A binocular test of sensory eye dominance based on the Pulfrich effect

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Abstract

10 Many studies have shown inconsistent results among traditional measures of sensory ocular dominance (SED), seriously questioning the very concept of SED as a unitary aspect of the visual system (e.g. Mapp et al., 2003; Skottun & Freeman, 1984; Walls, 1951). The test outcomes may also change even if the same measure is repeated under different conditions, for example by varying the distance and eccentricity of the target (e.g. Khan & Crawford, 15 2001; Rice et al., 2008). On the other hand, some authors suggest that such inconsistencies may result from uncontrolled variables. A candidate to produce confusing variables is the frequent format of these tests, often dichotomous and introspective.

In this paper, we propose a possibility of measuring SED on a continuous scale and in a comparative way using a stimulus that induces a Pulfrich effect. Here a dichoptic 20 motion stimulus, borrowed from a previous study (Reynaud & Hess, 2017), was used, which produced different degrees of 3D illusory perception strength through the variation of retinal disparity. We observed that the responses of the subjects varied according to their classical SED test outcomes and we estimated the differences in terms of the time delay of the information coming from the two eyes. In our sample, it appears that 25 information from the dominant eye was processed 8.2 ± 5.8 ms faster than that of the fellow eye. People with a left dominant eye showed more marked differences in processing time (6.8 ± 2.0 ms) than people with a right dominant eye (1.8 ± 0.9 ms). Eyes without a clear dominance did not show significant differences in processing time (1.2 ± 1.7 ms). These results are consistent with the previous literature and could lead to the development 30 of a new continuous-scaled SED test.

Keywords: eye dominance, Pulfrich effect, psychophysics, methodology

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Background

Binocular vision is based on an asymmetric use of the two eyes (Ehrenstein et al., 2005; Freeman & Ohzawa, 1990; Porac & Coren, 1975; Rakic, 1976; Skottun & Freeman, 1984) not only in amblyopic subjects (Daw, 1998; Horton & Hocking, 1996; Schröder et al., 2002) but also under physiological conditions (Chaurasia & Mathur, 1976; Ehrenstein et al., 2005; Reiss & Reiss, 1997). As for other members of any bilateral pair of structures of the body, such as hands, this kind of functional priority or preferential activity is commonly called *dominance*. Approximately two-thirds of the population has a dominant right eye and only a small portion seems to have balanced eyes (Chaurasia & Mathur, 1976; Kommerell et al., 2003). Determining eye dominance (ED) can be important 1) in clinical optometry contexts, e.g. for monovision, cataract and refractive surgery and contact lens wear (Evans, 2007; Handa et al., 2004; Handa et al., 2005; McMonnies, 1974; Zheleznyak et al., 2015), 2) in experimental contexts, e.g. for accurate eye movements measures (Chaumillon et al., 2017), 3) in sports, when one eye is used more than the other, such as shooting, baseball and golf (Dalton et al., 2015; Jones 3rd et al., 1996; Laby et al., 1998).

Some studies reported that information from the dominant eye is faster (Metalis & Niemiec, 1984; Minucci & Connors, 1964) and more salient (Coren & Porac, 1976; Pascal, 1926; Porac & Coren, 1979, 1981; Wade, 1975) than information from the non-dominant eye. Sensory eye dominance (SED) appears to be based on an imbalance of inhibitory connections between the two eyes in various brain areas (Sengpiel et al., 1998; Sengpiel & Blakemore, 1996; Sengpiel et al., 2006). Notably, changes in cortical metabolism of V1 that depended on SED have been recorded with functional magnetic resonance imaging (fMRI) in the human brain (Rombouts et al., 1996).

