

# The relationship between visual function and performance in Para-swimming

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# Abstract

Paralympic swimmers with vision impairment (VI) currently compete in one of three classes depending on their visual acuity (VA) and/or visual field. However, there is no evidence to suggest that a three-class system is the most legitimate approach for classification in swimming, or that the tests of VA and visual field are the most suitable. An evidence-based approach is required to establish the relationship between visual function and performance in the sport. Therefore, the aim of this study was to establish the relationship between visual function and performance in VI swimming. The swimming performance of 45 elite VI swimmers was evaluated during international competitions by measuring the total race time, start time, clean swim velocity, ability to swim in a straight line, turn time and finish time. Visual function was measured using a test battery that included VA, contrast sensitivity, light sensitivity, depth perception, visual search, and motion perception. Results revealed that VA was the best predictor of total race time, though the relationship was not linear. Decision-tree analysis suggested that only two classes were necessary for legitimate competition in VI swimming, with a single cut-off between 2.6–3.5 logMAR. No further significant association remained between visual function and performance in either of the two resulting classes. Results suggest that legitimate competition in VI swimming requires one class for partially sighted and another for functionally blind athletes.

## Key Points

1. This empirical study sought to establish the relationship between visual function and performance in elite para-swimming.
2. It was found that the current classification system for visually impaired swimmers may not be fit for purpose, with two classes better capturing the relationship between visual function and performance than three.
3. It is recommended that no further vision tests should be added in the classification procedure of swimmers with vision impairment.

## 1. Introduction

Classification is vital in sports to ensure fair competition. Classification is the process of grouping athletes together for competition on the basis of characteristics known to impact performance [1]. For example, a heavy-weight wrestler is likely to have an advantage over a light-weight opponent, and therefore wrestling uses a classification system that places competitors into weight categories. Following this principle, sports use classification systems to reduce the impact of a range of factors on the outcome of competition, for instance to account for an athlete's gender, age, or maturation status [1].

Classification systems are necessarily sport-specific. Indeed, while being heavier can be advantageous in some sports, it will be disadvantageous in others (e.g., gymnastic). However, the number of factors that can be controlled for in a given sport is limited. Indeed, there are limited number of event slots in major competitions (e.g., Olympic games, Paralympic games; [1]). Also, sports that use too many classes encounter logistical challenges when structuring competition. Moreover, by awarding too many medals, those sports can risk devaluing the worth of an individual medal, especially at the highest level. Therefore, only those factors that have the greatest impact on performance are usually controlled for.

In Para sports for people with impairment, classification is required to account for the degree to which an athlete's impairment impacts their performance in the sport [2]. Indeed, Para athletes should compete against others with an impairment that has a comparable impact on their sport performance. Classification of impairment in Para sports was originally based on each athlete's medical diagnosis (e.g., on the location of a spinal cord injury). A problem with this approach though is that it does not consider the impact of impairment on performance in a particular sport. Moreover, a medical condition such as a spinal cord lesion can leave some individuals with more functional ability than others [1]. For these reasons, the International Paralympic Committee (IPC) within its *Athlete Classification Code* requires all member sport federations to develop their own evidence-based system of classification designed to be suitable for their sport. To do so, sports must provide evidence that demonstrates if and how impairments are related to performance within the sport [3, 4]. Based on those findings, the sport can determine who should be eligible to compete, and what is the fairest manner by which to place athletes into sport classes.

Most sports for athletes with vision impairment (VI) continue to use an outdated classification system that remains the same across almost all sports, and therefore fails to account for the sport-specific relationship between impairment and performance in each sport. The existing system of classification places eligible athletes into one of three classes that were designed largely on the basis of the World Health Organisation's definitions of low vision and blindness. Athletes who are functionally blind (generally those with either no or only marginal light perception) are placed in the B1 class, while athletes in the B2 and B3 classes have progressively better visual functions [5][1]. However, change is on the horizon. VI rifle shooting recently became the first VI sport to implement their own sport-specific system of classification. Research in VI rifle shooting demonstrated that only one class was necessary in that sport, because functionally blind athletes could perform just as well as athletes with much less impairment (presumably because they can effectively exploit the auditory feedback used in the sport to guide the rifle; [7-12]). Note that research has also begun in other VI sports including football [13, 14], judo [15-20], skiing [21, 22], athletics [23], goalball [24] and swimming [6].

### 1.1. Classification in VI swimming

Available empirical evidence suggests that the existing system of classification for VI swimming may not be fit for purpose. Indeed, studies suggest there may be no difference in the performance of athletes in the S12 and S13 classes (i.e., equivalent to B2 and B3; [25-27]). Both groups perform better than the S11 athletes (i.e., equivalent to B1), suggesting that VI does impact performance but in a non-linear fashion. In particular, S11 swimmers take more time than S12s and S13s to turn, suggesting that specific aspects of a race might be influenced by their poorer visual function.

It might seem as though the existing evidence comparing the three classes should be sufficient to restructure VI swimming into two rather than three classes, but that is far from the case. There are a number of reasons why research that simply compares the performance of existing sports classes is not sufficient for designing an evidence-based system of classification [1]. First, a comparison of the existing class system relies on the assumption that the measures of visual function used in that system (visual acuity [VA] and visual field) are the most suitable and only measures needed. That, however, is far from established, with

a recent Delphi review revealing that experts in VI swimming feel that classification based only on VA and visual field might not fully capture the impact of VI on swimming performance [6]. Indeed, those experts mentioned that other visual functions including depth perception (DP), light sensitivity (LS), contrast sensitivity (CS), and motion perception (MP) are not currently measured but should be considered. For instance, athletes with impaired DP might have a disadvantage in their ability to evaluate their distance to the wall and would fail to properly prepare a turn or finish the race. Similarly, impaired CS could impact the ability of swimmers to navigate if they are less able to identify the black line at the bottom of the pool. It remains possible that a subset of athletes may exist in the S12 and S13 classes who are disadvantaged because of an impairment to a visual function that is important for swimming but is not yet assessed during classification. In that case, those athletes would warrant their own separate sport class.

A second limitation of an approach that compares the performance of existing sport classes is that it is not possible to identify whether an existing class should be separated into multiple sport classes. For instance, it could be that the swimmers with the poorest VA in the S12 class are at a disadvantage and should either join the S11 class or should be placed in their own separate class. These types of decisions can only be made when knowing each athlete's specific level of visual function rather than just their sport class.

A third limitation when comparing sport classes is that, even if access to the measures of visual function is available, those measures may not be sufficiently reliable for research purposes. The aim of the classification assessment is not to establish the exact level of VA, but rather to determine which sports class an athlete should be allocated to. In particular, classifiers sometimes do not establish the exact level of VA or visual field if they have already established the class the athlete will be allocated, especially when VA is worse than 2.6 logMAR and so the classifier knows that the athlete will be in the S11 class irrespective of any further testing [18, 20]. Clearly, to properly establish the relationship between visual function and performance, a study is necessary that accurately measures different aspects of vision.

An examination of the relationship between VI and performance in swimming should focus on those aspects of swimming performance most likely to be impacted by VI. Of course, the overall race time is the most common way of measuring performance in swimming, but there are also specific components of the swim time more likely to be impacted than others and therefore would provide a more sensitive measure to changes as a result of impairment [1]. In the same vein, certain visual pathologies have particular visual function impairments that could impact performance differently. Based on their Delphi study canvassing the views of experts in VI swimming, Ravensbergen and colleagues [6] proposed a conceptual model that outlined the components of a swimming race most likely to be impacted by VI. That model included the ability of a VI swimmer to optimise their performance in each of the start time, the clean swim velocity (with a specific emphasis on the ability to swim in a straight line in the lane), the turn time, and the finish time. For instance, the start and turn times are likely to be affected by an inability to effectively use the full extent of the allowed underwater distance (i.e., 15 m) to streamline underwater, with longer underwater distances in particular at the start associated with better race times [25, 26, 28]. Each of these measures of swim performance could be impacted in their own right by specific aspects of VI.

