Measuring the reliability of binocular rivalry

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Binocular rivalry is a widely used tool in sensory and cognitive neuroscience to investigate different aspects of vision and cognition. The dynamics of binocular rivalry (e.g., duration of perceptual dominance phases and mixed percept proportions) differ across individuals; based on rivalry dynamics, it is also possible to calculate an index of ocular dominance (by comparing the perceptual dominance of the images in the two eyes). In this study, we investigated the reliability of binocular rivalry dynamics using different methods for dichoptic stimulation and different rivalry stimuli. For the three main indices we defined (ocular dominance, phase durations and mixed percept proportions), we found a high test–retest reliability across sessions. Moreover, the test–retest reliability of the ocular dominance index was predictable from its internal consistency, supporting its stability over time. Phase durations and mixed percept proportions, in contrast, had worse test–retest reliability than expected based on internal consistency, indicating that these parameters are susceptible to state-dependent changes. Our results support the use of the ocular dominance index and binocular rivalry in the measurement of sensory eye dominance and its plasticity, but advise caution when investigating the association between phase durations or mixed percepts and stable characteristics like psychological traits or disorders.

Introduction

Binocular rivalry is a form of perceptual bi-stability that occurs when the two eyes are simultaneously presented with incompatible images (Levelt, 1966; Alais & Blake, 2005). Observers track and report their visual perception by indicating periods of complete dominance of the image presented in either eye and periods of mixed percepts, that is, transient periods of binocular fusion in which either a piecemeal combination or a superimposition or fusion of the two images is perceived. This technique is a widely used tool in visual psychophysics to study various aspects of vision and cognition (Baker, 2010).

One characteristic that is often studied with binocular rivalry is ocular dominance, or the degree to which our visual perception relies on the input from either eye (Ooi & He, 2001; Handa et al., 2006; Dieter, Sy, & Blake, 2017a; Ding, Naber, Gayet, der Stigchel,

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& Paffen,2018). The dynamics of binocular rivalry provide an elaborated measure of ocular dominance, more quantitative and precise (Ooi & He, 2020) than other sighting eye dominance tests, such as the Porta test (Porta, 1593; Lederer, 1961) or the hole in card test (Durand & Gould, 1910). For example, binocular rivalry made it possible to unveil a form of plasticity in adult humans, consisting of an ocular dominance shift after a brief period (approximately 2 hours) of monocular deprivation (Lunghi, Burr, & Morrone, 2011, 2013; Han, Alais, MacDougall, & Verstraten, 2020; Wang, McGraw, & Ledgeway, 2020).

Besides ocular dominance, the dynamics of binocular rivalry have been linked to multiple aspects of perceptual and cognitive function. The temporal frequency with which alternative percepts take turns during binocular rivalry (measured by the duration of exclusive dominance phases or its inverse, the switch rate) shows large inter-individual variability (Ooi & He, 2001; Gallagher & Arnold, 2014; Dieter et al., 2017a) and it correlates with switch rates in other forms of perceptual rivalry (Carter & Pettigrew [2003]; but see Brascamp, Becker, & Hambrick [2018] for a recent reevaluation of this result). These and other observations suggest that rivalry dynamics may be an intrinsic ultradian rhythm—a stable, trait-like characteristic of every individual. There is evidence for genetic factors affecting this rhythm (Miller et al., 2010; Shannon, Patrick, Jiang, Bernat, & He, 2011), which tends to be similar across monozygotic twins. There is also evidence for the association between the rhythm of perceptual alternations during binocular rivalry and psychological traits or disorders. For instance, binocular rivalry dynamics are slower in individuals with autism (Robertson, Kravitz, Freyberg, Baron-Cohen, & Baker, 2013; Spiegel, Mentch, Haskins, & Robertson, 2019), in neurotypical individuals with stronger self-reported autistic traits (Dunn & Jones, 2020), and in patients with schizophrenia (Xiao et al., 2018; Ye, Zhu, Zhou, He, & Wang, 2019). Other studies found that rivalry dynamics are slower in people with bipolar disorder and depression (Miller et al., 2003; Ngo, Mitchell, Martin, & Miller, 2011; Jia et al., 2015), but faster in those with anxious personality traits (Nagamine et al., 2007; Jia et al., 2020). Thus, differences in binocular rivalry dynamics may emerge as a potential proxy for complex psychological constructs, such as personality traits and disorders.

Given the diverse uses of binocular rivalry, it is important to establish its reliability. Indices such as mean phase duration and proportion of mixed percepts have been shown to be stable within a given experimental session (van Ee, 2005; Dieter et al., 2017a; Dieter, Sy, & Blake, 2017b), implying good internal consistency. What is missing is an assessment of their test–retest reliability, that is, their stability over experimental sessions performed on different days, which is expected to be high for any trait-like characteristic. For ocular dominance, reliability was recently questioned by Min et al. (2021), who compared different techniques for the assessment of ocular dominance (binocular rivalry, binocular phase combination, and dichoptic masking). The authors report that ocular dominance estimates obtained by parallel-oriented dichoptic masking and binocular phase combination tasks show a higher test–retest reliability compared with binocular rivalry, which exhibited poor stability across experimental sessions. In particular, ocular dominance estimated in different days using binocular rivalry showed a high variability and no significant correlation across participants. These results partially contradict previous studies, which show that binocular rivalry provides precise and reliable estimates of ocular dominance across days (Dieter et al., 2017a), and even proposed binocular rivalry as the standard technique to quantify sensory eye dominance in adult humans (see Ooi & He, 2020 for review).

To address these issues, here we examined the reliability of binocular rivalry dynamics and derived ocular dominance measures using four relatively large datasets, and a variety of methods and stimuli. Inspired by Min et al.'s approach, we separately assessed two aspects of reliability: internal consistency, based on the variability of estimates within a single experimental session, and test–retest reliability, based on the variability across experimental sessions conducted on separate days.

Methods

Participants

A total of 118 volunteers with normal or corrected to normal vision participated in the four experiments presented here. All except the authors were naïve to the purposes of the study. Part of these data were collected in the context of past studies, the results of which have been reported previously.

Forty volunteers, mean age 28.6 ± 0.72 years, 25 females (including authors I.S. and C.L) took part in experiment 1 (Sarı & Lunghi, 2023). Thirty-three volunteers, mean age 25.8 ± 0.11 years, 18 females (including authors M.A. and C.L.) took part in experiment 2 (Acquafredda, Binda, & Lunghi, 2022). Thirty-four volunteers, mean age 23.9 ± 0.79 years, 24 females (including authors C.L. and C.S.) took part in experiment 3 (Lunghi & Sale, 2015; Steinwurzel, Animali, Cicchini, Morrone, & Binda, 2020). Twenty volunteers, mean age 27.5 ± 0.4 years, 14 females (including author C.S.) took part in experiment 4 (unpublished); 7 of these had also participated in experiment 3.

