. Descriptive (mean ± standard deviation) characteristics of the experimental sample.

	Stroboscopic group (n =25)	Non-stroboscopic group (n = 25)	p
Age (years)	16.4± 0.7	16.6 ± 0.5	0.254
Female (n)	12	12	0.777#
Male (n)	13	13	
Height (cm)	180.2 ± 8.2	181.9 ± 8.1	0.470
Weight (kg)	74.3 ± 10.4	71.6 ± 8.9	0.340
Sports experience (years)	6.7 ± 1.1	6.6 ± 1.3	0.732
The effective time duration of training intervention (min/week)	45.0 ± 1.4	46.1 ± 2.0	0.152

Note. The 'p' column corresponded to the t-test, except for one instance marked with '#' where it represented the chi-square statistic with Yates correction.

Table 2(on next page)

Descriptive statistics of the visual, visuomotor and reactive agility parameters in the stroboscopic and non-stroboscopic groups in pre-tests, post-tests, and retention tests.

Table 2. Descriptive statistics of the visual, visuomotor and reactive agility parameters in the stroboscopic and non-stroboscopic groups in pre-tests, post-tests, and retention tests.

Variable	Group	Pre-test mean±SD (min-max)	Post-test mean±SD (min-max)	Retention-test mean±SD (min-max)
Simple motor time [ms]	stroboscopic	133.40±36.75 (80.00-222.00)	118.80±37.39 (61.00-219.00)	121.20±40.49 (77.00-227.00)
	non-stroboscopic	130.32±34.51 (75.00 -207.00)	129.12±32.18 (79.00-212.00)	131.24±26.61 (87.00-195.00)
Simple reaction time [ms]	stroboscopic	270.96±44.51 (195.00-386.00)	263.20±35.98 (206.00-322.00)	272.44±41.03 (206.00-392.00)
	non-stroboscopic	273.72±52.66 (220.00-447.00)	272.56±43.59 (206.00-393.00)	273.64±42.56 (203.00-401.00)
Complex reaction speed [ms]	stroboscopic	737.20±62.49 (620.00-850.00)	674.40±61.58 (570.00-800.00)	662.80±81.27 (540.00-870.00)
	non-stroboscopic	719.60±69.49 (630.00-870.00)	697.20±77.81 (600.00-860.00)	684.80±78.91 (580.00-890.00)
Sensory sensitivity [Hz]	stroboscopic	44.01±5.69 (33.90-57.25)	46.60±5.22 (39.04-59.88)	44.80±6.23 (30.64-56.20)
	non-stroboscopic	46.84±4.31 (39.91-55.36)	46.68±5.51 (38.53-58.83)	47.08±6.46 (37.51-59.88)
Saccade dynamics [°/s]	stroboscopic	94.30±9.73 (81.03-116.93)	99.26±9.09 (84.17-119.07)	101.38±6.89 (88.44-116.58)
	non-stroboscopic	100.10±11.07 (81.92-121.49)	98.20±9.37 (84.32-119.23)	100.93±8.51 (85.50-119.65)
Reactive agility [s]	stroboscopic	18.18±1.23 (16.35-20.58)	17.62±0.98 (16.40-19.25)	17.88±1.32 (15.92-20.32)
	non-stroboscopic	18.61±1.09 (16.24-20.40)	18.39±1.14 (16.00-20.35)	18.04±1.15 (16.19-20.80)

Table 3(on next page)

Results of visual, visuomotor and reactive agility tests in relation to gender within the stroboscopic group: descriptive and statistical values in pre-tests, post-tests, retention tests, and interaction effects (TIME x GENDER).

Note. F - female, M- male; F - interaction effect (TIME x GENDER). [a] *Denotes significant differences within groups (between post-test vs pre-test and retention-test vs pre-test);* [b] *Denotes significant group difference (female vs male);* [a/b] $p<0.05$; [aa/bb] $p<0.01$

Table 3. Results of visual, visuomotor and reactive agility tests in relation to gender within the stroboscopic group: descriptive and statistical values in pre-tests, post-tests, retention tests, and interaction effects (TIME x GENDER).