Many authors have proposed a surprising number of criteria to determine ED (Gronwall & Sampson, 1971; Jasper & Raney, 1937; Lederer, 1961; Walls, 1951), to the point to questioning the usefulness of the very concept of dominance as a unitary

characteristic of vision (Laby & Kirschen, 2011; Mapp et al., 2003; Walls, 1951). Two types
of ED, motor dominance (MD) and sensory dominance, are identified through several
clinical tests (Li et al., 2010; Pointer, 2012). Although their satisfactory test-retest
repeatability, they are generally inconsistent with each other and depend crucially upon a
number of other variable, e.g. the distance to the target and the direction of gaze (Ho
et al., 2018; Jasper & Raney, 1937; Khan & Crawford, 2001; Mapp et al., 2003; Rice et al.,
2008; Walls, 1951). This leads many researchers to question their validity. Since working
tests of the same property should give the same result, there must be either a problem with
the tests or with the understanding of the ED. Walls (1951) listed 25 different ways to test
and conceptualise ED and proposed that only the measurements that involved stereopsis
and fusion were actually about dominance. In other terms, tests that do not allow the
subjects to use their normal binocular vision may not accurately assess SED. In their
review, Laby and Kirschen (2011) confirmed that only tests that allow for maintenance of
binocular vision should be used to accurately evaluate SED. On the other hand, it is
possible that ED is a multifactorial phenomenon and there could exist several types of
dominance (Mapp et al., 2003; Rice et al., 2008).

Although eye dominance and handedness are not related (Mapp et al., 2003; Rice
et al., 2008; Walls, 1951), the research on these two topics is much more similar than it may
appear at first glance, and bringing them together might produce some insight. Commonly
we talk about right-handed and left-handed people, but it is long been known that
handedness is not dichotomous. The Edinburgh Inventory (Oldfield, 1971) is a set of items
investigating the ways people use their hands in various contexts. In a variable number of
these items, people do not report the same preferred hand. Researchers do not interpret
these results as a problem with the construct of handedness, but as the evidence that it is
not a dichotomous variable: there exist more degrees of handedness that are expressed by
the level of coherence of the responses to the test, and the more the coherence, the more
the degree of laterality (Isaacs et al., 2006). From the Edinburgh Inventory, it is possible to

obtain an index, the Laterality Quotient, ranging from -100 (pure left) to 100 (pure right), in which to place the handedness of each person. The underlying logic is that a construct that is not directly observable (for example, SED) may manifest itself in different ways from person to person. If the manifestations (phenomena) do not agree with each other, this does not necessarily mean that the construct is faulty, but that it might be necessary to discuss how the related observations are measured and interpreted.

Back in the field of vision research, we point out that generally SED classification in the clinical practice is made on a dichotomous basis. Indeed, significant efforts to develop continuous scale tests have been made in experimental research (see Bossi et al. (2018) for a review). Another problematic feature of clinical sensory testing is to require subjects to perform an introspective task. For example, when using a red filter or fogging one eye with a positive lens, the observer is asked to report when his perception of a target is most disrupted, and no performance index is recorded. The use of introspection poses various epistemological and methodological problems (Gronwall & Sampson, 1971).

Bossi et al. (2018) reviewed eight methods for quantifying SED, six of which are based on the individuation of a *balance point (BP)* or a *point of subjective equality (PSE)* between the two eyes regarding a particular parameter of the stimulus. For instance, in the Letter-Polarity test, two superimposed letters are presented with opposite luminance polarity to the two eyes, and the observer is asked to report which letter appears brighter: the SED measure, in this case, is the contrast balance point between the two eyes (Bossi et al., 2017), which can be derived from the psychometric function between the proportion of responses in a 2 alternative forced-choice task and the respective stimulus intensities. This method allows a continuous and performance-based measure of SED, but still, the eyes compete with each other rather than cooperate to process the information.