The aim of this study was to establish the relationship between visual function and performance in VI swimming. To do so, we measured different visual functions and swimming performance of international-level swimmers with VI. We first sought to establish which visual functions best predicted sports performance, and then to characterize the optimal number of sport classes necessary to minimise the impact of VI on the outcome of competition. Based on the views of the experts in the existing Delphi study [6], we expected that the relationship between visual function and performance would be better explained by the addition of new visual functions (e.g., CS) than when using VA alone. Further, we expected that at least two classes would be necessary to minimise the impact of impairment on the outcome of competition [25-27].

[1] Two measures of visual function are used to classify athletes: (i) visual acuity, a measure of the sharpness of central vision, and (ii) visual field, a measure of the size of the area which is seen. An athlete is allocated class B3 when they have a VA between 1.0 and 1.4 logMAR inclusive, or if their visual field is less than 40 degrees diameter. Athletes are allocated to the B2 class if their VA is between 1.5 and 2.6 logMAR inclusive, or their visual field is less than 10 degrees diameter. Finally, B1 can only be allocated based on VA, which must be greater than 2.6 logMAR [6].

## 2. Methods

### 2.1. Participants

Seventy-eight ( $N = 78$ ) international level VI swimmers (46.2 % females;  $M_{age} = 21.3$ ,  $S.D. = 6.9$ , range 13-52) participated in this study. However, to allow a comparison of visual function with performance while controlling for training volume and age, we included only those participants (i) who compete in 100m freestyle swimming, and (ii) for whom training volume and age data were available ( $n = 45$ ; 48.9% females;  $M_{age} = 20.8$ ,  $S.D. = 6.8$ , range 13-52). Table 1 describes the participants who met the inclusion criteria according to sports class (S13, S12 or S11). The study was conducted in accordance with the Declaration of Helsinki. All athletes provided written informed consent prior to participation, with the study approved by the local research ethics committee and the International Paralympic Committee. Parental consent was obtained for participants aged under 18 years.

Measures of personal characteristics, visual function, and swimming performance were collected for each athlete. **2.2. Measures**

#### 2.2.1. Personal characteristics

##### 2.2.1.1. Developmental history questionnaire

An adapted version of the Developmental History Athlete Questionnaire (DHAQ; [29]) was used to collect personal information about each athlete. This self-administered questionnaire consisted of 32 questions (one dichotomous, 19 short-answers and 12 multiple-choice responses) that collected general information including the athlete's age, nationality, age at onset of VI, progression of VI over time, other impairments, participation in other sports, and lifetime

training volume. Participants' sex was deduced from the competition in which they took part. The questions were read out loud by an experimenter or one of the participant's coach.

### **2.2.2. Tests of visual functions**

The objective of the tests of visual functions was to assess each athlete's habitual level of visual function during competition. The athletes were therefore asked to wear any visual correction (i.e., prescription goggles or contact lenses) that they used during competition. For the same reason, tests of visual functions were conducted binocularly rather than monocularly which is standard procedure within the current classification assessment. All visual function test procedures took place in a room with standard room illumination ( $\approx 200$  lux).

#### **2.2.2.1. Visual acuity (VA)**

The Berkeley Rudimentary Vision Test (BRVT; [30]) was used to assess each athlete's VA in logMAR units. The BRVT is designed to assess VA in individuals with low vision, using both a logMAR vision chart (with five tumbling E's per line) and a series of cards showing a single E optotype when VA is too poor to be assessed using the chart. To ensure consistency across participants, we only used the cards. The BRVT has three types of cards (single tumbling E's, grating, and black/white discrimination) that measure VA by establishing the distance at which the optotype on the cards can be resolved. The single letter E shown on each card (either 25, 40, 63, or 100M size) can be presented in one of four orientations (left, right, up, down) to test VA up to 2.6 logMAR. The grating cards contain a series of black and white parallel lines (either 50, 80, 125, or 200M size) that can be presented in one of two directions (horizontal or vertical) to measure VA up to 2.9 logMAR. The black/white discrimination cards are split into black and white sections or are entirely black or white. The task for participants is to verbalise the direction of the E, grating, or location of the black/white areas respectively. Gratings were only shown when VA was worse than 2.6 logMAR, and black-white discrimination when VA was worse than 2.9 logMAR. When participants were unable to discriminate black from white, the experimenter assessed whether they had any perception of light. A pen torch was directed towards their eyes and the athlete was asked to respond whether the light was on or off. When they responded correctly 3 out of 4 times, the experimenter moved the pen torch either horizontally or vertically before the athlete's eyes and asked the athlete to indicate the direction of the movement. 'Perception of light direction' was recorded if the athlete could respond correctly 3 out of 4 times. Black/white discrimination was nominally defined as 3.5 logMAR, light perception as 3.7 logMAR, and no light perception as 4.0 logMAR [9, 22, 31]. In alignment with the IPC's VI classification decision making rules for the single letter E cards, when multiple cards were used, the card yielding the second-best VA score was taken as the athletes' true VA (to minimise the chance of erroneous scores with a single better-than-expected result). Also, reliability of each measurement was tested at a different distance. A lower logMAR value indicates better VA.

#### **2.2.2.2. Contrast sensitivity (CS)**

CS was assessed using Mars charts (Mars Perceptrix, Chappaqua, NY). The Mars number test consists of three charts, each having a sequence of eight rows of six numbers, starting with the highest contrast of 1.92 logCS on the top left and each number successively decreasing in contrast by 0.04 logCS unit. The charts were placed almost vertically on a reading stand, with the athlete asked to read out the numbers. The examiner stopped the test when two consecutive incorrect answers were given. The CS threshold was defined as the contrast level of the final correct number minus 0.04 logCS unit for each incorrect response prior to the final correct answer. A higher logCS value on the Mars chart indicates better CS. The acuity demands of the Mars chart meant that not all athletes were able to perform the test ( $n=16$ ). A dummy value of 0.00 logCS was attributed in those cases.

#### **2.2.2.3. Light sensitivity (LS)**

LS was measured as the difference in logCS (using the Mars test) when viewed with standard lighting versus when viewing through a bright light simulated using the Brightness Acuity Tester (BAT) at its brightest setting of 400 foot-lamberts (Marco Ophthalmic, Inc., Jacksonville, FL). The BAT is a hand-held instrument consisting of an internally illuminated small white bowl that the participant holds over one eye. The bowl has a central opening of 12mm for the participant to look through. The Mars test was performed monocularly on the athlete's better eye because the BAT only allows monocular testing. All athletes first performed the test under standard lighting conditions. The test was then repeated while looking through the BAT with the light source switched off to assess whether the central opening affected test performance. Finally, the light source was turned on and the Mars test repeated. The difference in logCS between normal lighting (through the central opening) and bright light was calculated. Results were transformed logarithmically because the distribution was skewed towards zero. A bigger logarithmic difference indicates higher LS. A dummy value of zero was allocated to athletes who were not able to perform the test ( $n = 16$ ; i.e., highest possible value on the test), largely because their visual function/CS was so bad that bright lighting made little difference to their ability to see.

#### **2.2.2.4. Depth perception (DP)**

A modified version of the Howard-Dolman test was specifically created for individuals with low visual function and used to assess DP [32]. One stationary white rod (20mm diameter) was placed 300mm to the left of an identical target placed on a rail (both reaching 555mm above the table surface). The athlete could move the sliding target with a pole attached to the slider. Athletes were seated 1.5 m away from the stationary target. The background of the test was black, and a black barrier blocked the lower part of the athlete's view to remove any visual cues from the base of the targets and the sliding rail. The sliding target was placed at the far end of the slider (approximately 400mm further away than the stationary target). The athlete was instructed to move the sliding target until it was the same distance from them as the stationary target. This task was repeated twice more, and the deviation in distance between the centres of the two targets was determined in millimetres. The sliding target was then moved to the end of the slider closest to the athlete (approximately 400mm closer than the stationary target). Again, the athlete was instructed to move the target until it was equidistant with the stationary target. This task was repeated twice more, with the distance between targets determined. The mean absolute value across all six trials was used as the dependent variable. Results

were transformed logarithmically because the distribution was skewed towards zero. A lower logarithmic value indicates better DP. A dummy value equal to the maximum observed mean distance plus 10% was allocated to athletes not able to perform the test ( $n = 17$ ).