Ethics statement

All four experimental protocols were approved by local ethics committees. The "Comité d'éthique de la Recherche de l'université Paris Descartes" approved experiments 1 & 2 (CER-PD:2019-16-LUNGHI) and the "Comitato Etico Pediatrico Regionale—Azienda Ospedaliero-Universitaria Meyer—Firenze" approved experiments 3 and 4 (protocol "Plasticità del Sistema visivo"). All experiments were performed in accordance with the Declaration of Helsinki (DoH-Oct2008). All participants gave written informed consent.

Apparatus, stimuli, and procedure

A diagram of the experimental setups for the four experiments included in the study is reported in Figures 1A–D. All experiments shared the same logic and design, which we describe first, followed by the specific features of each individual experiment.

For all experiments, participants took part in two experimental sessions, at least 24 hours apart. Each session was divided into two trials of 3 minutes each (6 minutes in total), except for experiment 2, where four 3-minute-long trials (12 minutes in total) were tested. Participants viewed the monitor from a 57 cm distance; a chin and forehead rest stabilized head position. The stimuli consisted of small circular gratings presented dichoptically in central view; they were inscribed in a binocular frame to facilitate fusion. Participants reported rivalrous alternations through the computer keyboard, by continuously pressing one of three keys to report exclusive percepts of orthogonally oriented gratings (right arrow for clockwise and left arrow for counterclockwise) or a mixture of those (piecemeal or fusion: down arrow key). The orientation of gratings presented in either eye was counterbalanced across participants and switched on every trial to avoid adaptation. For experiment 1, the swapping procedure was done every 90 seconds, that is, halfway through a trial.

Experiments mainly differed in the method used for dichoptic stimulation. Experiments 1 and 2 used a mirror stereoscope placed in front of an LCD monitor (BenQ XL2420Z, 1920 × 1080 pixels, 144 Hz refresh rate, Taipei, Taiwan). Experiment 3 and the first session of experiment 4 used CRS ferromagnetic shutter goggles (Cambridge Research Systems, Kent, UK) and a CRT monitor (Barco 6551, 800 × 600 pixels, 140 Hz refresh rate, Kortrijk, Belgium). The second session of experiment 4 used anaglyph red-blue goggles and a LED monitor (LG IPS 24EA53, 1920 × 1080, 60 Hz refresh rate, Seoul, South Korea).

There were also differences in the stimuli used to induce rivalry (recall that these experiments were run for independent studies). In experiments 1 and 3 and in the first session of experiment 4, stimuli were monochromatic sinusoidal gratings (orientation: ±45°, spatial frequency: 2 cpd, contrast: 50%, size: 3° or 2° in experiments 1 and 3 and experiment 4, respectively) presented against a uniform gray background (experiment 1: luminance 110 cd/m^2, C.I.E. $x = 0.305$, $y = 0.332$; experiment 3 and 4: luminance 37.4 cd/m^2,

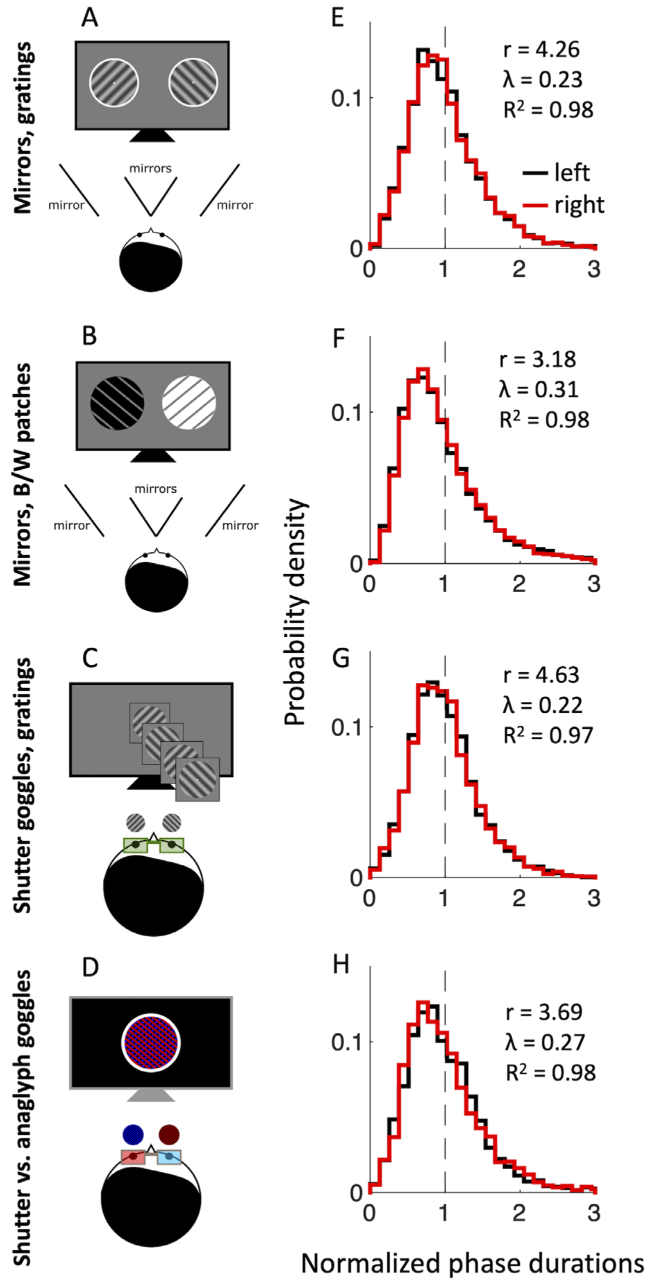

Figure 1. Experimental set-ups and parameters of rivalry dynamics. (**A**–**D**) Schematics of the stimuli and set-ups. (**E**–**H**) Probability density function of the normalized phase durations for exclusive dominance of left and right eyes (black and red lines, respectively), with best-fitting parameters of the Gamma distribution.

C.I.E. $x = 0.442$, $y = 0.537$). In the second session of experiment 4, stimuli were red and blue gratings (orientation: ±45°, size: 3°, spatial frequency: 2 cpd, maximum luminance: 0.5 cd/m^2), presented against a black uniform background. In experiment 2, stimuli were 3° disks, one white (maximum screen luminance 295 cd/m^2) and one black (minimum screen luminance 10 cd/m^2) shown against a uniform gray background (luminance 152 cd/m^2). To discourage binocular fusion, the disks were overlaid with orthogonal gray lines (45° clockwise or counterclockwise, 0.033° or 1 pixel wide, and 0.5° apart).

Descriptive statistics

For each binocular rivalry trial, we used our participants' continuous perceptual reports to extract the following parameters.