A recent study describes an interesting paradigm that might be used in continuous-scaled and objective ED measurements where eyes do not compete but cooperate to perception with their imbalanced contributions, as recommended by some

authors (Laby & Kirschen, 2011; Walls, 1951). In 2017, Reynaud and Hess (2017) used a dichoptic paradigm in which an illusory 3D percept for a moving object generated
115 ambiguous to strong depth sensations manipulating independently the contrast, luminance, and the interocular processing delay of the stimuli given to the two eyes (Treue et al., 1991). Two independent moving groups of Gabor patches were presented to the observer and fused to create an illusory rotating cylinder. When the experimenter varied the interocular angular phase difference between the two stimuli, the observer perceived a
120 clockwise or counter-clockwise rotation. This paradigm allowed the measurement of a psychometric curve and a PSE. Varying contrast or luminance resulted in a decreased or increased velocity of information coming from one eye and had effects very similar to changing the angular phase difference. This phenomenon is known as the Pulfrich effect (Burr & Ross, 1979; Farr et al., 2018; Pulfrich, 1922), that has been observed to occur at
125 the level of retina (Raz et al., 2002) and, in humans and primates, at the level of motion-disparity detectors in V1 and MT areas (Anzai et al., 2001; Blake & Logothetis, 2002; Bradley et al., 1995; Geisler et al., 2007; Heravian-Shandiz et al., 1991; Katsumi et al., 1986; Sanada & DeAngelis, 2014). In their study, Reynaud and Hess (2017) demonstrated that contrast can modify the dynamics of neurons resulting in an interocular
130 processing velocity difference. Interestingly, they observed that when their stimuli were well-balanced in terms of luminance, contrast, and angular phase difference, most subjects' PSEs were offset from 0° , characterizing a spontaneous Pulfrich phenomenon in the normal population that they observed for the first time. In some cases, this *innate bias* could not be reversed by contrast or luminance variation, probably because it was stronger than the
135 stimulus imbalance. These authors interpret this result as a "bias due to a low-level innate contrast imbalance between the two eyes" (Reynaud & Hess, 2017).

The present work aims to replicate the results of Reynaud and Hess (2017) and to investigate the possibility that the innate bias that they discovered consists in the observers' SED. If this is the case, their paradigm could be the basis for a new

continuous-scaled and objective test for SED, based on the imbalanced cooperation of eyes in stereopsis (Laby & Kirschen, 2011; Walls, 1951).

Methods

Setup and stimuli

In order to implement the experiment and analyse data we used an Apple MacBookAir 13" (2017) with a 1.8 GHz Intel Core i5 processor, 8 Gb RAM and an Intel HD Graphics 6000 1536 MB graphic card. The operating system was MacOS Mojave 10.14.2. The monitor had a 1440x900 pixels resolution with pixel size 0.02 cm and a 60Hz refresh rate and was calibrated using a Minolta LS-100 photometer. The data was collected in a dimly lit room. We used Python 2.7 in conjunction with many modules as for example SciPy (Jones et al., 2001), Numpy (Oliphant, 2006), Matplotlib (Hunter, 2007) and PsychoPy (Garaizar & Vadillo, 2014; J. Peirce & MacAskill, 2018; J. W. Peirce, 2007, 2009).

The stimuli presented to the two eyes were fused through two 8Δ prisms mounted on a stereoscope created ad-hoc by our laboratory, as shown in Figure 1. They consisted of two groups of 100 Gabor patches, each with $\sigma = 0.25^\circ$, random phase, and spatial frequency = 2.5 c/deg, that were displayed for 1.5 s independently to the two eyes. The viewing distance was 75 cm. Gabors presented a 100% coherent harmonic motion that gave to the subject an impression of a $8 \times 6^\circ$ cylinder rotating on its axis at $23^\circ/\text{s}$. The two cylinders were presented dichotopically to the subject (Figure 1). Two parameters could be manipulated:

1. the angular phase difference between the two stimuli, that could vary randomly on a trial basis from 0.04° to 0.75° in log progression. Crucially, the illusory tridimensionality of the rotating cylinder and the direction of rotation depended directly on this parameter: coherently to the Pulfrich effect, when the Gabors on the right sides preceded their correspondent Gabors on the left, subjects perceived a

clockwise rotation; otherwise, when left Gabors preceded right Gabors, subjects perceived a counter-clockwise rotation (Pulfrich, 1922; Reynaud & Hess, 2017; Treue et al., 1991).

