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Refractive Intervention

Monovision Correction Preference and Eye Dominance Measurements

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Purpose: To propose new methods for eye selection in presbyopic monovision corrections.

Methods: Twenty subjects with presbyopia performed two standard methods of binary eye dominance identification (sensory with +1.50 diopters [D]and +0.50 D and sighting with “hole-in-the-card”) and two psychophysical methods of perceived visual quality: (1) the Preferential test, 26 natural images were judged with the near addition in one eye or in the other in a 2-interval forced-choice task, and the Eye Dominance Strength (EDS) defined as the proportion of trials where one monovision is preferred over the other; (2) the Multifocal Acceptance Score (MAS-2EV) test, the perceived quality of a natural images set (for 2 luminance levels and distances) was scored and EDS defined as the score difference between monovision in one eye or the other. Left-eye and right-eye dominance are indicated with negative and positive values, respectively. Tests were performed using a Simultaneous Vision Simulator, which allows rapid changes between corrections.

Results: Standard sensory and sighting dominances matched in only 55% of subjects. The Preferential EDS (ranging from −0.7 to +0.9) and MAS-2EV EDS (ranging from −0.6 to +0.4) were highly correlated. Selecting the eye for far in monovision with the MAS-2EV, sensory, or sighting tests would have resulted in 79%, 64%, and 43% success considering the Preferential test as the gold standard.

Conclusions: Tests based on perceptual preference allow selection of the preferred monovision correction and measurement of dominance strength.

Translational Relevance: The binocular visual simulator allows efficient implementation of eye preference tests for monovision in clinical use.

Introduction

Monovision is a widespread treatment strategy for presbyopia, the age-related loss of dynamic focusing of the eye from far to near vision, where one eye is corrected for far vision and the other for near vision. In conventional clinical practice, the eye considered dominant is corrected for far vision, and the nondominant is corrected for near vision.[1,2] Numerous tests for eye dominance have been proposed in the literature and a few are performed clinically, yet it is not clear whether the dominance that they capture is relevant to the prescription of monovision. The tests used can be grouped into three categories[3]: (1) sighting dominance test, (2) binocular rivalry tests, and (3) sensory dominance tests.

Sighting dominance tests identify the eye that is selected to look at a (far) target, such as the “hole-in-the-card” test.[4] Because of the simplicity of this test, it remains the dominance test of choice in most clinics, and monovision correction is frequently prescribed based on this test. The relation of that selection to comfort or preference in monovision is not conclusive.[5]

Traditional psychophysical tests based on binocular rivalry measure the relative duration of the period of predominance of each eye, which may be considered a measurement of eye dominance (see Evans 2007[5] for a review). There have been proposals to use rivalry tests to identify the dominant eye in the clinic, for possible applications in monovision management. However, the dominant eye identified by binocular rivalry methods appears to depend on the variables of the test[6,7] and the retinal location,[8] as they may be eliciting different mechanisms.[9]

Blur suppression is presumably easier in the nondominant eye.[10,11] For this reason, several proposed ocular dominance tests rely on finding the eye that best suppresses images that contain artifacts (such as blur) and assigns the contralateral eye to be the dominant eye (sensory dominant by inhibition). Typical measurements of sensory dominance in the clinic involve the introduction of monocular dioptric blur (normally +1.50 D).[5] The patient compares the comfort during right-eye versus left-eye blurring while viewing binocularly an optotype at far distance. The dominant eye is the one with which the patient feels less comfortable upon induction of the blur. This approach appears to be more directly related to monovision as, ultimately, the most comfortable far/near eye combination of lenses is sought in a monovision treatment.

Several studies found discrepancies among tests applied on the same subjects.[12–15] There is strong evidence that the sighting eye dominance and sensory dominance do not necessarily reside in the same eye of an individual.[15,16] This supports the idea that sighting eye dominance does not even have a relevant underlying physiological cause and may just be the result of a "habit".[3] The clinical literature on the impact of the choice of the eye on the outcomes of monovision is contradictory,[5] likely as a result of the lack of a well-defined test for eye dominance and even a conclusive definition of eye dominance, suggesting that the selection of the eye for monovision based on eye dominance could be, to some extent, arbitrary.

A better way to determine whether a patient must be compensated with conventional (far vision in the dominant eye) or crossed monovision (near vision in the dominant eye) may be to directly measure the preference of each correction. To a large extent, the clinical sensory test evaluates the preference to blur introduced to one or the other eye. However, it has limitations, as the trial lenses that are held in front of the patient's eye can produce interocular differences in magnification and prismatic effects. In addition, the lenses need to be changed and the results recorded manually, making an increase in the number of repetitions lengthy and inefficient. The test can also be performed with contact lenses, allowing a more faithful representation of monovision by eliminating magnification and prismatic differences, though it is impractical for multiple testing. Besides, for both the trial lenses and the contact lenses version, the eye which is blurred is not masked to the patient.

Binocular vision simulators[17–19] allow the presentation of monovision corrections. The SimVis Gekko is a head-mounted see-through binocular simultaneous vision simulator that uses tunable lenses (which mimic spherical or multifocal corrections)[23] projected onto the eye's pupil plane, allowing a noninvasive and rapid switching of the near add between the eyes without magnification differences. This device allows efficient and effective measurements of monovision correction preferences. In earlier studies,[21,22] we introduced the Multifocal Acceptance Score (MAS-2EV), which is a test that uses natural images to measure perceived visual quality with presbyopic corrections (multifocal lenses, monovision, and modified monovision) at near/far, and under day/night conditions, showing its suitability for fast measurements of monovision corrections.