Variable	Group	Pre-test mean±SD	Post-test mean±SD	Retention-test mean±SD	F	p	ηp^2
Simple motor time [ms]	F	157.92±35.54	146.09±33.77	146.42±41.78	0.21	0.809	0.01
	M	110.77±19.70^{bb}	93.62±17.87^{abb}	97.92±21.36^{bb}			
Simple reaction time [ms]	F	289.25±54.87	280.33±40.41	288.42±50.31	0.13	0.875	0.01
	M	254.08±23.67^{b}	247.39±23.00^{b}	257.69±23.58^{b}			
Complex reaction speed [ms]	F	755.83±56.96	690.83±59.92^{aa}	691.67±75.30^{aa}	2.29	0.113	0.09
	M	720.00±64.55^{bb}	659.23±61.44^{aabb}	636.15±80.06^{aabb}			
Sensory sensitivity [Hz]	F	44.07±6.51	47.63±5.82	43.76±4.80	1.44	0.247	0.06
	M	43.96±5.08	45.66±4.63	45.75±6.22			
Saccade dynamics [°/s]	F	87.08±5.18	95.65±8.61^{a}	100.70±7.43^{aa}	6.72	0.003	0.23
	M	100.97±8.04^{bb}	102.59±8.49	102.00±6.59			
Reactive agility [s]	F	19.23±0.79	18.26±0.64^{aa}	19.03±0.66	6.21	0.004	0.21
	M	17.21±0.56 ^{bb}	17.03±0.62 ^{bb}	16.81±0.72 ^{bb}			

Note. F - female, M- male; F - interaction effect (TIME x GENDER). [a] Denotes significant differences within groups (between post-test vs pre-test and retention-test vs pre-test); [b] Denotes significant group difference (female vs male)
$^{a/b}$ $p<0.05$
$^{aa/bb}$ $p<0.01$

Figure 1

A schematic of the reactive agility test.