2. the interocular contrast difference between the two stimuli, that varied on a session basis. The contrast of one cylinder could be decreased by 0%, 30%, or 60% with a mean luminance of 156 cd/m². Coherently to the Pulfrich effect (Farr et al., 2018; Pulfrich, 1922; Reynaud & Hess, 2017), this parameter affected the perceived rotation of the stimulus.

Procedure

After been provided with a first test session to become familiar with the stimulus and task, subjects collected at least 100 trials per contrast condition. Each session started with the presentation of two red circumferences containing two letters, *F* and *L*. When the observer reported perceiving the letter *E*, fusion was obtained and the experiment started when the observer pressed any key on the keyboard. After the presentation of the stimulus for 1.5 s, subjects were asked to report the perceived orientation of the cylinder by pressing the left or right arrow on the keyboard. During the test session, the angular phase difference was high to be confident that the subject could understand the task. During the experiment sessions, the angular phase difference randomly varied on a trial basis while the contrast of the left or the right stimulus varied on a session basis.

The ED of each subject was assessed based on three traditional tests, one for motor dominance (pointing test) and two for sensorial dominance (Bagolini's red filter and 1.5Δ positive lens tests), with a target stimulus distance of 4 m. We decided to use these tests and conditions because of their widespread use in the professional community. Observers were classified as showing an uncertain dominance (ND) when their introspective response was still uncertain after the second measurement attempt.

Statistical analysis

The ED of each observer was classified based on the traditional testing results. When the three tests were consistent, the observer was assigned to the right (RE) or left (LE) dominance groups. When at least one test was inconsistent with the others or
 195 resulted uncertainly, the observer's dominance was classified as null (ND). Similar methods of classification have been already used in other recent studies (e.g. Lopes-Ferreira et al., 2013).

As in Reynaud and Hess (2017), we calculated the point of subjective equality (PSE) in terms of angular phase difference from the psychometric curves that we obtain for
 200 each contrast condition. The PSE indicates the angular phase difference at which the subject could not tell the motion orientation of the cylinder. We fitted the data with a logistic curve:

$$f(x) = \frac{a}{1 + b \cdot e^{-c \cdot x}} + d \quad (1)$$

where a indicates the superior asymptote of the curve, b and d are the positions of the curve relative to the x-axis and the y-axis respectively, and c is the slope. Since we wanted
 205 to force (1) to be limited from 0 to 1 along the y-axis, we used the equation:

$$f(x) = \frac{1}{1 + b \cdot e^{-c \cdot x}} \quad (2)$$

The PSE corresponds to the inflection point for (2) when the $f(x) = 0.5$, that is:

$$P_{x(PSE), y(0.5)} = \left(\frac{\ln b}{c}, 0.5 \right) \quad (3)$$

The parameters b and c were derived from the logistic curve that best fitted the data points using a least-square estimation.

The normality of the sample PSE distributions for each dominance category and the
 210 equality of their variances were assessed by performing a Shapiro-Wilk test (Kleinbaum et al., 2013; Shapiro & Wilk, 1965) and a Fisher F test (Box, 1953), respectively. We performed an ANOVA followed by two-tailed t-tests to compare the mean PSEs for

different EDs when the Shapiro-Wilk and F tests indicated that the assumptions for an ANOVA were respected (Scheffé, 1953). In case it was not possible to perform an ANOVA, we made the comparisons using a t-test with a Bonferroni correction (Abdi et al., 2007; Bonferroni, 1936). Finally, in order to decide if the observed consistencies between the traditional ED tests were significant, we performed a one-tailed binomial test on their successfully coherent output rate (Dodge, 2008).

We performed a sample size estimation (Cohen, 2013) by using the data recollected by Reynaud and Hess (2017) to decide in advance the number of subjects to be enrolled in this study to have sufficient statistical power to detect a difference between the PSE as a function of ocular dominance.

