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SHORT REPORT Interpreting the temporal dynamics of perceptual rivalries

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Abstract. Diverse forms of perceptual rivalry are claimed to tap a common causal mechanism. One of the bases for this claim is that the reported dynamics of binocular rivalry and motion-induced blindness are similar on an individual basis (Carter & Pettigrew, 2003 *Perception*, **32**, 295–305). We examined this relationship and found no evidence for a strong correlation. We therefore question the proposition that the dynamics of diverse forms of rivalry are driven by a common mechanism.

Keywords: multistable perception, binocular rivalry, motion-induced blindness

1 Introduction

Perceptual rivalries are characterised by alternations in the content of conscious awareness without changes to physical input. Given the unchanging physical input, processes intrinsic to the central nervous system must be responsible for the perceptual changes. Diverse forms of rivalry therefore seem to offer an opportunity to examine the neural substrates of perceptual awareness, by measuring the dynamics of a perceptual rivalry and correlating this with measures of neural activity (Leopold & Logothetis, 1999; Levelt, 1968; Logothetis, Leopold, & Sheinberg, 1996; Tong & Engel, 2001; Tong, Nakayama, Vaughen, & Kanwisher, 1998). However, the measurement and interpretation of rivalry dynamics remain a conceptual challenge.

One school of thought suggests that diverse forms of rivalry likely have diverse causes and neural substrates (Blake, 1989; Quinn & Arnold, 2010). Another hypothesis is that diverse forms of rivalry reflect a common cause and substrate (Andrews & Purves, 1997; Leopold & Logothetis, 1999). A compelling piece of evidence for a common cause is that the dynamics of different perceptual rivalries are reportedly consistent on an individual basis. An individual who reports slow perceptual changes for one type of rivalry is likely to report slow dynamics in another, and vice versa (Carter & Pettigrew, 2003; Shannon, Patrick, Jiang, Bernat, & He, 2011). This type of evidence is consistent with the existence of a common causal mechanism that governs the rate at which different forms of perceptual rivalry fluctuate (Andrews & Purves, 1997; Carter & Pettigrew, 2003; Logothetis et al., 1996).

While there is evidence to suggest diverse forms of perceptual rivalry are driven by a common mechanism, we suggest this evidence is inconclusive due to problems associated with reporting on the dynamics of subjective changes. By definition, there are usually no *physical* changes to report when viewing perceptual rivalry. Consequently, subjective decisional criteria could impact measures of rivalry dynamics. For example, take what is perhaps the best-known form of perceptual rivalry—binocular rivalry (BR). In BR discrepant images are shown to the two eyes; and instead of seeing a single fused image, people *can* experience perceptual switching, with either image alternately dominating perception (this rarely, if ever, happens in daily life—see Arnold, 2011). When described like this, one could be forgiven for assuming that measuring the dynamics of BR is trivial, but the reality is more complicated. In BR the salience of a dominant percept might begin to fade, only to rebound and again become more salient. This can happen several times before a transition finally takes place. Then the next period of dominance might be transient. Faced with this stochastic scenario, one participant, slavishly trying to follow instructions and report all perceptual changes in real time, might

report transitions that did not occur—anticipating perceptual switches when only fading occurred. Another might be more cautious, waiting until a new percept has persisted for a brief period before reporting its existence. Hence, the reported dynamics of BR are prone to the subjective criterion used to decide *when* to report a perceptual transition. Hypothetically, two people could experience identical perceptual experiences, but report very different dynamics.

Subjective criteria could similarly impact the reported dynamics of all other perceptual rivalries. Another pertinent example is motion-induced blindness (MIB). In MIB usually salient static objects can seem to intermittently disappear when in close proximity to a moving (Bonneh, Cooperman, & Sagi, 2001; Graf, Adams, & Lages, 2002; Hsu, Yeh, & Kramer, 2006; Wallis & Arnold, 2009) or flashing (Kawabe & Miura, 2007; Wallis & Arnold, 2008) stimulus. Sometimes these disappearances will persist for several seconds. Often, however, disappearances are very brief. It can be ambiguous as to whether a static element has disappeared or simply flickered. Some participants are likely to report on any impression of a disappearance, whereas others might be more conservative and wait for a persistent disappearance before committing to a report. Again, the reported dynamics of a perceptual rivalry, in this case MIB, would be subject to the individual's response criterion.