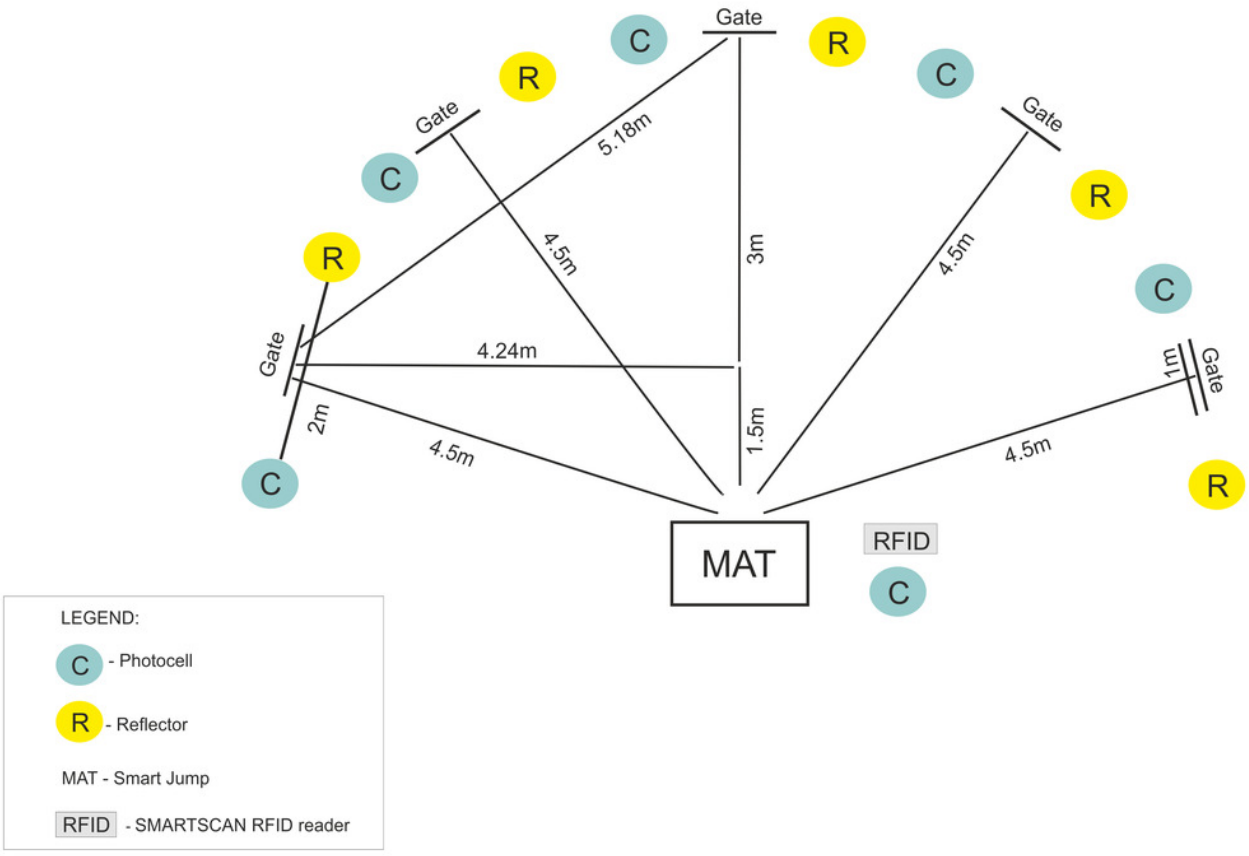


Figure 2

A graphical illustration of the study protocols with examples of the exercises;

(A) Protocol I: "Wall Passing Drills": The player stands in front of a wall on which numbers are placed as optotypes. They bounce the ball off the wall, make an overhead pass above themselves, and then touch the designated number before returning to the starting position for the next bounce. (B) Protocol II: "Partner Passing Drills": The player makes an overhead shot above themselves, and on the second touch, passes the ball to their partner. During the first pass, the partner signals one of four colors (blue, green, red, yellow). After the pass, the player must touch the designated color marker and return to the defensive position, and be ready for the next pass. (C) Protocol III: "Passing Rotation Drill": The players are arranged in two pairs and positioned facing each other. They make overhead or forearm passes to their partner, then simultaneously switch positions according to a rotation scheme to keep the ball in play. The graphic illustrations were prepared using Easy Sports-Graphics software.