Exclusive dominance phases were defined as periods of time during which participants reported seeing exclusively the image presented to their right or left eye. Phase durations were computed separately for each eye; durations shorter than 0.25 second were considered keypress errors and discarded from the analysis. We also measured the time spent reporting mixed percepts (fusion or piecemeal combinations of the images presented in the two eyes) and expressed it as a proportion of the total testing time.

Ocular dominance was defined as the proportion of exclusive right-eye dominance, according to the following equation:

$$ODI = \frac{Time_{RE} - Time_{LE}}{Time_{RE} + Time_{LE}}, \quad (1)$$

where ODI stands for Ocular Dominance Index and $\mathrm{Time}_{\mathrm{RE}}$ and $\mathrm{Time}_{\mathrm{LE}}$ are the total amount of time (in seconds) spent seeing through the right eye or left eye, respectively. Participants with an ODI of greater than 0.25 or less than –0.25 in the first session were excluded from further testing, leaving the sample sizes as reported in the above section. This exclusion criterion was applied because all studies were aimed at investigating the impact of external factors (e.g. short-term monocular deprivation or voluntary attention) on ocular dominance. Participants showing extreme ocular dominance values at baseline were excluded to avoid a possible saturation effect.

We checked that the distribution of exclusive dominance phase durations followed a gamma distribution. First, we normalized phase durations separately for the right and left eye to their mean phase duration. Next, we pooled phase durations from all participants.

Finally, these normalized phase duration distributions (Figures 1E–H) were fit with a two-parameter Gamma distribution, with shape α and scale β parameters:

$$f(x|\alpha, \beta) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{\frac{-x}{\beta}} \text{ for } x, \alpha, \ \beta > 0, \quad (2)$$

where Γ is the gamma function and x is the number of dominance phases. Best fit parameters are reported in the text insets of Figures 1E–H.

Measurement reliability: Test–retest reliability and internal consistency

Estimates of internal consistency and test–retest reliability were obtained from the intra-session and the inter-session variability, respectively, of the three main parameters of interest: ODI, mean phase durations (pooled across eyes), and mixed percept proportions.

By internal consistency, we mean the stability of a parameter within a given trial (i.e., a portion of an experimental session that was run without interruptions). Our aim was to compare this with the stability of the same parameter across sessions. The latter was measured as the difference in the parameter estimates from one trial in the first session vs estimates from one trial in the second session. For each trial we represented perceptual reports as a list of phases, each linked with its duration and type (left eye, right eye, mixed). This list was resampled 10,000 times with reinsertion; for each resampling, we estimated the three parameters of interest and computed their difference between the two trials coming from different sessions. Finally, we took the standard deviation across these 10,000 differences as a measure of standard error and combined standard errors across trials by taking the median. We used this value as indicative of internal consistency. By including this step in our analysis, we estimated intra-session variance in a way that 1) does not need the a priori assumption of equal variance on the two sessions, 2) is independent of the means, and 3) is directly comparable with inter-session variance (from which we derived our measure of test–retest reliability). By test–retest reliability, we mean the stability of a parameter across experimental sessions conducted on separate days. To estimate this, we computed inter-session correlations and inter-session differences as visualized in Bland–Altman plots.

Inter-session correlations were computed as the Pearson's r of the values obtained for each parameter in the two sessions; vertical and horizontal lines around each data point (leftmost panels of Figures 2–5) showing the bootstrapped standard error of the index obtained for each session.

Bland–Altman plots (Altman & Bland, 1983) were generated by plotting, for each parameter, the difference between the two sessions (inter-session difference)