The main goal of this study is to determine directly in which eye patients prefer the near addition in monovision corrections and compare the selection of the eye to be corrected for far, with that obtained from conventional methods of eye dominance measurement. For that purpose, we present two new eye dominance scores from the preference tests performed using the SimVis Gekko and naturalistic stimuli. In both tests, eye dominance (and the strength of dominance) is directly obtained by quantifying perceived visual quality through monovision between the two eyes. We also measured the conventional sighting and sensory eye dominance tests. We hypothesize that the new psychophysical tests based on monovision preference provide a more precise description of the eye dominance relevant for that presbyopia correction than the conventional tests. To address this hypothesis, we compared the eye dominance provided by the two conventional tests (left or right eye) and the two new psychophysical tests (both eye and dominance strength) and estimated the expected success of the monovision correction had the conventional or new tests been applied.

Methods

Subjects

Twenty subjects with early presbyopia (51 ± 5 years old) participated in the study. All subjects had normal stereovision (<40 arc seconds), normal color vision, and no history of eye surgery, amblyopia, or any other eye disease. The spherical error ranged between −2.50 and +2.50 diopters (D) and the cylindrical error from −0.75 to 0.00 D. The required addition for near vision ranged from +1.25 to +2.25 D, determined as the minimum addition needed to achieve 0.00 logMAR visual acuity with a near vision eye chart binocularly. Subjects were habitually corrected for far vision with spectacles or contact lenses and 14 of them used a near aid to read. None of the subjects had their presbyopia corrected with monovision. The study followed the tenets of the Declaration of Helsinki. Study protocols were approved by the Spanish National Research Council (CSIC) Institutional Review Board. Subjects signed a consent form after receiving an explanation of the nature and possible consequences of the study.

Apparatus

The binocular Simultaneous Vision Simulator SimVis Gekko (2EyesVision SL, Madrid, Spain)[23] was used to rapidly (in less than 0.5 seconds) switch the optical power between both eyes of the patient. The variable optical power was induced by two tunable lenses (Optotune Inc., Dietikon, Switzerland). Previous calibrations show a precision of 0.05 D in the power induced by the system.[23] Far distance refraction (sphere and cylinder) was applied with a trial lenses holder in the SimVis Gekko, according to the subject's spectacle prescription, and adjusted using the fogging technique for the sphere and Jackson's Cross Cylinder for astigmatism, following standard optometric procedures,[24] to guarantee accurate baseline refraction.

The Psychophysical Toolbox-3[25] of MATLAB (Math Works Inc., Natick, MA, USA) was used for stimuli presentation and response collection. Custom-developed software was written in MATLAB to control the optical power in the right and left eye channels of the SimVis Gekko and to synchronize the sequence of images presented on the displays with the sequence of corrections programmed in the device.

Far vision stimuli were presented on a UK UHD 49-inch monitor LG49UH850V (LG, South Korea), driven by an NVIDIA Quadro P4000 dual Graphic card. The display resolution is 3840 × 2160 pixels, with a refresh rate of 60 Hz, and maximum luminance of 200 cd/m^2. This display was used for the sensory eye dominance and sighting eye dominance targets (subject located at 4 m) and to present the far images for the Preferential test and far MAS-2EV test. The subjects viewed the display from 2 m for the last 2 tests.

Near vision stimuli were presented on a 10.1-inch tablet (Commander3D, Toronto, Canada), driven by a PowerVR SGX544 Graphic card. The tablet's resolution is 1920 × 1200, with a refresh rate of 30 Hz, and maximum luminance of 8.75 cd/m^2.[26] This display was used for the near Preferential test and the near MAS-2EV test. The subjects viewed the tablet from 40 cm.

Experiments

We measured eye dominance using two clinical methods (sighting eye dominance and sensory eye dominance, each providing a binary metric, left- or right-eye dominance) and performed two tests that quantified the preferred combination of monovision (far correction in the right or the left eye), using a two-interval forced choice paradigm (Preferential test) and a perceptual scoring test (MAS-2EV test). Those two tests provide a measure of the ocular dominance strength (under a monovision correction). The monovision corrections were automatically and randomly changed using a wearable binocular simultaneous-vision simulator (SimVis Gekko) that projected optotunable lenses onto the eye's pupil. Unless otherwise noted, all tests were conducted in a room with the lights on (400 lux).

Measurements were performed by an experienced optometrist. The experimenter first performed the clinical sensory and sighting eye dominance tests. Subsequently, the Preferential and MAS-2EV tests were done at far and at near. The conditions (conventional or crossed monovision) were presented in random order and the experimenter was blind to the results of the Preferential and MAS-2EV tests.

Clinical Sensory Dominance

We tested sensory dominance using a clinical test that evaluates the tolerance to interocular blur difference placing a positive trial lens in front of one eye while the fellow eye is kept in focus. We performed the test with two levels of positive defocus (+1.50 D and +0.50 D) in front of the right and left eyes alternately while the subject was looking binocularly at a far distance letter stimulus of 0.2 logMAR size larger than their best visual acuity. The subject had to indicate the eye that appears more bothered by defocus blur, which is considered to be the dominant eye. This procedure was repeated three times (randomly assigning the first eye where the trial lens was placed) for the two levels of defocus. The order of the first level of defocus evaluated was also randomized. The dominant eye was determined if the subject selected the same eye two or three times. The result of the test was recorded as –1 for left-eye dominance and +1 for right-eye dominance. The sensory dominance test was only performed for far vision, and it took typically 45 seconds for each blur level, in total, 1.5 minutes.

Sighting Eye Dominance

We measured sighting eye dominance using the "hole in the card" method.[4] Subjects were asked to look at a stimulus (an optotype of 0.2 logMAR size larger than their best visual acuity) at far distance with both eyes open through the hole in the card held in both hands with arms stretched forward. The experimenter then covered each eye alternately and the subject had to indicate if the letter disappears when either the right or the left eye was covered. The dominant eye is the one where the letter disappeared when covered. In this study's notation, –1 indicates left-eye dominance, and +1, right-eye dominance. The sighting eye dominance test was performed only for far vision, and it took typically under 60 seconds to be performed.