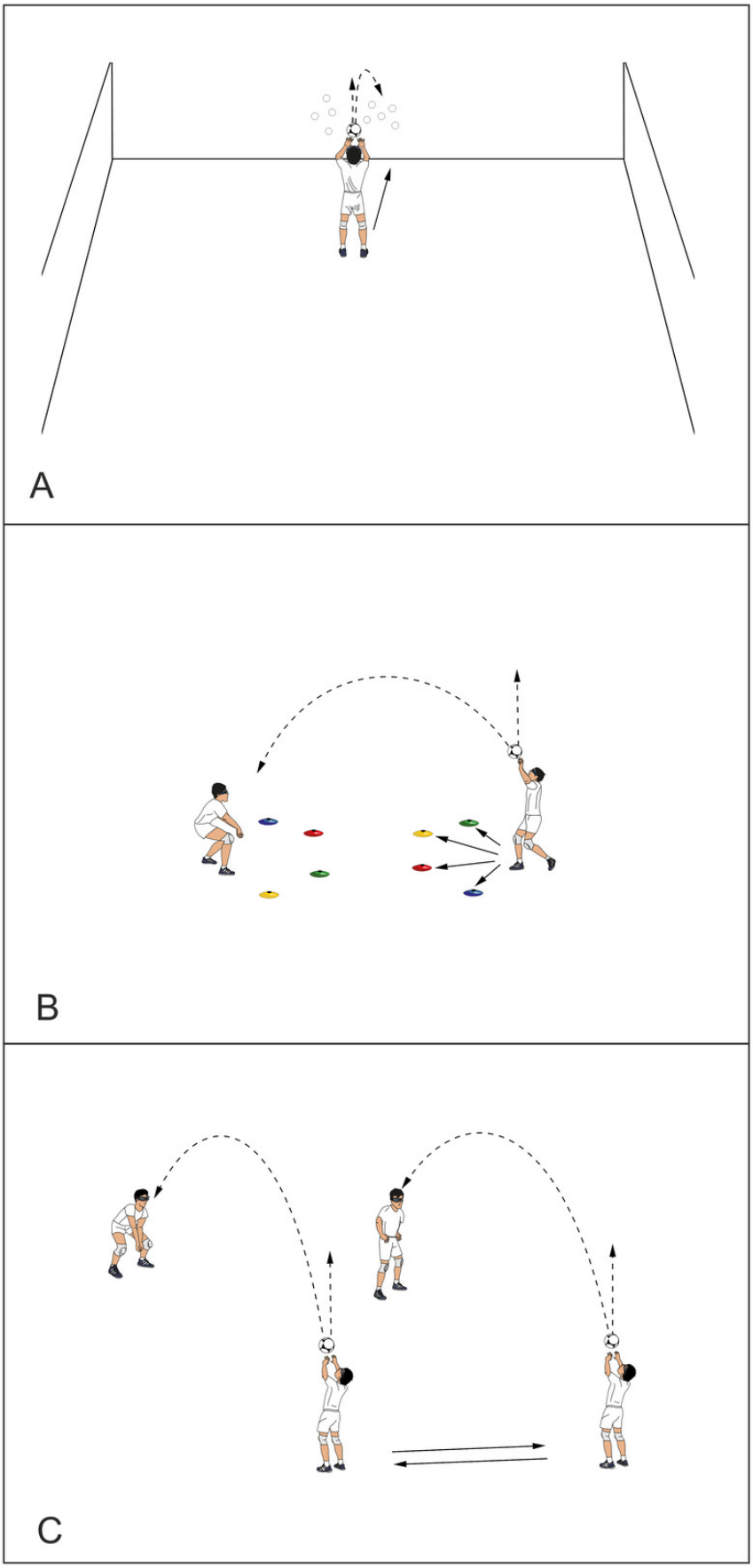
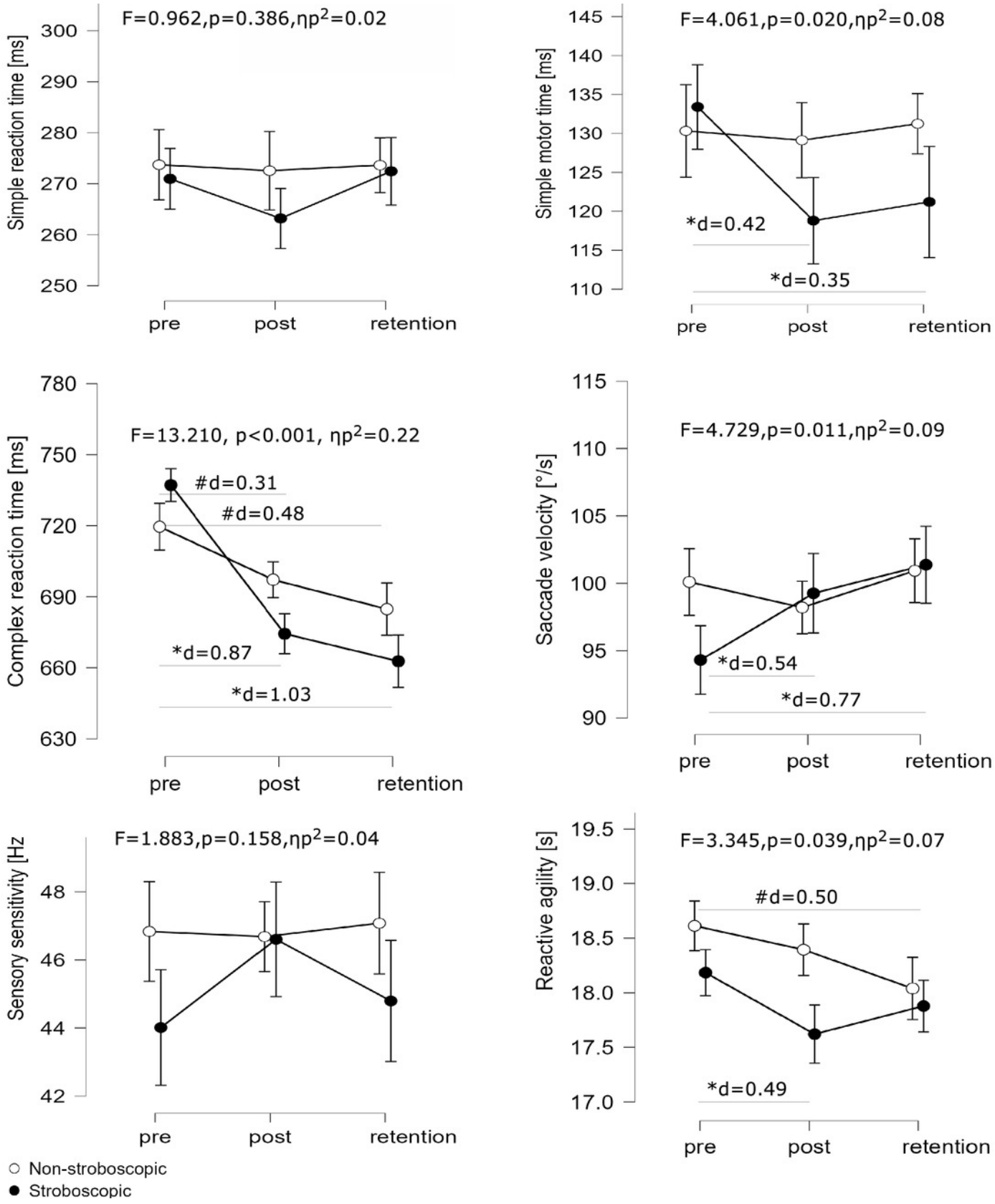