Participants

Nineteen observers (53% men, 47% women; age= 26 ± 8) participated in the experiment. All of them did not present any pathological abnormality and had a visual acuity of 6/6 or better when corrected. Two out of them could not fuse the stimuli and other four participants were excluded because their responses were invariant. Indeed, they perceived the stimulus as rotating in the same direction $> 85\%$ of times, and no psychometric curve could be obtained from the data. Our tentative interpretations for this behavior are illustrated in the Discussion section.

Results

Descriptive statistics and traditional test results

Table 1 reports the results in the traditional dominance tests. In the pointing test, 41% of observers showed a right dominance, and 53% showed a left dominance. One observer (6%) could not perform the task nor fuse together the targets. In the red filter test, 24% of observers showed a right dominance, 35% showed a left dominance and 41% did not show a clear dominance. In the positive lens test, 35% of observers showed a right

dominance, 47% a left dominance, and 18% showed an uncertain dominance. Comparing the outputs of each test on a within-subject basis, we observed that the most consistent results were obtained by the pointing and positive lens tests (76%), but this value is not significantly different from the random level for a binomial test performed on the number of successes in reporting the same output using a Bonferroni correction ($p=0.024$).

Therefore, classical ED tests did not produce reliable results, as reported in some other studies (Mapp et al., 2003; Rice et al., 2008; Walls, 1951). However, four observers were consistently classified as right-dominants (RD) by all the traditional tests, and other four observers were consistently classified as left-dominants (LD).

Psychometric curves and PSE estimations

Figures 2a, 2b and 2c show the individual psychometric curves in five interocular contrast difference conditions for three observers. The curves express the relation between the perceived rotation and the angular phase difference between eyes. When this difference was -0.75° , observers perceive counter-clockwise motion and when it was 0.75° , they perceive a clockwise motion. These results are consistent with the well-known Pulfrich effect and are dependent on the interocular delay of visual information (Anzai et al., 2001; Pulfrich, 1922; Reynaud & Hess, 2017). Interestingly, reversals of the perceived rotation (i.e., the observed PSEs) presented deviations of varying degrees from zero. For some observers, the PSE values were negative as in the case of FN (Figure 2a and 2d). Notably, their PSEs did remain negative even when the contrast of the right stimulus was decreased, as observed by Reynaud and Hess (2017). Other observers presented the opposite pattern with positive PSEs, as in the case of FP (Figure 2c and 2f) and a few participants did show near-zero PSEs with an inversion of their sign when interocular contrast difference varied (Figure 2b and 2e).

Comparison between traditional tests and PSE estimations

The results presented in the previous section confirm the observations of Reynaud and Hess (2017) and, in particular, we found evidence for what they called "an innate bias" that is different for each subject. To determine whether such an innate bias can be related to the eye dominance of subjects, we performed a grouped psychometric function estimation for different eye dominances. The results for the balanced contrast conditions are shown in Figures 3a and 3b and Table 2. Here we grouped our observers merging the traditional test results, considering right- or left-eye dominant only the subjects that obtained coherent results to all tests. The psychometric curves for right-eyed subjects (magenta) are shifted toward negative values in respect to those for the left-eyed subjects (green), while those for the subjects with uncertain dominance (grey) stand in the middle and seem very similar to those of right-eyed observers. Moreover, the absolute values of left-eyed observers' offsets from zero are higher compared to those of right-eyed subjects' ones.

Figure 3c-3f and Table 2 show the results and statistical analysis for the comparison of the PSEs obtained for the different types of eye dominance in the balanced contrast condition. The merged tests condition (3c) refers to the mean PSEs obtained when the dominance resulted from the three tests producing the same output coherently. Here, four observers in our sample were right-eyed (RE), four left-eyed (LE), and five had an uncertain dominance (ND). The PSEs values of the three groups were normally distributed (Shapiro-Wilk test, $0.91 < p < 0.93$) and their variances were not significantly different (F test, $0.1 < p < 0.85$). An ANOVA for the comparison of the mean PSEs of the RE, ND, and LE groups showed a significant between-group difference ($p = 0.017$). Notably, the PSE means for the RE and LE groups were significantly different ($RE = -0.036 \pm 0.041^\circ$, $LE = 0.156 \pm 0.094^\circ$, t-test: $p = 0.01$), while the other comparison for this condition did not show any significant difference (RE-ND: $p = 0.22$, ND-LE: $p = 0.1$).