#### 2.2.2.5. Visual search (VS)

A test of VS was developed in Psykinematix to assess the ability of participants to search for a target (i.e., whether a circle was present in a grid of squares using Sloan-style characters; [33, 34]). The test was conducted on a 27" Apple display screen with a refresh rate of 60 Hz and a resolution of 2560 x 1600. The task was separated into three difficulty levels, with six trials per level. Athletes always started with the easiest level and only continued to the next level if they answered four out of six trials correctly. For the first level, a 3x3 grid was shown (subtending 18.5° of visual angle) with black shapes (each subtending 8.3° equivalent to 2.0 logMAR) on a white background. At the intermediate level, an 8x8 grid was used with shapes subtending 2.6° (equivalent to 1.5 logMAR). The most difficult level consisted of a 15x15 grid with shapes subtending 0.83° (equivalent to 1.0 logMAR). Each trial was presented for a maximum of 30 seconds, during which the athlete was required to respond as quickly as possible using the up or down key on a keyboard to respectively indicate whether a circle was present or absent. The circle was present in two-thirds of trials. The order of the present and absent trials was randomly selected by Psykinematix, as was the location of the circle. The response time for the most difficult level completed by the athlete (considering only trials where the target was present) was used for analyses, as it was the only measure not correlated with VA, providing a potentially unique contribution to the analysis (i.e., response time in other levels and response accuracy in all levels correlated significantly with VA). Results were transformed logarithmically because the distribution was skewed towards zero. A lower logarithmic value indicates better VS. A dummy value equal to the maximum recorded score plus 10% was allocated to athletes not able to perform the test ( $n = 15$ ).

#### 2.2.2.6. Motion perception (MP)

A test of global motion coherence was designed in Psykinematix (KyberVision Japan LLC) specifically for individuals with VI and conducted on the same display monitor as the VS test [20, 35]. One hundred dots subtending 1.66° of visual angle were presented in a square envelope of 25°. The lifetime of each dot was 200 ms and the movement speed was 6°/s. Dots moved either vertically (up or down), or in any other random direction, with the percentage of dots moving in a coherent direction (up or down depending on the trial) systematically manipulated to find the threshold number of dots that needed to be coherent for each athlete to correctly identify the global direction in which the dots were moving. Athletes were asked to determine the general direction of the movement of all the dots from two options (upward or downward motion) using the upward and downward key on the keyboard. Each trial was presented for a maximum of 8 seconds within which athletes were required to respond.

The test started with a set of six familiarisation trials where all 100 dots were moving in the same direction (i.e., 100% coherence). When athletes provided at least four correct responses, the full test protocol commenced. A 1-up-2-down staircase procedure with five reversals was used, where the coherence levels of the final four reversals were averaged to determine the threshold coherence level where global motion could be detected in 66.7% of presentations. Within the staircase, global motion coherence started at 100% coherence and decreased by 25% prior to the first reversal and decreased or increased by 10% after the first reversal. The test was aborted if six successive incorrect responses were provided at 100% coherence.

Initial inspection of the results showed a dichotomous pattern, with athletes recording motion coherence levels either similar to or below that of a control group of unimpaired individuals. Accordingly, the results were dichotomized as "normal" or "impaired". A cut-off was established between the two categories at 56% threshold coherence using k-means cluster analysis, with a higher threshold reflecting poorer MP. Participants not able to perform the test were classified as 'impaired' ( $n = 11$ ).

#### 2.2.3. Performance measures

For measures of swimming performance, the objective was to assess aspects of the athletes' performance that experts had nominated were likely to be impacted by VI during competition [6]. In-competition data were collected at international swim meets between June 2016 and April 2017. Competition data were only included if collected within 6 months before or after that athlete's testing of visual function. The performance measures were: (i) best race time; (ii) start time; (iii) clean swim velocity; (iv) turn time; (v) finish time; and (vi) mean lateral position in the lane. Note that athletes in the S11 sports class compete with blackened swimming goggles and so it remains possible that the performance of these athletes *could* be better than what was measured if they were to swim without blackened goggles.

The *best race time* was defined as each athlete's fastest 100m freestyle race time recorded at an international competition within 6 months of their test of visual functions. Data were obtained from official race results held by World Para Swimming, the International Federation for Para swimming. To assess other aspects of swimming performance, video footage of the swimmers was recorded using GoPro 3 cameras during 100m freestyle races at international competitions in 50m pools (side-on cameras unless stated otherwise). *Start time* was defined as the time taken from the start of the race to first reach the 15 meter flags. *Clean swim velocity* was defined as the average speed (m/s) across the 15<sup>th</sup> to 45<sup>th</sup> meter and the 55<sup>th</sup> to 95<sup>th</sup> meter markers. *Turn time* was the time taken to turn (i.e., time between the 45<sup>th</sup> meter and 55<sup>th</sup> meter marks). *Finish time* was the time taken to swim through the final five meters. Finally, *mean lateral position* was the average absolute distance of the swimmer from the centre of the lane (in cm). Video footage was recorded from an elevated position at the end of the pool so that the lateral position of the swimmer in the lane could be manually digitised throughout the race (1 Hz, Kinovea, Bordeaux, France; <https://www.kinovea.org/>). Note that footage from nine participants were not clear enough to produce usable data on at least one of those measures. Data were not replaced in those cases.

### 2.3. Procedure

Each athlete was tested individually on the visual functions test battery. Athletes were either tested at competition between training and races, or outside of competition. Athletes were free to choose their preferred testing time. VA was always tested first, and LS last, but the order of other tests was not

necessarily controlled. Testing of visual functions lasted approximately one hour but could be shorter for athletes with rudimentary vision who were not able to perform most tests. Swimming performance was determined from official race results and video footage after all athletes had completed their testing of visual function.

## 2.4. Data analysis

Analyses were conducted using R Studio Version 1.3 (RStudio, PBC, Boston, MA; <https://rstudio.com/products/rstudio/>), supported by R version 4.0.0 (The R Foundation, Vienna, Austria; <https://www.r-project.org/foundation/>). One-way ANOVAs (with Bonferroni post-hoc tests) and Pearson's Chi-square tests were run on the descriptive statistics to verify sport classes homogeneity (Table 1). Correlations were first run to assess the relationship between swimming performance and (i) training volume in hours and (ii) age, because these variables could confound the relationship between visual functions and swimming performance. When correlations were detected, performance measures were adjusted to account for the relevant confounders (i.e., we report the residuals of the regression of confounders on performance).

### 2.4.1. Relationship between visual function and performance for all athletes

Correlations were conducted to assess the relationship between measures of visual functions and swimming performance (point biserial correlation in the case of MP). Where appropriate, partial correlations were conducted to control for other measures of visual function to establish the *unique* contribution of each vision measure on performance. For each performance measure related to visual function after partial correlation, an identical series of three analyses was carried out. First, a decision tree algorithm using the *ctree* function from the *partykit version 1.2-7* R package was run to find if the performance measure could be split according to the appropriate measure of visual function. The number of splits and the border between splits are reported, as well as Welch t-tests (i.e., correction for unequal variances) to compare swimming performance above and below the split. Second, when the decision tree found at least one split in performance, bootstrapping of the decision tree with replacement 10,000 times was run to confirm the validity of the split [20]. The distribution of the splits from the 10,000 trees is reported. Third, performance was dichotomized (*low* or *high* performance) according to optimal classification. Dichotomization was done using the groups created based on the decision trees and bootstrapping. Using those two groups, optimal classification of those 'high performing' and 'low performing' athletes was determined at Youden's J (i.e., indicating optimal sensitivity and specificity). This binary performance outcome was included in a hierarchical logistic regression to determine whether the incorporation of additional measures of visual function would improve the classification of swimmers as those with low or high performance as opposed to a single visual function measure. For all analyses, the alpha threshold was fixed at .05.