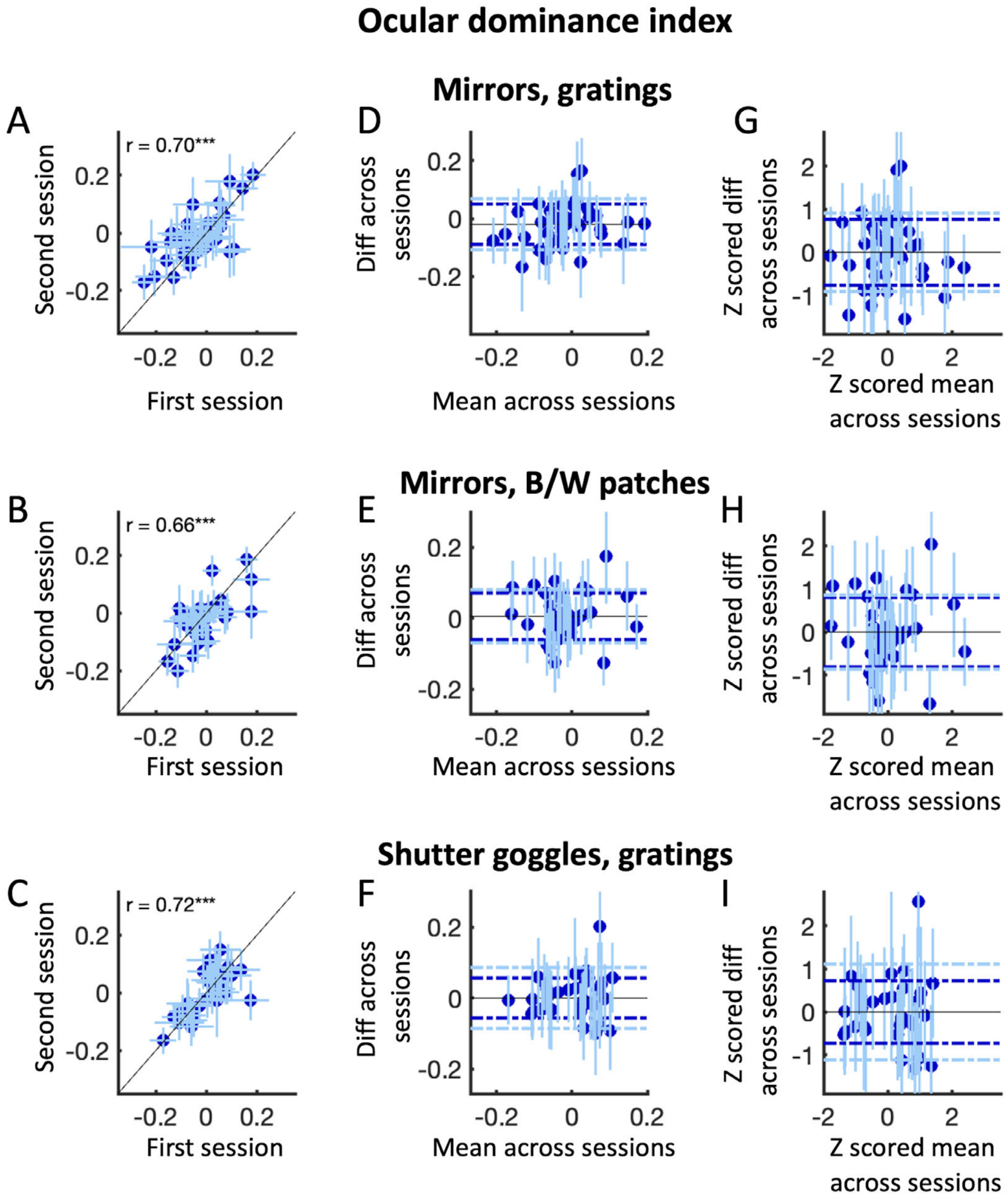

Figure 2. Ocular dominance: variability across sessions and within-session. (**A**–**C**) Individual participants' ocular dominance indices for the first (*x*-axis) and the second session (*y*-axis). The cyan error bars around data points represent the bootstrapped standard error of a single participant's ocular dominance index within a single session. Continuous black lines mark the bisector, indicating no difference between the two sessions. In-text values report Pearson's correlation indices and significance (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$). (**D**–**F**) Bland–Altman plots where the difference in ocular dominance between the first and second sessions is plotted as a function of the mean across two sessions. The horizontal continuous black line indicates the mean difference across subjects. The outer horizontal dark blue dashed lines indicate the relative 95% limits of agreement, indicative of test–retest reliability. Cyan continuous lines around each point show the bootstrapped standard error of the single-subject measurements, indicative of internal consistency. Cyan horizontal dashed lines indicate the 95% confidence interval of internal consistency across participants. In all panels, the three rows report data from experiments 1, 2, and 3 respectively. (**G**–**I**) Bland–Altman plots based on z-scored data. All indicators are the same as (**D**–**F**). The continuous black line reports the $y = 0$ function.

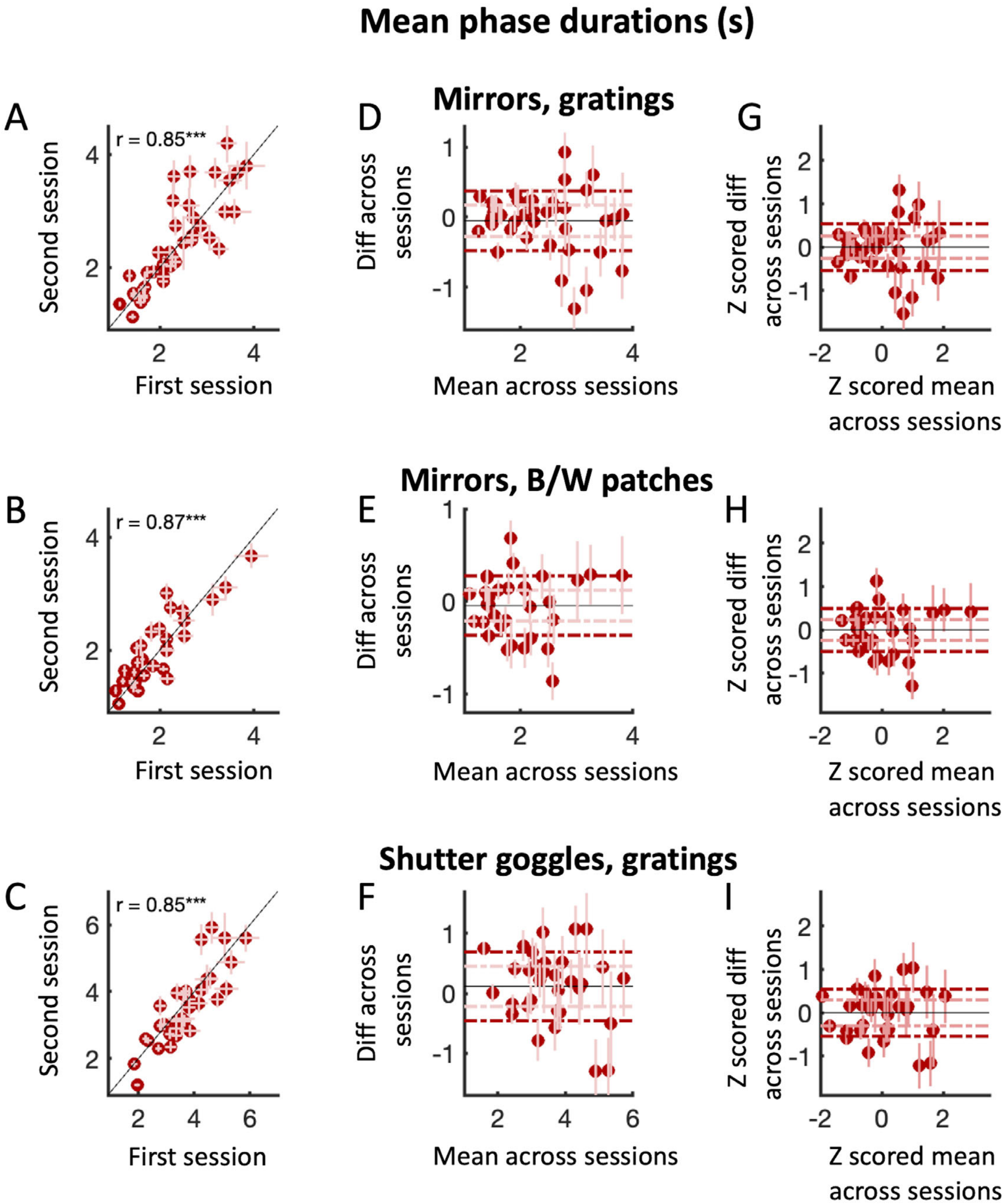

Figure 3. Mean durations of exclusive dominance phases: variability across-sessions and within-session. (**A**–**C**) Individual participants' mean phase durations (s) for the first session (*x*-axis) and second session (*y*-axis). All indicators are the same as Figure 2. (**D**–**F**) Bland–Altman plots. All indicators are the same as Figure 2. Horizontal dark red lines mark the 95% confidence interval of test–retest reliability and light red ones mark that of internal consistency. (**G**–**I**) Bland–Altman plots based on z-scored data. All indicators are the same as (**D**–**F**).

against the mean across sessions. We integrated this representation with our measure of internal consistency by showing the bootstrapped standard error of the inter-session difference as vertical lines around each data point. Horizontal dashed lines show summary statistics of both test–retest reliability and internal consistency in the form of 95% confidence intervals, allowing for a direct comparison of the two. Dark blue, red, an green horizontal dashed lines show the 95% limits of agreement, computed as the mean $\pm$ 1.96 $\times$ standard deviation of the inter-session differences across participants. Light blue, red, and green horizontal lines show the 95% confidence interval of the inter-session difference, computed as the $\pm$1.96