Preferential Test

Subjects had to indicate whether the perceived quality of an image is preferred with the monovision correction (near addition of +2.00 D) induced in the near addition of the left eye (NAL) or in the near addition of the right eye (NAR) presented with the SimVis Gekko, in a Two Interval Forced-Choice (2IFC) task. In each trial, the monovision correction was induced in one eye for 1.5 seconds, then the monovision correction was flipped to the other eye for 1.5 seconds. An inter-interval gray screen was presented for 0.7 seconds between intervals. The eye in which monovision was first induced was randomized for each trial (Fig. 1).

Subjects judged a total of 26 different natural images extracted from the "Barcelona Calibrated Images Database,"[27] and generally contained scenes of vegetation and fruits (1/f spatial spectrum). Images were achromatic grayscale and subtended an 8 × 8 degrees field both for far and near vision. The display for far vision was physically located 2-m from the subject, but optically at infinity using +0.50 D lenses in the trial lens holder of the SimVis Gekko. The near distance was 40 cm, but optically at infinity with the use of +2.50 D lenses. Subjects viewed the same image twice, in counterbalance order, for a total of 52 trials, therefore assessing their preference for NAL or NAR for 26 natural images. Eye Dominance Strength (EDS) is defined as the proportion of trials that the subject prefers monovision in one eye. For far vision, a stronger preference for NAL indicates right-eye dominance (+1) and for NAR indicates left-eye dominance (−1). For near vision, a stronger preference for NAL indicates left-eye dominance (−1) and for NAR indicates right-eye dominance (+1). The Preferential test was performed for far and near vision and took about 7 minutes to be run for each distance.

Multifocal Acceptance Score

The MAS-2EV is a multicomponent metric to measure the perceived quality of natural images with a given presbyopic (monovision) correction.[21] Previous work has demonstrated the use of MAS-2EV both in combination with contact lenses and with corrections simulated in the SimVis Gekko to measure perceived quality with multifocal lenses, standard monovision, or modified monovision.[21,22] Subjects judged the perceived quality of images from two distances and under two illumination conditions (far-day; far-night; near-day; and near-night). Images for every distance and illumination condition represented common visual activities. The far images subtended 27 × 15 degrees and were presented on the far monitor. The near images subtended 5.5 × 3.5 degrees and were presented on the tablet. The room lights were turned off for the far-night and near-night conditions. For the far-night component, two white LEDs are superimposed on the headlights of a car in the left image of the far-night stimulus to simulate glare.

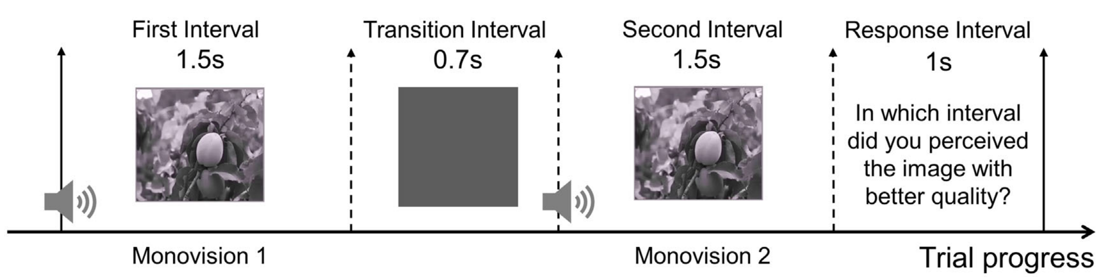

Figure 1. Trial sequence in the Preferential test. A representative trial of the test is shown. In each interval, a monovision condition (randomly NAL or NAR) is presented for 1.5 seconds, separated by a gray field (during 0.7 seconds) and an auditory tone (speaker). Subjects were given 1 second to respond between trials. The example shows one of the 26 natural images used. The test consisted of 52 trials.

In every component, each subject scored the perceived image quality on a scale from 0 to 10, although data are reported scaled from 0 to 1, for comparison purposes with other tests. Each scoring was repeated three times (final scores are obtained as the average across repetitions). The four components are plotted in a polygon, where the left-upper corner represents the score for far-night, the right-upper corner for far-day, the bottom right corner for near-day, and the left-bottom corner for near-night.

The MAS-2EV test was performed for three different corrections: far vision in both eyes (FF), and monovision with +2.00 D in the left eye (NAL) and in the right eye (NAR). The SimVis Gekko was used to automatically induce the FF, NAL, and NAR corrections. For a given correction, the scoring of 3 conditions takes about 2 minutes.

The difference between MAS-2EV for NAR minus NAL (Equation 1) defines the EDS metric that indicates MAS-2EV score dominance (left or right eye) in a monovision correction and is calculated for far and near (averaging the day and night scores).

$$EDS_{MAS} = MAS_{NAR} - MAS_{NAL} \quad (1)$$

All Experiments

To compare between experiments, each test provides a value varying from −1 to +1, as explained in each section above. For conventional tests (sighting and sensory) the eye dominance can only be binary, −1 (left-eye dominance) or +1 (right-eye dominance). For the Preferential test and the MAS-2EV, the eye dominance value can vary continuously within that range, providing a metric for the EDS, defined above. If strength falls between −0.1 and +0.1, it is said that the eye does not have a clear dominance.[28] Values between −1 and −0.1 stand for left-eye dominance and between +0.1 and +1 stand for right-eye dominance.

Statistical Analysis

Paired *t*-tests and correlation coefficients are used to compare between same measurements performed at far and near distances, in all experiments. The Chi-square test is used to compare the results of the clinical dominance tests, $P < 0.05$ is considered significant. Reliability analysis is performed for the Preferential test to estimate the number of trials needed to obtain a Cronbach alpha value of 0.9. Point-biserial correlation coefficient and two-tailed unpaired *t*-test with equal variances for the correlation coefficient were estimated to determine the association between clinical tests (binary response) and psychophysical tests.