## 3. Results

### 3.1. Confounding factors that could influence swimming performance

Correlations were first run between the measures of swimming performance and those variables that might confound any relationships between visual function and performance (i.e., age and training volume). Table 2 presents the correlations. Note that age and training volume were also highly correlated with each other ( $r = .79, p < .001$ ).

Because training volume had the highest correlation of the two confounders in almost all cases (mean lateral position being the exception), we chose to control for training volume. To check whether age should also be controlled for, partial correlations were run between age and each performance measure while controlling for training volume. Results indicated no remaining associations ( $|rs| \leq .27, ps \geq .14$ ). This suggested that performance need only to be adjusted according to training volume. Therefore, performance measures (except for mean lateral position) were adjusted for the athlete's total training volume in hours (i.e., we report the standardized residuals of the regression of training volume on each performance measures). The residuals can be interpreted as follows: zero represents the level of performance that would be expected based on the swimmer's training volume, a positive value represents poorer performance than what would be expected based on their training volume (e.g., +1 corresponds to a race time one standard deviation slower than expected), and a negative value represents better performance than expected based on their training volume (i.e., faster race time). For mean lateral position, a lower value represents a swim closer to the centre of the lane.

### 3.2. Relationship between visual function and swimming performance

#### 3.2.1. Excluding missing values for measures of visual function

Correlation analyses presented in Table 3 reveal VA to be significantly associated with each of the performance measures. CS was the only other visual function measure related to performance, with significant associations with the finish time and mean lateral position in the lane. Some visual function measures were correlated with each other, with VA and CS showing the strongest association ( $r = -.84, p < .001$ ; see Table 4). Partial correlations between CS and performance measures while controlling for VA confirm that there were no remaining associations for any of the performance measures ( $|rs| \leq .11, ps \geq .522$ ). These results provide the first suggestion that VA remains the best candidate measure of visual function for predicting swimming performance.

#### 3.2.2. Including missing values (using dummy values) for measures of visual function

The preceding analysis excluded from the correlations any participants for whom it wasn't possible to measure each visual function (i.e., we didn't use dummy variables). Accordingly, a relationship between VA and swim performance may be more likely because it was possible to measure VA for all participants, but not for any of the other visual functions (particularly for those athletes with only rudimentary vision). Therefore, we ran additional correlations when allocating dummy values to participants who were not able to complete each visual function test. All the significant correlations found previously remained (i.e., between VA, CS and performance), in addition to correlations between LS, DP, VS, and measures of swimming performance (see Table 3). However, almost all measures of visual function significantly correlated with each other when dummy values were allocated (Table 4). Partial correlations were conducted to determine

whether any of the visual function measures remained correlated with swimming performance while controlling for VA. Results revealed that only an association between DP and mean lateral position in the lane remained when controlling for VA ( $r = -.33, p = .049$ ; all other association between visual function and performance,  $|r| \leq .25, ps \geq .13$ ). These results provide further support for VA being the best predictor of swimming performance, but also suggest a potential association with DP.

### 3.2.3. Measures of performance

VA was used as the main measure of visual function for further analyses given its primacy as the key predictor of performance. To verify the relative impact of visual function on the different measures of swimming performance, partial correlations were conducted between VA and each of the performance measures while controlling for the best race time (i.e., theoretically and practically the most relevant measure of performance in swimming). Results revealed no further association between VA and start time ( $r = .14, p = .44$ ), clean speed ( $r = .05, p = .80$ ), or turn time ( $r = .04, p = .80$ ). Those measures of performance were therefore dropped from further analyses. However, VA remained related to finish time ( $r = .42, p = .012$ ) and mean lateral position in the lane ( $r = .68, p < .001$ ). In the following subsections, we explore how visual functions, with a specific emphasis on VA, is related to each of the three remaining measures of performance. Analyses are fully described for the best race time, but for the sake of brevity, only a summary of the findings (using the same analyses) are presented for finish time and mean lateral position.

#### 3.2.3.1. Best race time

A decision tree was conducted to find the optimal number of splits, and the border between them, to best differentiate race times on the basis of VA. Results revealed that a single split at a VA of 3.5 logMAR provided the best possible split (Figure 1a). Performance was significantly poorer in the group with VA worse than 3.5 logMAR ( $n = 11; M = 0.872$ ) than it was in the group with VA better than or equal to 3.5 logMAR ( $n = 34; M = -0.281$ ),  $t(17.64) = 3.88, p < .002, d = 1.35$ [1] (note though the lack of data between 2.6-3.5 logMAR). The algorithm found no further split based on VA. Because swimming races typically contain eight competitors, Figure 1b illustrates the top eight performers from each group. Results show that even the best athlete from the  $> 3.5$  logMAR group would not make the final if conducted for the top-8 performers in the  $\leq 3.5$  logMAR group.

We ran bootstrapping on the decision tree with replacement 10,000 times to confirm the validity of the single split. Results were indeed consistent with the single split at 3.5 logMAR. The dataset was found to split at least once in 55.0% of the 10,000 bootstrap samples, with a single split being the most likely outcome (54.3% of all cases). Two splits were found in only 0.7% of cases. Of the trees that found at least one cut-off point (Figure 2), the majority of the first splits were either at 3.5 logMAR (36.6%) or 2.6 logMAR (33.3%). The next most frequent were 2.2 logMAR (14.2%) and 2.5 logMAR (9.2%). **Fig. 1** Residual race time and VA for (a) all participants, and (b) the eight best performers in each group created on the basis of the decision tree analysis. Circles represent participants with VA  $> 3.5$  logMAR, and triangles represent participants with VA  $\leq 3.5$  logMAR. The crosses represent the means of each group, with the horizontal and vertical branches representing the standard errors of the means of VA and residual race time respectively

Having classified the data into two groups on the basis of VA, we sought to establish whether classification would improve if additional measures of visual functions were included. To do so, first the performance of each swimmer was itself classified as a binary outcome variable by using the optimal classification of those in the VA  $\leq 3.5$  logMAR as 'high performing' and those with VA  $> 3.5$  logMAR as 'low performing'. This optimal classification occurred when standardized residual best race time was 0.352 (i.e., at Youden's J, sensitivity = .85, specificity = .82). Performance was indeed poorer in those placed in the low performance group ( $n = 14; M = 1.19$ ) than it was in those placed in the high performance group ( $n = 31; M = -0.54$ ),  $t(21.43) = 8.42, p < .001, d = 2.98$ . **Fig. 2** Histogram of the first VA split points of best race time using 10,000 bootstrapped samples. The data split at least once in 5,498 cases

Second, a hierarchical logistic regression was performed to establish whether the incorporation of additional visual function measures would improve the classification of swimmers into those with low or high performance when compared to that possible when using VA alone. VA was forced into the model at Step 1 using the enter method, and the additional measures of visual functions were entered at Step 2 with a stepwise method. Dummy values for CS, LS, DP, VS and MP were used for participants not able to complete those tests. Not surprisingly, VA significantly predicted group membership at Step 1 before the addition of further variables ( $B = -1.26, S.E. = 0.39$ ), odds ratio = 0.28 (95 % C.I. = 0.13-0.61), where poorer VA indicated higher odds of being categorized in the low performance group, Nagelkerke  $R^2 = .36$  (82.2 % of correct classification). The goodness of fit Hosmer-Lemshow test was not significant,  $\chi^2(7) = 6.67, p = .464$ , indicating good reliability of the model. Vitality, the stepwise method found that no further predictors added to the quality of the prediction at Step 2 (i.e., no further significant predictors, and therefore no change in Nagelkerke  $R^2$  nor percentage of correct classification, see Table 5 for regression statistics). Results suggest that the use of VA alone provides the most parsimonious means of separating the group into two classes[2].