The histograms reported in Figures 3d-3f refer to the mean PSEs grouped only for the pointing, red filter or positive lens tests. The mean PSEs of left motor dominance

subjects ($N=6$) do not differ from those of right motor dominance subjects ($N=7$) (figure
 290 3d; Shapiro Wilk test, $0.65 < p < 0.74$; F test: $p = 0.48$; RE-LE t test: $p = 0.28$). At the
 red filter test, 4 observers were right dominant, 4 uncertain and 5 left dominant. PSE
 values in these three groups were normally distributed (Shapiro Wilk test: $0.69 < p < 0.99$)
 but we could not perform an ANOVA because right dominant variance differed significantly
 from left dominant variance (F test: $p = 0.03$). We then perform the comparison between
 295 the three mean PSEs using a Bonferroni correction with $\alpha = 0.016$. Right dominant PSEs
 resulted significantly different from left dominant ones ($RE = -0.036 \pm 0.041^\circ$,
 $LE = 0.124 \pm 0.1^\circ$, t-test: $p = 0.015$) and uncertain dominants did not differ from the other
 two groups (RE-ND: $p = 0.22$, ND-LE: $p = 0.23$)(3e). Finally, the mean PSEs for the
 groups that depended only from the positive lens test were normally distributed
 300 ($0.6 < p < 0.97$) but right and left dominants' variance was different (F test: $p = 0.003$). In
 this case, two comparisons were significantly different applying a Bonferroni test with
 $\alpha = 0.016$: right-left dominance ($RE = -0.017 \pm 0.054^\circ$, $LE = 0.157 \pm 0.081^\circ$, t-test:
 $p = 0.005$) and uncertain and left dominance ($ND = -0.024 \pm 0.048^\circ$, t-test: $p = 0.014$),
 while right and uncertain dominants did not significantly differ (t-test: $p = 0.87$).

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Discussion

After replicating the results of Reynaud and Hess (2017), a substantial difference
 was observed between the PSEs of people with left and right eye dominance, which can be
 easily converted into the temporal domain in terms of interocular delay (ID). Since the
 stimulus presented a rotation of about $23^\circ/s$, our results indicate that information from the
 310 dominant eye could anticipate information from the fellow eye of about 8.2 ± 5.8 ms.
 Notably, while balanced eyes seem to have a non-significant temporal difference
 (ID= 1.2 ± 1.7 ms), left dominant eyes show a more pronounced temporal difference
 (ID= 6.8 ± 2.0 ms) than right dominant eyes (ID= 1.5 ± 0.9 ms).

A possible explanation of the asymmetry observed in this study might derive from a

stimulus artifact. The left cylinder was drawn before the right by the software and, even though the drawing phase was kept separate from the presentation phase in the program, we had to make sure that everything worked as expected. Therefore, three subjects of the study repeated the measurement observing the stimulus through a slot that allowed its fusion when the left stimulus was seen by the right eye and vice versa. In this way, it was possible to make a first analysis of the repeatability of the results of the paradigm and at the same time to exclude that there was an error in the software that was responsible for the observed asymmetry. The tests were repeatable (t-test for dependent samples: $p=0.157$), and we can therefore exclude that the observed asymmetry was due to an artifact.