Results

We compared the eye dominance identified by two clinical tests with the monovision preference (in a preferential perceptual preference and a perceptual scoring tests). Results are shown with subjects ordered according to the EDS calculated from the Preferential test.

Clinical Sensory and Sighting Eye Dominance

Figure 2 shows the eye dominance evaluated with the blur tests (sensory eye dominance) with +1.50 D and +0.50 D tolerance and the "hole-in-the-card" test (sighting eye dominance). We found right-eye dominance in 45% of the subjects using the sensory dominance test with +1.50 D, 60% using the sensory dominance test with +0.50 D, and 60% using the sighting eye dominance test. Comparing both sensory tests, 75% of the subjects selected the same eye dominance ($X^2(1) = 5.69$, $P = 0.02$). Sensory dominance and sighting dominance were in agreement in 75% of the subjects for 1.50 D ($X^2(1) = 5.69$, $P = 0.02$) and in 60% for 0.50 D ($X^2(1) = 0.56$, $P = 0.46$). Only 55% subjects selected the same eye using all 3 clinical tests.

Preferential Test and Monovision

The Preferential test was a 2IFC task between conventional monovision and crossed monovision (for a near addition of +2.00 D). Figure 3 shows an

Figure 2. Eye dominance with clinical eye dominance tests for all subjects. The −1 stands for left-eye dominance and +1 is for right-eye dominance. *Dark and light green bars* represent sensory eye dominance using +1.50 D and +0.50 D blur, respectively, and *dark magenta* represents sighting eye dominance.

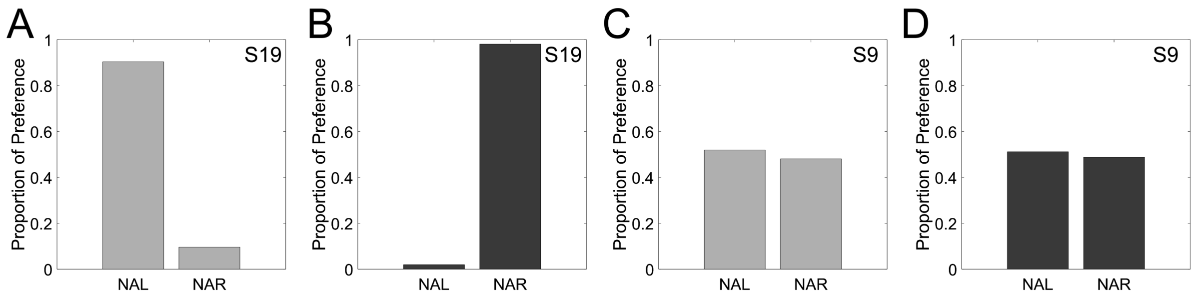

Figure 3. Examples of individual subjects' results with the Preferential test. (**A**) For subject 19 for far vision, the proportion of preference for monovision in the left eye (NAL) and monovision in the right eye (NAR). (**B**) For subject 19 for near vision, the proportion of preference for NAL and NAR. This subject has a strong monovision preference and, consequently, high EDS. (**C**) For subject 9 for far vision, the proportion of preference for NAL and NAR conditions. (**D**) For subject 9 for near vision, the proportion of preference for monovision NAL and NAR. This subject is an example of weak monovision preference and, consequently, low EDS.