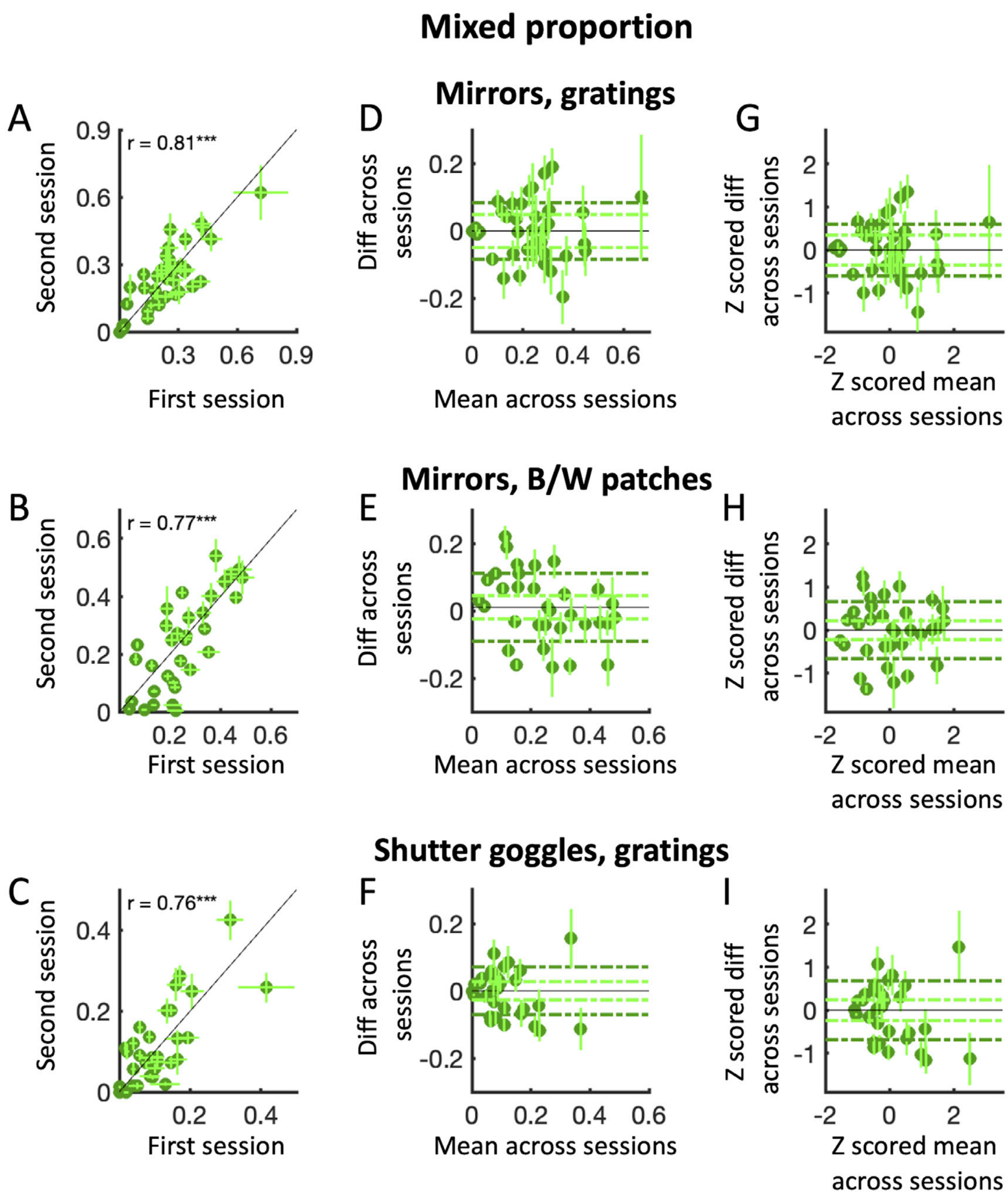

Figure 4. Mixed percept proportions: variability across sessions and within session. (**A**–**C**) Individual participants' mixed percept proportions for the first session (*x*-axis) and second session (*y*-axis). All indicators are the same as in Figures 2 and 3. Horizontal dark green lines mark the 95% confidence interval of test–retest reliability and light green ones mark that of internal consistency. (**D**–**F**) Bland–Altman plots. All indicators are the same as in Figures 2 and 3. (**G**–**I**) Bland–Altman plots based on z–scored data. All indicators are the same as (**D**–**F**).

× the median bootstrapped standard error across participants. We show these representations in two versions, before and after z-scoring of the data (central and rightmost panels of Figures 2–5, respectively); the latter allows for comparing test–retest reliability and internal consistency across indices (note that *x*- and *y*-scales of the rightmost plots are kept consistent across all figures). To facilitate comparison with Min et al. (2021), the z-scored confidence intervals of the ocular dominance indices are also reported in Table 1.

Hypothesis testing

We checked that all variables were normally distributed (Kolgorov-Smirnov test (Limiting form)