A
B
C

Figure 3

Interaction plots of visual and visuomotor parameters by TIME and GROUP: stroboscopic (black dots) vs. non-stroboscopic (white dots) groups in a pre-post-retention design.

Pre-test, post-test, and retention test values are presented as means and 95% CIs. Significant changes ($p < 0.05$) in visual and visuomotor parameters are denoted by an asterisk (*) for the stroboscopic group and a pound sign (#) for the non-stroboscopic group, with accompanying effect sizes (d).


F=0.962,p=0.386,ηp²=0.02
Simple reaction time [ms]
300
290
280
270
260
250
pre
post
retention
F=4.061,p=0.020,ηp²=0.08
Simple motor time [ms]
145
140
135
130
125
120
115
110
*d=0.42
*d=0.35
pre
post
retention
F=13.210, p<0.001, ηp²=0.22
Complex reaction time [ms]
780
750
720
690
660
630
#d=0.31
#d=0.48
*d=0.87
*d=1.03
pre
post
retention
F=4.729,p=0.011,ηp²=0.09
Saccade velocity [°/s]
115
110
105
100
95
90
*d=0.54
*d=0.77
pre
post
retention
F=1.883,p=0.158,ηp²=0.04
Sensory sensitivity [Hz
48
46
44
42
pre
post
retention
F=3.345,p=0.039,ηp²=0.07
Reactive agility [s]
19.5
19.0
18.5
18.0
17.5
17.0
#d=0.50
*d=0.49
pre
post
retention
Non-stroboscopic
Stroboscopic