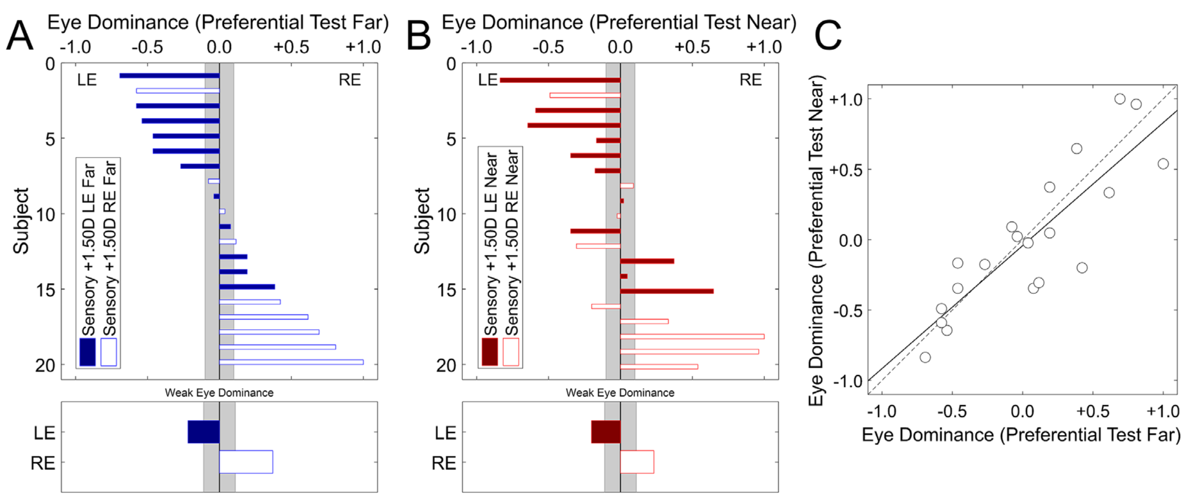

Figure 4. Eye Dominance Strength (EDS) with the Preferential test. (**A**) Preferential test EDS for far vision (all subjects). *Filled blue bars* indicate that the subject selected left-eye dominance with the clinical Sensory dominance test with +1.50 D and *empty blue bars* that the subject selected right-eye dominance. The *shaded gray band* indicates weak dominance (±0.1). Results above +0.1 indicate right-eye dominance, and below –0.1 left-eye dominance. Bottom subplot represents the average Preferential test EDS across subjects that selected left-eye dominance with clinical Sensory dominance test with +1.50 D (*filled blue bar*) and right-eye dominance (*empty blue bar*). (**B**) Preferential EDS for near vision (all subjects). *Filled red bars* indicate that the subject selected left-eye dominance with the clinical Sensory dominance test with +1.50 D and the *empty red bars* indicate that the subject selected right-eye dominance. Bottom subplot represents the Preferential test EDS across subjects that selected left-eye dominance with clinical Sensory dominance test using 1.50 D (*filled red bar*) and right-eye dominance (*empty red bar*). (**C**) Relationship between Preferential test EDS for far and near vision. The *solid line* represents a linear correlation ($m = 0.87$; $r = 0.86$; $P < 0.05$) and the *dashed line* represents a 1:1 relationship.

example of results for subject 19 for far vision (see Fig. 3A) and near vision (see Fig. 3B). This subject shows a clear preference for monovision in the left eye (NAL) at far (i.e. addition in the left eye, and full far correction in the right eye, indicative of right eye dominance). Conversely, some subjects do not show a clear preference (weak dominance; i.e. subject 9 in Figures 3C and 3D.

Figure 4A shows the EDS for far vision (blue bars) and Figure 4B shows the eye dominance for near vision (red bars) for all subjects. According to this metric, four subjects (20%) showed weak eye dominance (falling within the ±0.1 gray band), three of them both at far and near vision. Filled bars indicate left-eye dominance and empty bars indicate right-eye dominance according to the clinical sensory test (with +1.50 D blur). There was a mismatch between the eye dominance identified by the clinical sensory test and the Preferential test in six subjects (4 with strong Preferential dominance: subjects 2, 13, 14, and 15) at far vision and four subjects at near vision. We averaged the Preferential test EDSs of subjects clinically identified as having left-eye and right-eye dominance, respectively, with the different tests. For far vision, the average EDS with the Preferential test for subjects that had left-eye dominance was −0.2 and for right-eye dominance was +0.34 (for sensory eye dominance +1.50 D; see Fig. 4A subplot). For near vision, the average EDS with the Preferential test for left-eye and right-eye dominance was −0.18 and +0.21, respectively, for sensory eye dominance +1.50 D (see Fig. 4B subplot).

Figure 4C plots the EDS obtained with the Preferential test for near vision versus that for far vision, showing a highly statistically significant positive correlation ($r = 0.86$; $P < 0.05$). A paired t-test did not find a significant difference ($P = 0.77$) between the Preferential EDS for far and near, suggesting the test could be equally applicable at both distances to select the best eye for monovision correction.

A reliability test estimated a Cronbach Alpha value of 0.941 for far and 0.976 for near vision. Considering 0.9 as a value that guarantees the reliability of the data, the number of trials could be reduced to 30 in the far vision test and to 12 in the near vision test. Reducing the number of trials to the minimum number while still estimating the EDS reliably could reduce the time of performance of the Preferential test to less than 4 minutes for far, and less than 2 minutes for near.

MAS-2EV and Monovision

In the scoring (MAS-2EV) test, subjects subjectively graded their perceived visual quality for four different stimuli and scenes, providing a multicomponent description of their perception, for different corrections.[21,22] We tested three different corrections: both eyes corrected for far vision (FF); monovision in the left eye (NAL), and monovision in the right eye (NAR). Figure 5A shows an example of a MAS-2EV polygon for subject 19. Each line represents a different correction (FF-black line, NAL-dotted light gray line, and NAR-dashed gray line). For FF correction, as expected in presbyopes, near vision scores decrease compared to far vision scores (score for far vision was 0.98 and for near vision 0.47 – averaged across the day and night components). In this subject, the MAS-2EV polygon for NAL is notably different than that for NAR. For NAL correction, the perceptual score for far vision (average night and day) is 0.62, whereas for NAR, it is 0.78. Both NAL and NAR improve vision at near compared to the FF correction (0.75 and 0.57), but NAR is largely preferred at far. Conversely, other subjects (for example subject 11, shown in Fig. 5B) do not show significant differences between NAR and NAL, while still showing a small visual degradation at far (0.88 and 0.83, respectively) and a significant improvement over FF at near (0.77 and 0.78, respectively).

The difference between the score given for NAR and the score given for NAL provided a metric for estimating eye dominance strength using MAS-2EV (EDS_{MAS}, Equation 1). This metric is equivalent to the Preferential test, but the main difference is that subjects gave scores instead of choosing forcibly between monovision corrections. Figures 6A and 6B plot the results of the MAS-2EV test EDS for far vision (blue bars) and near vision (red bars), respectively. As in Figures 4A and 4B, filled bars indicate left-eye dominance and empty bars right-eye dominance according to the clinical sensory test (+1.50 D blur). We averaged the MAS-2EV eye dominance strengths of subjects clinically identified as left-eye and right-eye dominance. For far vision, the average MAS-2EV