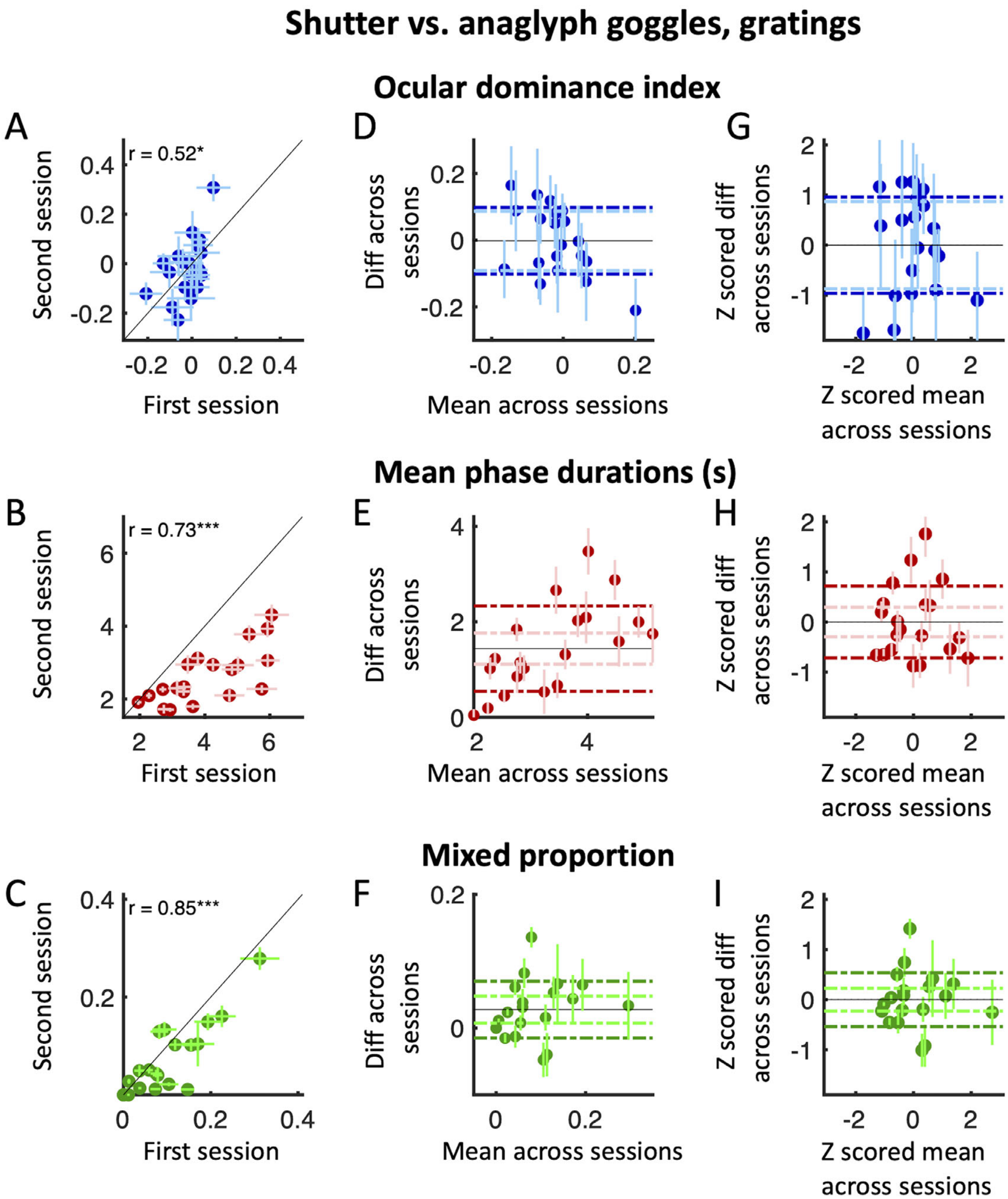

Figure 5. Consistency of binocular rivalry parameters across set-ups (experiment 4). In all panels, the three rows show data from experiment 4 for ocular dominance index, mean phase duration and mixed percept proportions, respectively. (**A**–**C**) Individual participants' measurement of interest for the first session (*x*-axis: shutter goggles) and the second session (*y*-axis: anaglyph goggles). All indicators are the same as in Figures 2–4. (**D**–**F**) Bland–Altman plots where the difference in measurement of interest between the first and second sessions is plotted as a function of the mean across two sessions. All indicators are the same as in Figures 2–4. (**G**–**I**) Bland–Altman plots based on z-scored data. All indicators are the same as (**D**–**F**).

$p > 0.05$). Statistical significance was evaluated using both p values and log-transformed JZS Bayes Factors, computed with the default scale factor of 0.707 (Wagenmakers, Wetzels, Borsboom, van der Maas, & Kievit, 2012). The Bayes factor is the ratio of the likelihood of the two models H1/H0 given the observed data, where H1 is the experimental hypothesis (effect present) and H0 is the null hypothesis (effect absent). A base 10 logarithm of the Bayes Factor (*logBF*) larger than |0.5| corresponds with a likelihood ratio larger than 3 in favor of either H1 (when $logBF > 0.5$) or H0 (when $logBF < -0.5$), and this value is conventionally used to indicate substantial evidence in favor of either hypothesis. Comparisons across parameters (Figure 6)

	Method	Inter-session	Intra-session
Current study	Binocular rivalry: mirrors, gratings ($n = 40$)	±1.53	±1.82
	Binocular rivalry: mirrors, B/W patches ($n = 33$)	±1.62	±1.73
	Binocular rivalry: shutter goggles, gratings ($n = 34$)	±1.46	±2.23
Min et al. (2021)	Binocular rivalry: shutter goggles, luminance modulated gratings ($n = 45$)	±2.49	±1.69
	Binocular combination at many contrasts ($n = 34$)	±2.08	±0.59
	Parallel-oriented masking ($n = 14$)	±1.83	±0.50

Table 1. Comparison of test–retest reliability and internal consistency. The first three rows show results from our experiments 1–3: the 95% limits of agreement of ODI (a measure of test–retest reliability) and the 95% bootstrapped confidence interval (a measure of internal consistency). All values are z-scored, as in Min et al. (2021) reported in the bottom rows (gray).

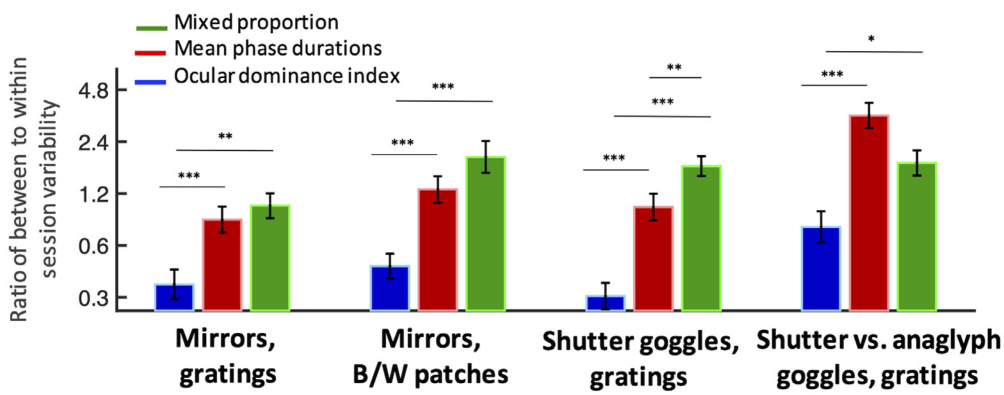

Figure 6. Comparison of the ratio of test–retest reliability and internal consistency. Bar plot of the ratio of test–retest reliability to internal consistency for ocular dominance index (blue bars), mean phase duration (red bars), and mixed percept proportion (green bars), separately for our four experiments. Ratios were log-transformed before averaging and comparing; their means and SEM (shown by the error bars) were transformed back into their natural values and visualized on a logarithmic scale; consequently, a value of 2 indicates that, on average, the variability between sessions is twice as large as the variability within sessions. Asterisks report significance of the post hoc *t*-tests. $*p < 0.05$; $**p < 0.01$; $***p < 0.001$.

were performed using two-tailed, paired-samples *t* tests. The *p* values were corrected for multiple comparisons with Bonferroni correction.

Results

We measured binocular rivalry in a total of 118 participants with three dichoptic stimulation set-ups and four different stimuli. Dichoptic stimulation was achieved through a mirror stereoscope in experiments 1 and 2 (Figures 1A, B), shutter goggles in experiment 3 (Figure 1C), and anaglyph red/blue goggles in experiment 4 (Figure 1D). In experiments 1, 2, and 3, data collection was repeated twice with identical stimuli and set-up, on different days, allowing us to gauge a measure of stability and reliability of rivalry indices; in experiment 4, data were acquired with two different set-ups testing the stability of those indices across time and stimulation conditions.