These results seem in line, both in logical and quantitative terms, with those found by Reynaud and Hess (2017) and with other neurophysiological studies (Lages et al., 2003; Read & Cumming, 2005a, 2005b). Reynaud and Hess (2017) found a time delay between the information coming from one or the other eye in almost all the subjects they tested, leaving open the interpretation of this observation. Here, it has been shown that ocular dominance can be a predictor of the results of this paradigm and in particular that people with right eye dominance tend to be associated with negative PSEs, while those with left eye dominance tend to have positive PSEs. Lages et al. (2003) used the Pulfrich effect to investigate the perception of motion in depth and measured the sensitivity to the interocular phase difference between sinusoidally oscillating sine-wave gratings in four observers judging the direction of motion in depth. Our results are similar to the delay thresholds reported in Lages et al. (2003), which ranged from 1.4 and 24.3 ms. Read and Cumming (2005a) studied on monkeys the temporal properties of neurons of the primary visual cortex sensitive to movement and retinal disparity. They noted that the selectivity to the retinal disparity of these neurons depends critically on the temporal characteristics of the stimuli coming from the two eyes: it gradually degrades with the increase of the temporal delay between the two eyes, and when this delay exceeds the integration time the

inputs coming from the two eyes become completely unrelated. The amplitude of this temporal window for the retinal disparity is 16 ± 5 ms, a value that is consistent with our results. Interestingly, Read and Cumming (2005a) have observed, similarly to what we
345 have found here, an asymmetry in favor of the inputs coming from the right eye, which would be faster than the left one by about 4 ms because of hemispheric lateralization of the visual pathways of the central nervous system. Such asymmetries are reported also in the review by Bossi et al. (2018) on experimental tests for ED. Notably, they seem to be more pronounced for motion stimuli.

350 As Jasper and Raney (1937) already observed, the tests used for sensory eye dominance do not take into account the distinction between two crucial processing steps: the retinal and the central stages. This means that assuming that the eyes are well corrected at the refractive level, ocular dominance tests do not distinguish between retinal and hemispheric dominance. Many eye-dominance tests could therefore really measure
355 different things but this does not reflect a characteristic of dominance, but inadequacy in measurement. The red filter test, for example, because it is based on binocular rivalry could be a more central test than the positive lens test based on visual acuity.

We are developing a test that firstly may allow us to disentangle more peripheral factors from central ones, inspired by the pioneering work of Jasper and Raney (1937). The
360 test will also be designed so that it can be administered more quickly and more easily in both the scientific and clinical fields. In any case, even if we believe we can resolve the confusion due to the lack of distinction between nasal and temporal hemiretina and the complexity of the test, a very important limitation of this paradigm is highlighted by the number of people we had to exclude from the final analysis. While for some of them the
365 motivation of their exclusion is very clear (not being able to merge or not having a stereoscopic vision in the norm), for 20% of the subjects we had to proceed to their exclusion because they had a rigid response set that prevented the measurement of a psychometric curve. At the moment we can only explain this assuming that these subjects

tended to respond based on a certain perceptual rigidity or influenced by an attentive bias
370 towards local information. This phenomenon, well described by the psychology of Gestalt,
refers to the possibility that, when a subject recognizes a specific pattern in an ambiguous
figure, it can be difficult to notice the second pattern present, as if there was certain inertia
or resistance to recombine the information differently. There is much evidence of such
perceptual rigidity in studies on perceptual styles of people with both psychopathologies
375 (Díaz-Santos et al., 2015; Tchanturia et al., 2001), where the phenomenon is very evident,
and in the normal population (Caparos et al., 2015). Another explanation for such a
response set could derive from the different use that people can make of information
coming from the stimulus and attentive variables. If, for example, an observer uses local
information from a single Gabor, global information from the whole cylinder becomes
380 inaccessible. In conclusion, this test could be heavily affected by the cognitive and
attentive strategies implemented by the subjects to perform the task (Hogeboom &
van Leeuwen, 1997).

In conclusion, in this work a paradigm already present in the literature (Reynaud &
Hess, 2017; Treue et al., 1991) has been used to compare its results with those obtained
385 with traditional tests of common use for the evaluation of eye dominance. This paradigm
seems to allow measurement of the SED on a continuous scale and not based on the
subject's introspection, which can be a useful tool to quantify the extent of eye dominance
that, with the appropriate modifications, could be used by clinicians and experimenters to
quantify the sensory eye dominance.