Table 6 presents the main results for finish time and mean lateral position, including the respective decision trees, bootstrapping, and logistic regressions. Three main conclusions differ between best race time and results regarding finish time and mean lateral position. First, the decision tree splits mean lateral position at 2.6 logMAR as opposed to 3.5 logMAR in best race time and finish time. However, the logistic regression to predict high/low performance suggests that VA alone is not sufficient to predict finish time, as VS and MP contribute to the quality of the prediction, and even replace VA at Step 2. However, the increase in percentage of correct classification is marginal (from 75.6% to 80.5%; Table 6). Similarly, VA alone is also not sufficient to predict mean lateral position, with DP contributing to the quality of the prediction (note though the decrease in the quality of correct classification from 89.5% to 86.9%; Table 6). Overall, results from finish time and mean lateral position suggest that other measures of visual function may be related to performance in some aspects of the swimming race, but that their addition does not practically improve the percentage of correct classification into high or low performing athletes.**3.2.3.2.**

#### Finish time and mean lateral position

### 3.3. Relationship between visual function and swimming performance for athletes with VA $\leq 3.5$ logMAR.

Further analyses were conducted on each measure of swimming performance within the groups created by the original decision tree to verify whether further splits would be needed. When VA was  $\leq 3.5$  logMAR, correlations were first run between visual function and performance measures. Then, linear multiple regression (enter method) was run to verify whether a combination of measures of visual function could be used to further predict performance.

### 3.3.1. Best race time

Correlation analyses were first run to establish any relationships between the best race time and visual function for athletes with VA  $\leq 3.5$  logMAR. No relationship was found for any measures of visual function ( $|rs| < .11$ ,  $ps > .54$ ; see Table 7 and Figure 3), suggesting that no further split may be necessary. Note that missing values were replaced with dummy values for CS, LS, DP, VS and MP.

Having ruled out the need to split the group using *individual* measures of visual function, we used linear multiple regression (enter method) to verify whether a *combination* of measures of visual function could be used to further predict best race time (i.e., whether one or more predictors predict performance when taking into account other predictors' influence on performance). Results revealed that, taken together, there was no combination of visual functions that were able to significantly predict the best race time,  $F(6, 27) = 0.36$ ,  $p = .897$ , Adjusted  $R^2 = -.13$  suggesting that no further split in this sub-group was necessary. **Fig. 3** Relationships between residual race time and each of the six measures of visual functions (a-f) for athletes with VA  $\leq 3.5$  logMAR

### 3.3.2. Finish time and mean lateral position

Table 8 summarises the results for finish time and mean lateral position, incorporating the respective correlations and multiple linear regression among athletes with VA  $\leq 3.5$  logMAR. Note that even if the initial decision tree for mean lateral position split the data at 2.6 logMAR, the analyses in this section were run on participants with VA  $\leq 3.5$  to facilitate comparison. The conclusions related to finish time and mean lateral position are the same as those from best race time, suggesting no further split was necessary.

When VA was  $> 3.5$  logMAR, a Welch t-test was conducted to examine whether light perception provided any performance advantage even though performance was measured with all athletes wearing blackened goggles to exclude all visual function during competition. Indeed, only two measures of VA were recorded for athletes with VA  $> 3.5$  logMAR (i.e., 3.7 or 4.0 logMAR for those with or without light perception respectively). The data were also examined by estimating a Bayes factor because of the sample size relative to the number of variables. **3.4. Relationship between visual function and swimming performance when VA  $> 3.5$  logMAR**

#### 3.4.1. Best race time

Results revealed no significant difference in the best race times of the athletes with light perception ( $n = 7$ ;  $M = 0.74$ ) and those without ( $n = 4$ ;  $M = 1.11$ ),  $t(8.97) = 0.80$ ,  $p = 0.447$ ,  $d = 0.47$ . The data were also examined by estimating a Bayes factor, comparing the fit of the data under the null hypothesis and the alternative hypothesis. An estimated Bayes factor suggested that the null hypothesis was 1.77 times more likely to be true than a model where there was a difference between the performance of those with and without light perception. This supports the preliminary suggestion that no further split is needed in athletes with VA  $> 3.5$  logMAR.

#### 3.4.2. Finish time and mean lateral position

Table 9 presents the main results for finish time and mean lateral position, that is for t-tests and Bayes factors among athletes with VA  $> 3.5$  logMAR. The conclusion related to finish time is the same as best race time, meaning that no further split is needed based on athletes with and without light perception. However, with respect to mean lateral position, the Bayes factor indicates that a further split could be made, with the alternate hypothesis 1.85 times more likely to be true than a model where there would be no difference between the performance of those with and without light perception.

[1] This split means that a S11 participant with VA = 3.5 logMAR was reclassified in the  $\leq 3.5$  logMAR group.

[2] Note that the interpretation of these results requires caution because of the low participant numbers. A suitable sample size for this analysis would typically have been  $N \approx 150$  ( $N = 10 k / p$ , where  $p$  is the smallest of the proportions of negative or positive cases and  $k$  is the number of predictors, here  $(10*6)/0.41$ ; [34]). Nonetheless, no other predictors were close to reaching significance.

## 4. Discussion

The aim of this study was to establish the relationship between visual function and performance in elite VI swimming. A test battery of visual function was administered to international level VI swimmers whose performance results were obtained from international competitions. The results confirm the necessity of visual information for optimal swimming performance, with swimmers with better visual function outperforming those with only rudimentary vision. However, the relationship between visual function and performance is not linear. In particular, the results revealed no measurable difference in the overall swimming performance of those athletes who had measurable VA, irrespective of how good or bad their VA was. VA remained the visual function best able to predict the overall performance of the swimmers (i.e., when considering best race time). However, performance in specific aspects of the swim race were also related to some small degree to other visual function measures such as a swimmer's DP, MP, and VS. These results not only help to further our understanding of the impact of VI on swimming performance, but also suggest that modifications are necessary to the current classification system used in VI swimming in the Paralympic Games.

### 4.1. Impact of VI on swimming performance

Despite criticism from experts that VA might not test an aspect of visual function likely to be vital for optimal swimming performance [6], the results of the present study show VA to be the *best* predictor of overall performance. Previous studies have indirectly inferred a relationship between VA and swimming

performance [25-27], but our study goes beyond this to show that it remains the *best* predictor of performance even when including other tests that might be more representative of the visual demands present when swimming. The primacy of VA was evident not only when examining correlations between measures of visual function and performance, but also when performing a logistic regression which showed that VA alone best predicts the high and low performing athletes based on their best race time. This result is probably because VA, as a measure, is likely to be a good proxy for a variety of different tests of visual function. Many often question why the test of VA is used for classification given that the task, that is, to distinguish the direction in which an 'E' or a grating is pointing, is not representative of the visual demands in sport. However, our results show that performance on the test of VA is highly correlated with numerous other measures of visual function which *are* assumed to be more functionally relevant in sport (e.g., DP, MP, CS; see Table 4). VA remains a good proxy for evaluating the overall capability of an athlete's visual system.

Having established VA as the visual function most closely related to overall race time, the present study also looked at the potential influence of other visual functions on the performance of specific aspects of a swimming race. More specifically, the results revealed that DP, VS, and MP help predicting *high* and *low* performing swimmers based on their finish time or mean lateral position in the lane. However, the practical implications of those results appear minimal, as the percentage of correct classification in those models was only marginally higher than that obtained when including VA alone, even with the addition of further predictors (i.e., less parsimonious models). In fact, a decrease in correct classification was even observed with respect to mean lateral position in the lane. Therefore, it remains questionable whether the benefits of including those additional measures of visual function to the classification procedure would outweigh the additional complexity and time associated with the inclusion of those measures. It is still noteworthy that although the contribution of these measures of visual function to performance is only modest, the findings do provide some support for the experts' opinion regarding the importance of other aspects of visual function in understanding VI swimming performance [6].