Figure 1E through H reports data from experiments 1, 2, 3, and 4. In all cases, the distribution of the normalized mean durations of exclusive dominance phases was well modeled by the Gamma function (all $R^2 > 0.96$; best-fit parameters are reported as text insets in Figures 1E–H), as expected (Levelt, 1966, 1967). Based on the Gamma-fits we gauged that all four experiments elicited a typical binocular rivalry phenomenon.

Next, we focused on three main indices of rivalry dynamics from the first three experiments: ocular dominance (Figure 2), mean phase durations (Figure 3), and mixed percept proportions (Figure 4). Results for the three indices from the fourth experiment are shown in Figure 5.

Ocular dominance (computed as in Equation 1) is well correlated across the two sessions of data collection, experiment 1: $r = 0.70$, $p < 0.001$, $lgBF = 4.42$; experiment 2: $r = 0.66$, $p < 0.001$, $lgBF = 2.83$; experiment 3: $r = 0.72$, $p < 0.001$, $lgBF = 4.49$ (Figures 2A–C). Inspection of the Bland–Altman plots shows that the confidence intervals of test–retest reliability (horizontal dashed blue lines) are within the confidence intervals of the internal consistency (horizontal dashed cyan lines). In other words, the test–retest reliability (distance of blue symbols from the $y = 0$ line) is expected from the internal consistency of the parameter (vertical blue lines representing ± 1 bootstrapped standard error). This means that the variance between sessions is fully explained by the variance within session (internal consistency), indicating that ocular dominance is not significantly affected by state-dependent day-to-day variations.

Table 1 reports summary statistics from Figure 2 using similar conventions as in Min et al. (2021) (including z-scoring of the data and reporting 95% limits of agreements and 95% confidence intervals to index test–retest reliability and internal consistency, respectively). Our values are not far from the values reported by Min et al. (2021) for their binocular rivalry experiments; in particular, measures of internal consistency are comparable across studies or marginally larger. However, our 95% limits of agreements are smaller than those in Min et al. (2021), indicating better test–retest reliability of our ocular dominance indices than any of the measures in Min et al. (2021), both those derived from binocular rivalry and from other tasks and paradigms.

Figure 3 uses the same format as Figure 2 to report the mean duration of exclusive dominance phases (pooled across eyes). Again, we found excellent correlations across sessions, irrespectively of the type of stimuli or set-up, experiment 1: $r = 0.85$, $p < 0.001$, $lgBF = 9.35$; experiment 2: $r = 0.87$, $p < 0.001$, $lgBF = 8.49$; experiment 3: $r = 0.85$, $p < 0.001$, $lgBF = 9.45$. However, contrary to what was observed for ocular dominance, the Bland–Altman plots (Figures 3D–F) show that the test–retest reliability (distance of red symbols from the $y = 0$ line) is worse than expected from the internal consistency of the parameter (vertical light red lines representing ± 1 bootstrapped standard error), suggesting that a significant portion of the between-sessions variance cannot be explained by the internal fluctuations occurring within the session, but is instead related to external or state-dependent factors.

Z scored values in the third column can be compared with the same values computed for ODI (Figures 2G–I). The spread of the datapoints indicating the differences across sessions is similar between the two measurements, and their limits of agreement are comparable. However, the light bars are much shorter for mean phase durations compared to ODI, indicating much higher internal consistency for mean phase durations than for the ODI.

Figure 4 uses the same format as Figures 2 and 3 to report proportion of mixed percepts. Values are well-correlated across sessions, experiment 1: $r = 0.81$, $p < 0.001$, $lgBF = 7.74$; experiment 2: $r = 0.77$, $p < 0.001$, $lgBF = 5.06$; experiment 3: $r = 0.76$, $p < 0.001$, $lgBF = 4.86$. However, as seen for the mean phase durations in Figure 3, the Bland–Altman plots (Figures 4D–F) show that the test–retest reliability (distance of blue symbols from the $y = 0$ line) is worse than expected from the internal consistency of the parameter (vertical green lines representing ± 1 bootstrapped standard error). The same conclusions hold for the z-scored values plotted in Figure 4G through I.

In our fourth experiment, we asked whether similar conclusions would hold when comparing binocular rivalry dynamics and ocular dominance indices across sessions collected on different days and with different stimulation conditions. We measured rivalry using either the stimulus of experiment 3 (first session: monochromatic gratings delivered via shutter goggles) or a new stimulus (second session: colored gratings delivered via anaglyph glasses). Figure 5A through C shows that rivalry dynamics were still correlated across sessions, ODI: $r = 0.52$, $p = 0.02$, $lgBF = 0.41$; mean phase durations: $r = 0.73$, $p < 0.001$, $lgBF = 2.14$; mixed proportions: $r = 0.85$, $p < 0.001$, $lgBF = 4.01$, although mean phase durations were systematically longer in the first session, as expected from the much lower contrast of the stimuli.

Bland–Altman plots show that the main difference across indices is in their internal consistency (better for mixed percept proportions, followed by mean phase durations and worse for ODI), in the face of homogeneously high and fairly similar test–retest reliability. This pattern of results is confirmed by the z-scored data (Figures 5G–I). Thus, the results of experiment 4 (comparison across days and experimental set-ups) are in line with the results of experiments 1-3 (comparison across days with identical experimental set-ups).

Figure 6 illustrates more directly the relationship between internal consistency and test–retest reliability for the three parameters of interest. For each parameter, we considered each individual participant's test–retest reliability (measured as the difference between sessions) and the same participants' internal consistency (instability of the measure in each session, measured as the bootstrapped standard error); we took the ratio of these meaures, log-transformed to distribute normally and finally averaged ratio values across participants. Large ratio values imply that indices vary more across sessions than within sessions, while small values imply that intersession differences are largely accounted for by internal (in-)consistency. A two-way analysis of variance with within-subjects factor "binocular rivalry parameter" (three levels: ODI, mean phase durations, and mixed percepts) and between-subjects factor "experiment" (four levels, from 1 through 4) revealed significant effects of parameter, $F(2,246) = 57.63$, $p < 0.001$; experiment, $F(3,123) = 10.65$, $p < 0.001$; and parameter by experiment interaction, $F(6,246) = 2.15$, $p = 0.048$. Post hoc t-tests reveled that, in all experiments, ODI showed the smallest value; smaller than mean phase durations, experiment 1: $t = 3.27$, $p < 0.001$, experiment 2: $t = 4.88$, $p < 0.001$, experiment

3: $t = 5.35$, $p < 0.001$, experiment 4: $t = 5.11$, $p < 0.001$, and smaller than mixed percept proportions, experiment 1: $t = 4.01$, $p < 0.01$, experiment 2: $t = 5.48$, $p < 0.001$, experiment 3: $t = 7.39$, $p < 0.001$, experiment 4: $t = 2.77$, $p < 0.05$.