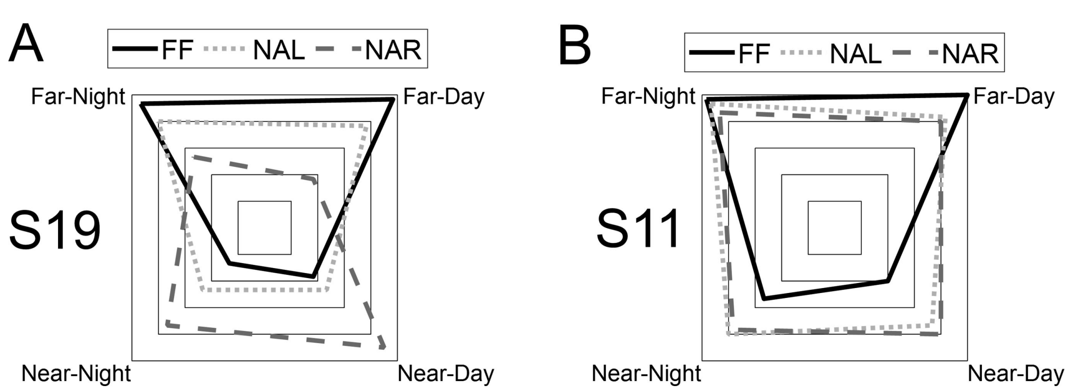

Figure 5. Example of individual subjects' results with the MAS-2EV test. The MAS-2EV polygons for two subjects. Lines represent the scores for FF (*black*), monovision in the left eye (NAL, *dotted light gray*), and monovision in the right eye (NAR, *dashed dark gray*). (**A**) Subject 19 shows a large degradation at far with NAR and significant differences between NAL and NAR (high Eye Dominance Strength [EDS]). (**B**) Subject 11 shows small differences between NAL and NAR (low EDS).

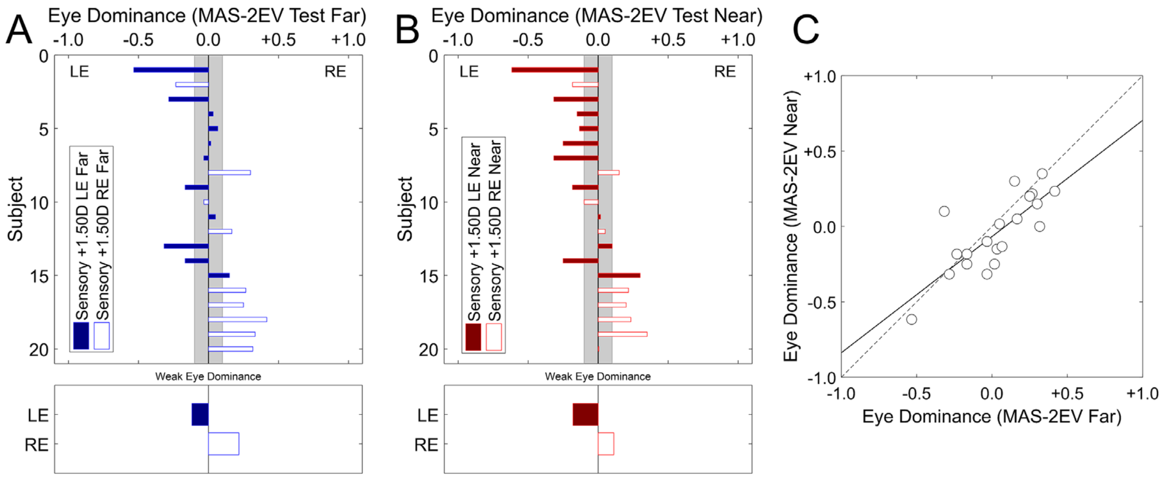

Figure 6. Eye Dominance Strength (EDS) with MAS-2EV test. (**A**) Relationship between MAS-2EV eye dominance for far vision versus near vision. The *solid line* represents a linear correlation ($m = 0.77$; $r = 0.79$; $P < 0.05$) and the *dashed line* represents a 1:1 relationship. (**B**) MAS-2EV test EDS for all subjects for far. *Filled blue bars* indicate that the subject selected left-eye dominance with the clinical Sensory dominance test with 1.50 D and *empty blue bars* that the subject selected right-eye dominance. The *shaded gray band* indicates weak dominance (± 0.1). Bottom subplot represents the average of the MAS-2EV test EDS across all subjects that selected left-eye dominance with clinical Sensory dominance test using 1.50 D (*filled blue bar*) and right-eye dominance (*empty blue bar*). (**C**) MAS-2EV test EDS for all subjects for near vision. *Filled red bars* indicate that the subject selected left-eye dominance with the clinical sensory dominance test with 1.50 D and *empty red bars* indicate that the subject selected right-eye dominance. Bottom subplot represents the average of MAS-2EV test EDS across subjects that selected left-eye dominance with clinical sensory dominance test using 1.50 D (*filled red bar*) and right-eye dominance (*empty red bar*).

test EDS for subjects that had left-eye dominance was -0.11 and for right-eye dominance was $+0.2$ (for sensory eye dominance $+1.50$ D; see Fig. 6A subplot). For near vision, the average of EDS with the MAS-2EV test for left-eye and right-eye dominance was -0.16 and $+0.1$, respectively (for sensory eye dominance $+1.50$ D; see Fig. 6B subplot). As in the Preferential test, there is a high statistical correlation between the eye dominance for far and near using the MAS-2EV metric ($r = 0.79$; $P < 0.05$), and a nonstatistical difference between the eye dominance selection for the two distances (paired *t*-test; $P = 0.35$), as shown in Figure 6C.

Correspondence Between Tests

Figures 4A, 4B, 6A, and 6B represent EDS based on the Preferential test and MAS-2EV (all subjects) for far vision, with filled and empty bars indicating left- and right-eye dominance obtained with clinical sensory eye dominance with 1.50 D, respectively. Negative values along the y-axis of each graph represent the strength of left-eye dominance from the different tests and positive values of right-eye dominance. We performed analysis by averaging the EDS obtained from the Preferential and MAS-2EV of all subjects with the same sign of sensory EDS with $+1.50$ D, sensory dominance with $+0.50$ D, and sighting eye dominance. The only tests that show a statistically significant correlation between them are sensory dominance $+1.50$ D with the Preferential test and MAS-2EV, and sensory dominance $+0.50$ D with the Preferential test (see the Table).