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Table 1

On the right, % of observers showing a right, left, or uncertain dominance (N=17). On the left, % coherence between tests along with Binomial test p-values ($\alpha=0.016$ after Bonferroni correction)

	RE	ND	LE	Pointing	Red filter	Positive lens
Pointing	41%	6%	53%	-	-	-
Red filter	24%	41%	35%	71% _(p=0.07)	-	-
Positive lens	35%	18%	47%	76% _(p=0.02)	71% _(p=0.07)	-

Table 2

Mean PSE values for each dominance groups when merging the results at each test and considering left or right dominant only those who give coherent left or right outcomes (first column), or considering only the result to pointing (second column), red filter (third column) or positive lens (fourth column).

	Merged	Pointing	Red	Positive
RE	$-0.036 \pm 0.041^\circ$	$0.012 \pm 0.086^\circ$	$-0.036 \pm 0.041^\circ$	$-0.017 \pm 0.054^\circ$
ND	$0.029 \pm 0.087^\circ$	-	$0.037 \pm 0.098^\circ$	$-0.024 \pm 0.048^\circ$
LE	$0.156 \pm 0.094^\circ$	$0.079 \pm 0.12^\circ$	$0.124 \pm 0.1^\circ$	$0.157 \pm 0.081^\circ$

Figure 1

Stimuli were independently presented to the right and left eye through a prismatic lens system that permitted a stereoscopic view. Two 8Δ prisms were temple mounted on a stereoscope to produce a virtual 3D stimulus. A separating septum made sure that only one of the stimuli on the screen was present on each retina. In the figure, the two black circles represent the eyes and the triangles represent the prisms. The stimuli are represented by a grey rectangle (the monitor) and the virtual stimulus is represented by the dashed rectangle. The stimulus consisted of 200 Gabor patches harmonically moving and presented dichotopically with different angular phase differences and contrast between the two Gabor groups. When the angular phase difference was positive (right > left) subjects tended to perceive a clockwise rotation of the cylinder; when it was negative (right < left), subjects tended to perceive a counter-clockwise rotation. The rotation perception was ambiguous when the angular phase difference was near zero. Interestingly, for many subjects, this zero point in perception did not correspond to the zero point in stimulus intensity, as observed by Reynaud and Hess (2017).

Figure 2

a-c. Individual psychometric functions of the perceived rotation direction for three subjects as a function of the angular phase difference between the stimuli independently presented to the two eyes and as a function of interocular contrast difference. Negative values reported in legends denote a decreased contrast in the left stimulus, positive values denote a decreased contrast in the right stimulus. Data points are fitted by logistic functions from which PSEs are derived (see section 2.4). **d-f.** PSE values as a function of interocular contrast difference. For most of the subjects a linear function is able to describe this relationship (slopes= $[0.13(d), 0.14(e), 0.14(f)]$; $r=[0.84(d), 0.93(e), 0.97(f)]$; $p=[0.08(d), 0.02(e), 0.005(f)]$). The slopes found in this study are consistent with those reported by Reynaud and Hess (2017)

Figure 3

Mean psychometric curves depicting the proportion of clock-wise perception as a function of angular phase difference for right (RE), left (LE) and uncertain eye dominant (ND) observers as resulted from merging the results of all the traditional tests used (a) and PSEs as a function of interocular contrast difference for the same groups (b). For the three groups, a linear function describes the relation between PSEs and interocular contrast difference (slopes=0.11[RE], 0.11[ND], 0.16[LE]; $r=0.85$ [RE], 0.87[ND], 0.88[LE]; $p=0.05$ [RE, ND and LE]). The slopes found in this study are very close to those reported by Reynaud and Hess (2017), which were about $0.11 \pm 0.07^\circ$ (Reynaud & Hess, 2017). c-f. Histograms of mean PSEs for RE, ND, and LE using four different criteria: merged tests, or using only pointing, red filter, or positive lens test. Each value and significance value is reported in table 2 and the main text.