#### 4.2. Implications for classification in para-swimming

Previous studies comparing performance across pre-existing vision classes in swimming (S13, S12, S11) have suggested that only two classes may be necessary for VI swimming [25-27]. However, those studies were not able to establish what should be the borders between the classes and what measures of visual function are best to delineate those classes. The present study addressed those shortcomings by directly measuring visual functions to examine the continuous relationship between VI and swimming performance, rather than simply comparing the performance of different competition classes [37]. This approach allows us to make suggestions for empirically driven sports classes to improve classification for VI swimming.

The results of the present study are in agreement with the opinion of experts in VI swimming who had suggested that only two classes may be necessary to provide legitimate competition in VI swimming [6]. Indeed, our decision tree analyses support the idea that only two classes are necessary. A single split in performance was favoured at a VA of 3.5 logMAR for the best race time and the finish time, and at 2.6 logMAR for the mean lateral position in the lane. At first sight, the difference between these two values may seem substantial. However, in this and other studies, it is rare to find athletes with a binocular VA between 2.6 and 3.5 logMAR (which could be due to the way VA is generally measured [9, 15, 20, 22]). Indeed, there were none in our study. This suggests that a decision to place the split at either 2.6 logMAR or 3.5 logMAR is a relatively inconsequential one because very few athletes have a VA within this range.

An important nuance to those results needs to be highlighted, which comes from the fact that bootstrapping the decision trees with replacement 10,000 times yielded a high variability between cut-offs, ranging mainly between 2.1 logMAR and 3.5 logMAR. Even more important, approximately 45 % of the bootstrapped samples found no split in best race time according to VA (though almost all trees found at least one split when considering finish time and mean lateral position in the lane). In other words, with a different sample of athletes, the decision tree could have found a different threshold, or no threshold at all (i.e., suggesting that all swimmers should compete together). Krabben and colleagues [20] also recently found a large range of VA cut-off points rather than a unique value when examining the relationship between VI and performance in judo. The authors explained that research might be able to provide, at best, a *range* of VA cut-offs, rather than a definitive single value. The options raised by Krabben and colleagues [20] on how to resolve the final cut-off include (i) setting the cut-off at a conceptual border between partially sighted athletes and functionally blind ones, (ii) or at 2.9 logMAR, which is the highest numeric VA value measurable by the BRVT [30], (iii) or that the decision should not be entirely scientifically based, but that it could also be an ethical issue that requires the input of multiple relevant stakeholders (e.g., athletes, coaches, scientists, sports philosophers).

The present study found little evidence to suggest that there would be any benefit of including a third class by separating the athletes who had some measurable visual function (i.e., VA < 3.5 logMAR). Effectively, these results are in disagreement with the current system of classification whereby athletes in the S12 and S13 classes are separated into distinct classes. The existing system implicitly suggests that S12 swimmers would have a disadvantage if they were to compete against S13 swimmers, however, our findings do not support this. Instead, S12 swimmers appear to have no disadvantage if competing against S13s. Given that some of our results showed relationships between specific visual functions (i.e., VS, DP, and MP) and specific aspects of the race (i.e., finish time and mean lateral position in the lane), it would remain possible that a specific class of athletes may exist in the S12 and S13 classes who are disadvantaged because of an impairment to a visual function that is important for swimming, but is not yet assessed during classification. Therefore, one could ask whether competition would be more legitimate for those athletes if other visual functions would be included in the classification procedure. In other words, would there be difference in performance between classes newly formed on the basis of further testing? We found no relationship between any visual function and overall performance, finish time and mean lateral position in the lane for athletes with VA ≤ 3.5 logMAR (Figure 3 and Table 8). It appears that further testing would not support a split between the S12 and S13 swimmers (or any other newly formed subgroups), contradicting the necessity of further tests of visual function for classification purpose.

There was some suggestion that a split might be necessary within the group of functionally blind swimmers (i.e., with light perception or no light perception), though such a split is unlikely to ever be practically necessary. Athletes with light perception appeared to have a modest advantage in their ability to remain in the middle of the lane while swimming, even though they swim with blackened goggles during competition. Caution is warranted though given the low participant numbers within that group (i.e., seven swimmers with light perception and four without) and that the association was only with the mean lateral

position in the lane and not with overall race time or any other measures of performance. Moreover, given the relatively low number of athletes with only light perception or no light perception taking part in VI competition [9, 15, 20, 22], a split within that class would result in two classes with very few athletes and therefore in a relatively low level of competition.

Within our study, the performance of the S11 swimmers was evaluated while swimming in competition with blackened goggles. It remains possible that the S11 athletes with light perception *could* have performed better if allowed to swim without the goggles. If that would have been to be the case, then it would provide some further support for the need to consider splitting those S11 swimmers into two separate classes *if* a decision was made to allow those swimmers to compete without blackened goggles (or even for them to compete against those athletes with measurable visual function). However, in our experience, those athletes with light perception anecdotally report that their visual function is so rudimentary that the benefit of swimming without goggles is negligible. Moreover, the experts in VI swimming remain largely satisfied with the use of blackened goggles during competition and so there is no plan to change the current requirement for S11 athletes to wear blackened goggles [6]. Finally, another limitation of the present study stems from the fact that only 100m freestyle swimmers were included.

## 5. Conclusions

The present study sought to further the development of a sport-specific system of classification in VI swimming by examining the relationship between visual function and performance in the sport [37, 38]. Our findings suggest that a two-class system with a separation based on VA (and only VA) somewhere between 2.6 and 3.5 logMAR would provide legitimate competition for athletes with VI. The opinions of key stakeholders in the sport and Paralympic movement (e.g., athletes, coaches, scientists, sport philosophers) would be useful to establish the most suitable cut-off between the two classes.

## 6. Declarations

### Funding

This study has been carried out with the support of a Classification Research Grant from the International Paralympic Committee.

### Conflicts of interest

The authors declare no conflict of interest.

### Availability of data and material

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

### Code availability

The code generated during the current study is available from the corresponding author on reasonable request.

### Author contributions

Conceptualization: Rianne Ravensbergen, David L. Mann; Methodology: Rianne Ravensbergen, David L. Mann; Formal analysis and investigation: Daniel Fortin-Guichard, Kai Krabben, Rianne Ravensbergen, David L. Mann; Writing - original draft preparation: Daniel Fortin-Guichard, David L. Mann; Writing - review and editing: Daniel Fortin-Guichard, David L. Mann, Kai Krabben, Rianne Ravensbergen, Peter M. Allen; Funding acquisition: David L. Mann, Peter M. Allen; Resources: David L. Mann, Peter M. Allen.

### Ethics approval

The study was approved by the institutional ethics committee of the Faculty of Behavioural and Movement Sciences of the Vrije Universiteit Amsterdam. The study was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

### Consent to participate

All participants provided written informed consent prior to participation. Parental consent was obtained for participants aged under 18 years.

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## 8. Tables

Table 1 *Characteristics of VI athletes according to sports classes.*

Variables	Sport Class		
	S13 (n = 19)	S12 (n = 14)	S11 (n = 12)
% women	58 <sup>a</sup>	29 <sup>a</sup>	58 <sup>a</sup>
Mean age (SD)	18.3 <sup>a</sup> (4.1)	21.6 <sup>a</sup> (5.5)	23.8 <sup>a</sup> (9.9)
Mean number of lifetime swimming training hours (SD)	5600 <sup>a</sup> (3329)	8274 <sup>a</sup> (5234)	7170 <sup>a</sup> (3911)
% health condition			
Albinism	16	0	0
Anterior eye	11	7	0
Macula	37	29	0
Nystagmus	0	7	0
Optic nerve	5	21	42
Retinal	5	29	42
Retinal + Macula	26	7	8
Whole eye	0	0	8

Note. Same letters (i.e., a) in superscript indicate no difference after Bonferroni correction ( $p < .05$ ) when compared to other groups. For the type of VI, frequencies were too small to run meaningful analyses. SD = Standard deviation

Table 2 Relationship between potential confounders and performance measures

Confounders	Performance measures					
	BRT (n = 45)	ST (n = 40)	CSp (n = 40)	TT (n = 42)	FT (n = 41)	MLP (n = 38)
Training volume (hours)	-.42**	-.50**	.34*	-.52***	-.34*	.01
Age	-.31*	-.38*	.28	-.38*	-.17	.14

\*  $p < .05$ , \*\*  $p < .01$ , \*\*\*  $p < .001$

Note. BRT = Best race time, CSp = Clean speed, FT = Finish time, MLP = Mean lateral position, ST = Start time, TT = Turn time.