Figure 7 shows the eye dominance strengths obtained from the MAS-2EV versus the Preferential test. There is a statistically significant correlation between the EDS obtained from either test, both for far ($m = 0.35$, $r = 0.70$; $P < 0.05$) and near ($m = 0.37$, $r = 0.76$; $P < 0.05$). Paired *t*-tests indicate nonstatistical differences between the dominance from both tests at far ($P = 0.92$) or at near ($P = 0.76$).

Table. Statistical Analysis of the Association Between Clinical Tests (Binary Response) and Psychophysical Tests

	Sensory +1.50 D	Sensory +0.50 D	Sighting
Preferential test EDS	r = 0.53 t = 2.74 *P* < 0.05**	r = 0.47 t = 2.35 *P* < 0.05**	r = −004 t = −0.18 *P* = 0.86
MAS-2EV test EDS	r = 0.60 t = 3.30 *P* < 0.05**	r = 0.23 t = 1.03 *P* = 0.32	r = 020 t = 0.91 *P* = 0.38

We show the point-biserial correlation coefficient (r) and a two-tailed unpaired *t*-test with equal variances for the correlation coefficient (t-statistic [t] and *P* value [*P*]). Statistical significance difference is indicated with two asterisks (**).

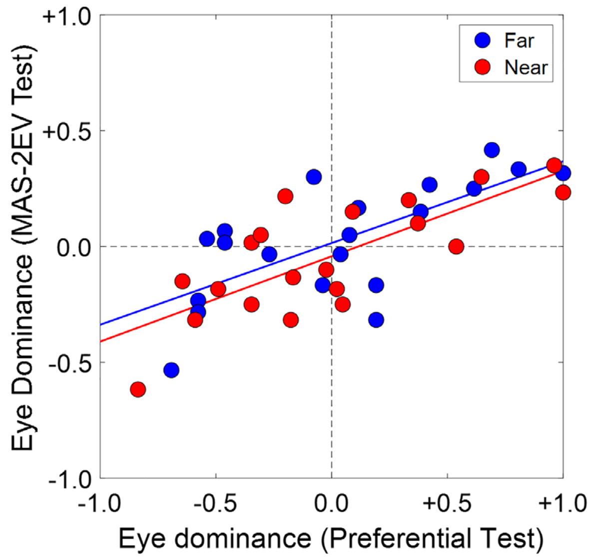

Figure 7. Correspondence between Preferential and MAS-2EV eye dominance tests. *Blue dots* indicate far vision and *red dots* indicate near vision.

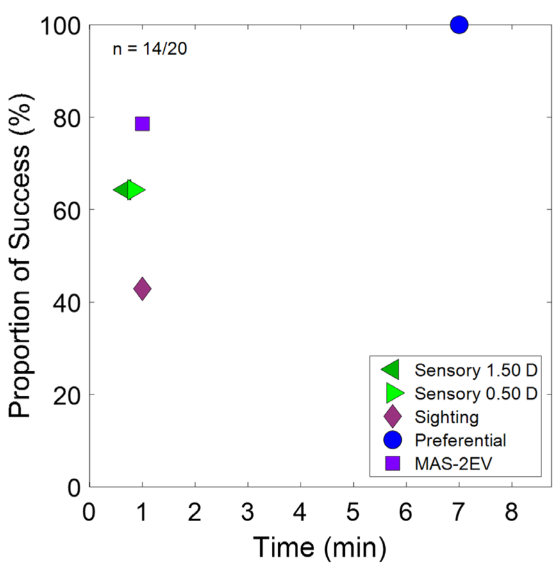

Figure 8. Proportion of successful patients. Proportion of subjects in whom the result of eye dominance provided for each test agreed with the results provided by the Preferential test, considered as the reference for monovision selection. The time to perform sensory eye tests with +1.50 D or +0.50 D is 45 seconds, although they are plotted shifted for visualization purposes.

Eye Dominance and Monovision

Considering the Preferential test as a reference for the selection of the eye to treat for monovision, we have tested how selection from other tests would have impacted the success of a monovision correction. The estimation was performed for far vision because the clinical tests are performed for far vision only. We removed from the analysis the 6 subjects that showed weak eye dominance provided by the MAS-2EV test. By this definition, the Preferential test (Fig. 8, blue circle) shows 100% success. Choosing the eye to treat monovision based on clinical eye sensory dominance (+1.50 D or +0.50 D blur) would result in a successful treatment in 64% of the patients. Choosing the eye to treat monovision based on clinical sighting eye dominance would result in a successful treatment only in 43% of the patients. In contrast, the test based on MAS-2EV results in agreement with the Preferential test in 79% of the subjects. MAS-2EV appears the most time-effective measurement, as scoring direct and crossed monovision for one condition (far-day) takes only 1 minute.

Discussion

Discrepancies Between Sensory and Sighting Dominance

As in numerous prior studies,[12–15] we also found that sighting eye dominance does not consistently match dominance obtained from sensory dominance tests (whether using +1.50 or +0.50 D of defocus). In our study, only 55% of the subjects reported the same eye dominance with the 3 tests most used in the clinic.

Eye Dominance Strength

Several authors have turned their attention to binocular rivalry tests to identify eye dominance (both the dominant eye and the strength of that dominance) and have proposed versions of the psychophysical paradigm of this test that could be amenable in clinical practice.[7] However, the typically high-contrast targets used in binocular rivalry tests make them less relevant to the natural visual content that the subjects are exposed to in the real world. Besides, the fact that results from these tests may be affected by physical features of the stimulus[6] and that they may target different types of dominance poses questions on the suitability of tests based on binocular rivalry to select the optimal monovision approach.