Discussion

We measured the reliability of three main parameters of binocular rivalry (an index of ocular dominance, the mean of dominance phase durations, and mixed percept proportions), related to two physiological constructs: sensory eye dominance and rivalry switch rate. We measured their stability over time (test–retest reliability) and their stability within each experimental trial (internal consistency).

The ODI showed lower internal consistency than the other two indices: phase durations and mixed percepts. However, this internal noise was sufficient to account for its variability across sessions, implying good stability of this index over time. On the contrary, the high internal consistency of mean phase duration and mixed percept proportions would have predicted higher test–retest reliability than observed. This implies that the test–retest reliability of these measurements is disturbed beyond their internal noise by other external or state dependent factors.

Binocular rivalry is often used to estimate ocular dominance (Xu, He, & Ooi, 2011; Dieter et al., 2017b; Ooi & He, 2020). In particular, it has been key to reveal a residual form of ocular dominance plasticity in adult humans (Xu, He, & Ooi, 2010; Lunghi, Burr, & Morrone, 2011, 2013; Lunghi, Berchicci, Morrone, & Russo, 2015; Lunghi, Emir, Morrone, & Bridge, 2015; Binda et al., 2017; Chadnova, Reynaud, Clavagnier, & Hess, 2017; Bai, Dong, He, & Bao, 2017; Wang et al., 2020; Nguyen, Malavita, Carter, & McKendrick, 2021), with potential translational impact for the treatment of amblyopia (Ooi, Su, Natale, & He, 2013; Lunghi et al., 2019; Zhou et al., 2019). This approach is predicated upon the reliability of the ocular dominance measurements made with binocular rivalry. Min et al. (2021) recently questioned this assumption, reporting that results from binocular rivalry are not particularly stable over time and fare worse than other tasks like binocular combination or masking. In the present study, using four independent binocular rivalry experiments, we found strong evidence in support of the stability of ocular dominance indices, which showed excellent test–retest reliability for a variety of methods and stimuli and demonstrated remarkable concordance even when comparing ocular dominance indices obtained with two very different rivalry-inducing stimuli and methods (shutter vs. anaglyph goggles, displaying monochromatic vs. colored stimuli). Using similar metrics as Min et al. (2021), we obtained similar estimates of internal consistency; however, we observed generally better test–retest reliability, implying better stability of our ocular dominance estimates over time (Table 1). We suggest that few differences between our binocular rivalry experiments and the experiment in Min et al. (2021) could account for this discrepancy. One is the larger amount of data per measurement: one session lasted between 6 and 12 minutes in our study (2 or 4 trials), but only 3 minutes in Min et al.'s. Another methodological issue concerns the possible impact of perceptual biases and/or adaptation. In all our experiments, we swapped grating orientations across eyes on every trial, to minimize the effects of adaptation and counterbalance the potential impact of subtle non-corrected anisometric refraction errors. In Min et al., most participants were tested without this orientation-swapping step. A third potential difference between our study and Min et al (2021) concerns the participants' ocular dominance range. In Min et al.'s sample, ocular dominance values range between approximately –0.8 and 0.5, whereas the largest range in our samples covers values from –0.25 to 0.4. The inclusion of participants with extreme ocular dominance in Min et al.'s sample might be adding to the difference in their reliability estimation and ours, suggesting that binocular rivalry dynamics might be less stable for participants with extreme ocular dominance.

We conclude that, provided that some methodological steps are taken, and that participants don't show extreme sensory eye dominance, binocular rivalry provides a robust and stable estimate of ocular dominance, which can be trusted for evaluating its short-term changes like those induced by monocular deprivation.

Turning to the other main parameters that may be extracted from binocular rivalry, the mixed percept proportions showed good internal consistency and test–retest reliability. A similar pattern was observed for the mean duration of dominance phases for which we observed high test–retest reliability, comparable to or better than the ODI, in line with previous reports (van Ee, 2005; Dieter et al., 2017a, 2017b). Mean phase durations were also well correlated across binocular rivalry measures obtained with different stimuli and methods, despite an overall difference in the average mean phase duration—lower contrast stimuli inducing slower switch rates (experiment 4). This indicates that some participants have faster or lower switch rates compared with the average across our sample and maintain this behavior irrespective of the exact stimuli and methods used to induce bistable perception. There is growing evidence that binocular rivalry switch rate reflects a perceptual trait and an internal ultradian rhythm (Carter & Pettigrew, 2003), that is, a stable and distinctive feature of each individual participant. Although our results confirm that part of the variance in this parameter is trait-like, they also highlight the impact of state-dependent factors. When comparing measurements collected on separate days, we found that differences between sessions were larger than could be expected from the internal inconsistency of this parameter. This finding suggests that a participant's psychological and/or physiological state contributes to setting their binocular rivalry switch rate while leaving ocular dominance estimates unaffected. This outcome is coherent with evidence showing that, when a binocular rivalry task is repeated over several days, ocular dominance estimates remain stable, while the switch rate is consistently altered by the task repetition (Bao, Dong, Liu, Engel, & Jiang, 2018); it is also coherent with our previous observation that switch rates are not predictive of ocular dominance or its plasticity (Steinwurzel et al., 2020). Our data offer no elements to understand the nature of these state-dependent variables. We speculate that they could be related to fluctuations in the participant's motivation and focus on the task, because attention could artificially reduce switch rates (Paffen, Alais, & Verstraten, 2006). In addition, they could be related to fluctuations in other ultradian rhythms that have similar rates as binocular rivalry, such as respiratory rates (0.16–0.33 Hz) (Russo, Santarelli, & O'Rourke, 2017) and sympathetic–parasympathetic dynamic balance (e.g., spontaneous fluctuations in pupillary diameter of <1 Hz) (Reimer et al., 2014) and metabolic factors, given previous indications of a relationship between these factors and cognitive/perceptual function (Binda & Lunghi, 2017; Pomè, Burr, Capuozzo, & Binda, 2020; Pfeffer et al., 2022; Animali et al., 2023).

In conclusion, our findings provide evidence for the reliability of the two main parameters extracted from binocular rivalry: ocular dominance and switch rate. We show that the switch rate is liable to state-related changes, which limits the possibility of reliably associating this parameter to trait-like characteristics like genetic make-up and psychological traits. In contrast, we provide evidence that ocular dominance is a trait-like characteristic stable over time, and thereby qualifies binocular rivalry as a valid tool to follow short-term changes of sensory eye dominance.

Keywords: binocular rivalry, ocular dominance, sensory eye dominance

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