Table 3 Correlation between visual functions and performance measures with and without missing values.

Visual functions	Performance measures					
	BRT	ST	CSp	TT	FT	MLP
Excluding missing values						
Visual acuity	.40**	.39*	-.32*	.32*	.54***	.71***
Contrast sensitivity	-.30	-.33	.28	-.21	-.50**	-.60***
Light sensitivity	-.06	.25	-.02	.07	.01	-.21
Depth perception	.06	-.09	.04	-.10	-.07	-.10
Visual search	-.20	.11	.05	-.05	.11	-.30
Motion perception	.09	-.23	-.17	-.04	.11	.37
Including missing values (using dummy values)						
Visual acuity	.40**	.39*	-.32*	.32*	.54***	.71***
Contrast sensitivity	-.27	-.27	.23	-.17	-.42**	-.54***
Light sensitivity	.27	.37*	-.23	.25	.34*	.41**
Depth perception	.32*	.23	-.22	.18	.42**	.47**
Visual search	.35*	.35*	-.26	.25	.56***	.53***
Motion perception	-.06	-.21	-.02	-.10	-.10	-.15

\*  $p < .05$ , \*\*  $p < .01$ , \*\*\*  $p < .001$

Note. BRT = Best race time, CSp = Clean speed, FT = Finish time, MLP = Mean lateral position, ST = Start time, TT = Turn time. The number of participants included in each correlation vary between  $n = 24$  and  $n = 45$ .

Table 4 Correlation matrix of visual functions for all participants with and without missing values.

Visual functions	1	2	3	4	5
Excluding missing values					
1. Visual acuity					
2. Contrast sensitivity	-.84***				
3. Light sensitivity	-.03	-.44*			
4. Depth perception	.44*	-.38	-.10		
5. Visual search	.25	.04	.10	.02	
6. Motion perception	-.38	.10	-.04	-.23	-.46*
Including missing values (using dummy values)					
1. Visual acuity					
2. Contrast sensitivity	-.79***				
3. Light sensitivity	.59***	-.76***			
4. Depth perception	.80***	-.80***	.55***		
5. Visual search	.77***	-.62***	.49***	.64***	
6. Motion perception	-.38**	.38**	-.26	-.51***	-.50**

\*  $p < .05$ , \*\*  $p < .01$ , \*\*\*  $p < .001$

Note. The number of participants included in each correlation vary between  $n = 27$  and  $n = 45$ .

Table 5 Hierarchical logistic regression of all visual functions on best race time, with VA being forced into the model at step 1, and other visual functions entered with a stepwise method at step 2.

Variables	$\chi^2_w$	$p$
Step 1		
<b>Intercept</b>	<b>13.28</b>	<b>&lt;.001</b>
<b>Visual acuity</b>	<b>10.56</b>	<b>.001</b>
Step 2		
<b>Intercept</b>	<b>13.28</b>	<b>&lt;.001</b>
<b>Visual acuity</b>	<b>10.56</b>	<b>.001</b>
Contrast sensitivity	1.61	.205
Light sensitivity	0.03	.855
Depth perception	0.82	.365
Visual search	0.26	.613
Motion perception	1.68	.195

Note. Bold indicate predictors kept in the model

Table 6 Results summary for finish time and mean lateral position for athletes with VA  $\leq$  3.5 logMAR

Main outcomes							
Performance measures	Decision tree split	Performance difference	Trees with at least one split	Frequency of first split	Splitting performance	Logistic regression included at step 1	Logistic regression included at step 2
Finish time	Single split at 3.5 logMAR	> 3.5 logMAR	91.36%	2.2 logMAR 26.5%	Youden's J 0.116	Intercept $p < .001$	Intercept $p = .030$
		$n = 11$ $M = 1.004$		3.5 logMAR 26.1%	Sensitivity .77	Visual acuity	Visual acuity
		$\leq$ 3.5 logMAR		2.6 logMAR 23.7%	Specificity 1.00	$p < .002$	$p = .409$
		$n = 30$ $M = -0.361$		2.1 logMAR 11.2%		$\chi^2 = 13.54$	Visual search $p = .024$
		$t(21.912) = 5.22,$ $p < .001, d = 1.7$		Others 12.5%		Nag. $R^2 = .38$	Motion perception $p = .046$
						% Cor. Class. = 75.6	$\chi^2 = 21.44^*$
							Nag. $R^2 = .55$
							% Cor. Class. = 80.5
Mean lateral position	Single split at 2.6 logMAR	> 2.6 logMAR	99.97%	2.6 logMAR 44.6%	Youden's J 0.505	Intercept $p < .001$	Intercept $p = .997$
		$n = 12$ $M = 0.689$		2.5 logMAR 27.4%	Sensitivity .85	Visual acuity	Visual acuity
		$\leq$ 2.6 logMAR		2.2 logMAR 17.8%	Specificity .91	$p < .001$	$p = .009$
		$n = 26$ $M = 0.277$		Others 10.2%		$\chi^2 = 22.59$	Depth perception <sup>a</sup> $p = .070$
		$t(23.79) = 7.37,$ $p < .001, d = 2.5$				Nag. $R^2 = .61$	$\chi^2 = 27.70^*$
						% Cor. Class. = 89.5	Nag. $R^2 = .71$
							% Cor. Class. = 86.8

Notes. % Corr. Class= Percentages of correct classification, Nag.  $R^2$  = Nagelkerke  $R^2$ .

<sup>a</sup> Predictor is kept in the model despite  $p > .05$ , because the selection criteria was based on the AIC.

\* Indicates a significant change in  $\chi^2$  from step 1 to step 2.

Table 7 Correlation matrix for measures of visual functions and best race time for participants with VA  $\leq$  3.5 logMAR.

Variables	1	2	3	4	5	6
1. Best race time						
2. Visual acuity	-0.09					
3. Contrast sensitivity	.07	-.65***				
4. Light sensitivity	-.03	.30	-.64***			
5. Depth perception	.03	.68***	-.68***	.32		
6. Visual search	.05	.53**	-.35*	.20	.39*	
7. Motion perception	.11	-.34	.29	-.14	-.45**	-.45**