Instead, our proposed tests directly evaluate monovision by placing the near addition in the right or left eye and are based on the subject's perceptual response (in a two-interval forced choice comparison in the Preferential test, or in a perceptual scoring in the MAS-2EV test). The use of natural images conveys a more realistic depiction of the far real world than high contrast optotypes or Gabor patches used in the psychophysical binocular rivalry tests of dominance. Whereas evaluation of the effect of image size, spatial frequency content, image brightness, chromatic features, or pupil diameter on the identification of eye dominance using this test is pending, our results suggest that the selection is, in fact, robust, given the large correspondence obtained between independent measurements at far and near vision. The Preferential test used monochromatic images (plants, trees, and fruits) subtending an 8-degree field, whereas the MAS-2EV test used color images (faces, urban landscapes, and signs) subtending a 27-degree field. Moreover, the MAS-2EV test was performed under two levels of illumination (day and night).

The EDS with the Preferential test ranged from −0.7 to +1 for far and from −0.8 to +1 (see Figs. 4A, 4B) and the EDS with MAS-2EV test ranged from −0.5 to +0.4 for far and from −0.6 to +0.4 for near (see Figs. 6A, 6B), and therefore constrained to a lower range. We think that these differences may come from the nature of the task, a forced-choice in the Preferential test, and a scoring in the MAS-2EV test. Despite all these differences, there is a statistically significant correlation between the eye dominance selected by these tests (see Fig. 7). Furthermore, whereas binocular rivalry tests and clinical eye sensory tests have shown a lack of predictability of eye dominance at near vision from eye dominance measured at far vision,[29] the eye dominance measured at far and near vision show a high degree of correlation (see Figs. 4C, 6C) in both tests, particularly in the Preferential test, as the same (natural) images are used for far and near. However, the correlation is also high in the MAS-2EV test, which uses primarily natural images at far and reading text at near.

For comparison with the standard clinical tests, we binarized the results from the new tests. However, unlike conventional tests in the clinic that provide only a binary identification of the dominant eye (right or left), the Preferential and MAS-2EV tests provide a measurement of the EDS. The MAS-2EV test is fast and allows evaluating perceived quality with several presbyopic corrections, including multifocal corrections.[21] In our subject cohort, 70% of the subjects showed clear differences in the perceptual judgment of the near addition in one eye or the other (indicating strong eye dominance), whereas 30% showed weak dominance. The clinical literature is inconclusive on whether patients with strong or weak eye dominance are the most suitable candidates for successful monovision. Nevertheless, having a graded metric to discern eye dominance appears highly valuable tool for presbyopia management, as it allows identifying patients for whom careful selection of the eye to treat for far and for near is more critical. The method can be easily extrapolated to other settings, to assess whether the same selection would hold with other visual stimuli, near add magnitude, or lens designs.

Subjects were instructed to judge the perceived quality of images based on their natural appearance and a higher degree of comfort. Judgments are highly repetitive at least in those subjects that appear to have stronger dominance (in fact, the dominance strength in the Preferential test is based on the repeatability of the response). Likely, the ability to suppress blur with either eye is the underlying mechanism in the perceived quality judgment, although this remains to be investigated. In addition, the assumption by which the success of a prescribed monovision treatment relies solely on optimizing perceptual image quality at far remains to be tested. Other perceptual factors not considered in this study include the effect of monovision on stereovision,[5] claimed by some authors to be a key factor in monovision success,[30] which could be added to the tests proposed in this study. In addition, tests were performed for fixed monovision near addition (+2.00 D). An interesting question is to what extent the identified eye dominance may be altered with a higher/lower near addition. Other open questions include the importance of the patient's lifestyle, and whether the eye dominance may change after adaptation to a given monovision correction[31]; making the eyes initially selected for far and near respectively eventually less important.

SimVis Gekko for Measuring Eye Dominance in Monovision

Key to the implementation of the proposed eye dominance tests has been the use of the SimVis Gekko. This system allows programming and rapid alternation between corrections enabling short measurement times and making them suitable for clinical use. Besides the mentioned advantages of this binocular visual simulator, the correction is applied in a plane conjugate to the pupil of the eye, unlike trial lens frames or even automatic phoropters, avoiding magnification imbalances or prismatic effects. The conventional sensory dominance test could be programmed similarly to the Preferential test using an optotype instead of natural images as stimuli. We chose to use natural images instead of high-contrast letter stimuli, as previous work has shown a higher correspondence between visual function questionnaires and perceived quality with natural images than with visual acuity.[21,22] The standard sensory test using trial lenses with +1.50 D had a low although significant correlation with the

Preferential test (see the Table, Fig. 8), and might be considered as another option instead of the automatic SimVis Gekko. However, the interocular differences in magnification and the higher measurement time using trial lenses should be acknowledged by the practitioner.

Furthermore, whereas the current study has only made use of monofocal lens corrections (and a single power change in the optotunable lens), the SimVis Gekko is actually conceived as a simulator of multifocal corrections, with the optotunable lens operating under the principle of temporal multiplexing.[24] The Preferential test and MAS-2EV test can be easily adapted, as shown in laboratory work[18,21,24] to include other presbyopia correction modalities (e.g. modified monovision or multifocal corrections) in the comparison. We have shown that the application times of the proposed tests (a few minutes) are compatible with reasonable clinical chair times. However, more research including a larger sample size should be addressed to identify the optimal set of parameters (i.e. number of repetitions in Preferential test or image set in MAS2-EV) in a clinical application.

In this study, we report tests based on perceptual preference or perceptual scoring of naturalistic stimuli deployed in a binocular simultaneous vision simulator to measure eye dominance and identify the eye for treating monovision. Although the effect of specific features of the stimulus on eye dominance measurements and strength remains to be investigated, the high repeatability of the test and the consistency between the measurements at near and far suggest that natural stimuli rather than artificial stimuli are well suited for testing eye dominance and monovision preference. Our results confirm previously published discrepancies between sighting and sensory dominance. The proposed method of systematic, automatized, non-binary ocular dominance measurement provides a useful framework for clinical practice.

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