\*  $p < .05$ , \*\* $p < .01$ , \*\*\*  $p < .001$

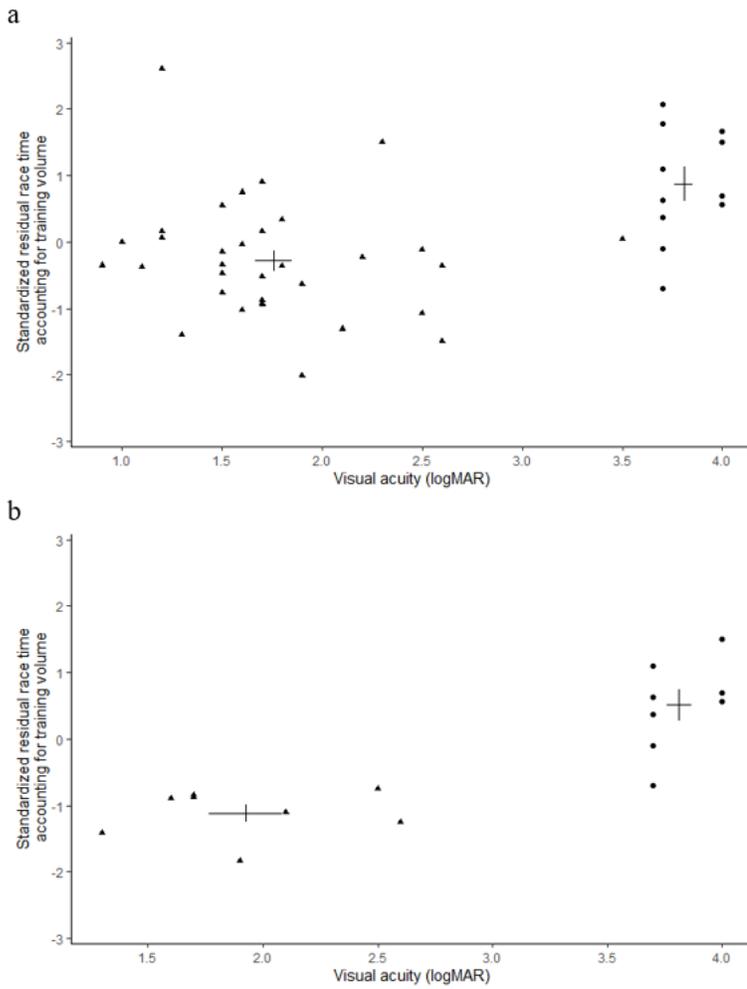
Table 8 Results summary for finish time and mean lateral position for participants with VA  $\leq$  3.5 logMAR.

Performance measures	Main outcomes	
	Correlations with visual function measures	Multiple linear regression
Finish time	$ rs  < .28$ $ps > .131$	$F(6, 23) = 0.94$ $p = .49$ Adjusted $R^2 = -.01$
Mean lateral position	$ rs  < .19$ $ps > .341$	$F(6, 20) = 0.59$ $p = .74$ Adjusted $R^2 = -.11$

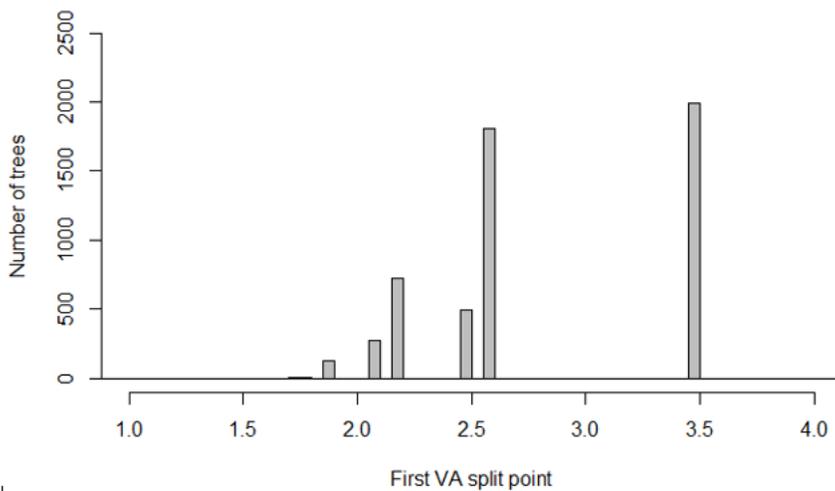
Table 9 Results summary for finish time and mean lateral position for participants with VA  $>$  3.5 logMAR.

Main outcomes		
Performance measures	t-test	Bayes factor
Finish time	Light perception $n = 7$ $M = 0.87$	1.63 times more likely to have no effect of light perception on performance.
	No Light perception $n = 4$ $M = 1.25$	
	$t(7.35) = 0.91, p = .39$	
	$d = 0.6$	
Mean lateral position	Light perception $n = 7$ $M = 0.62$	1.85 times more likely to have an effect of light perception on performance.
	No Light perception $n = 4$ $M = 0.82$	
	$t(6.73) = 2.32, p = .06$	
	$d = 1.6$	

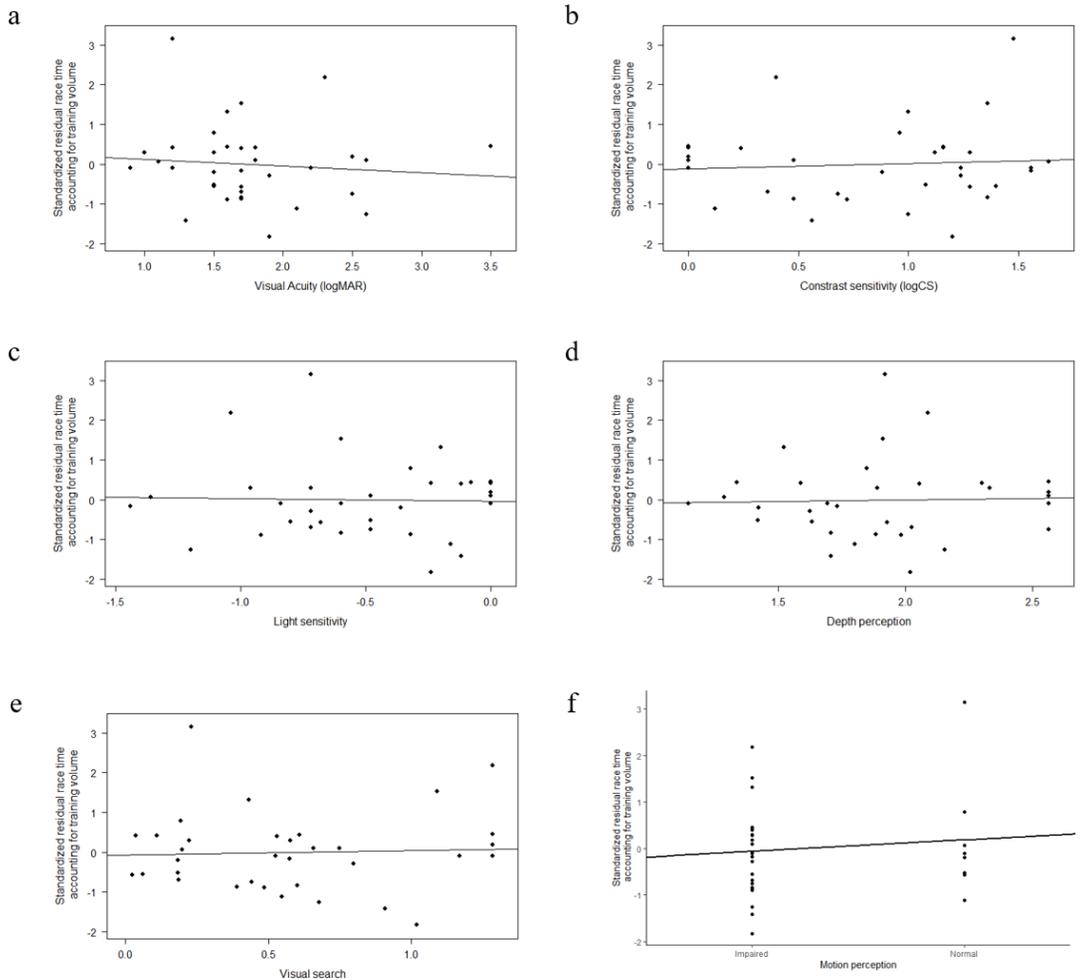
## Figures



**Figure 1**  
 Residual race time and VA for (a) all participants, and (b) the eight best performers in each group created on the basis of the decision tree analysis. Circles represent participants with VA > 3.5 logMAR, and triangles represent participants with VA ≤ 3.5 logMAR. The crosses represent the means of each group, with the horizontal and vertical branches representing the standard errors of the means of VA and residual race time respectively



**Figure 2**  
 Histogram of the first VA split points of best race time using 10,000 bootstrapped samples. The data split at least once in 5,498 cases



**Figure 3**

Relationships between residual race time and each of the six measures of visual functions (a-f) for athletes with VA  $\leq 3.5$  logMAR