Since the reported dynamics of diverse forms of perceptual rivalry can be shaped by subjective response criteria, we felt it was worth reexamining how similar the dynamics of diverse forms of perceptual rivalry are on an individual basis (see Carter & Pettigrew, 2003). Specifically, we wanted to reexamine the suggestion that any correlation, in terms of the dynamics of diverse forms of perceptual rivalry, speaks to a common mechanism that drives perceptual changes. Here we examine an alternative possibility: any such correlation can be explained by participants adopting similarly conservative or relaxed response criteria when reporting perceptual changes in diverse forms of perceptual rivalry. We addressed this latter possibility by also examining the dynamics with which people reported alternations in a physical nonrivalling stimulus undergoing stochastic changes, which mimic the dynamics of perceptual rivalry.

On the basis of previous reports (Carter & Pettigrew, 2003; Shannon et al., 2011), we expected to find a strong correlation between the reported rates of perceptual switching in BR, MIB, and when viewing a Necker cube (NC) (see figure 2 in section 4). Across three experiments we find no evidence for a strong correlation between the reported dynamics of diverse forms of perceptual rivalry, nor for a correlation between of the dynamics of perceptual rivalries and variance with which people report on stochastic physical stimulus alternations. Of the correlations we measure, the strongest was between one form of perceptual rivalry and participants' tendency to overreport or underreport on the dynamics of an unambiguous physical stimulus.

2 Results

In each of three experiments participants reported on perceptual alternations while viewing a rivalry stimulus (two of either BR, MIB, or a NC). Participants also reported on alternations within a physical stimulus undergoing stochastic changes. The nonrivalrous stimulus consisted of orthogonal sinusoidal Gabor gratings, oriented vertically and horizontally, interspersed with a plaid pattern to simulate periods of mixed perceptual dominance (see section 4). The dynamics of changes in this physical stimulus matched the dynamics reported by one of the authors while viewing a BR stimulus, meaning that all participants viewed the same alternation dynamics for the nonrivalrous stimulus. We reasoned that a participant who reports fewer alternations than there were physical alternations would be adopting a conservative criterion for reporting perceptual change, whereas a participant who reports more alternations than there were physical alternations a participant of reporting perceptual change (see subsection 4.1.5 for further details).

2.1 Experiment 1

The results of experiment 1 (N = 54) did not evince a strong relationship between the reported dynamics of MIB and BR (r = 0.23, p = 0.096; see figure 1). This relationship was even weaker when we excluded from analysis participants who reported outlying dynamics in either form of perceptual rivalry (± 2 standard deviations from sample average; N = 50, r = 0.15, p = 0.298). Results were also characterised by nonsignificant correlations between the reported dynamics of MIB and an overreported or underreported number of physical dominance periods in the nonrivalrous stimulus (r = 0.13, p = 0.174) and also between the reported dynamics of BR and an overreported or underreported number of physical dominance periods in the nonrivalrous stimulus (r = 0.09, p = 0.259).

Data suggesting a weak correlation between the reported dynamics of diverse forms of perceptual rivalry, which are actually well correlated perceptually, could have ensued if participants had not been, or were only intermittently, attending the task. We therefore assessed how consistent participants were, in terms of reported dynamics, across the five trials completed for each form of perceptual rivalry (ie test–retest reliability). These analyses revealed Cronbach's α of 0.95 for BR and 0.89 for MIB (see figure 1), so we believe participants were attending the task and were consistent in how they reported a particular form of rivalry. Our data therefore suggest our participants were reliably reporting on the dynamics of their perceptual experiences, but these dynamics were not well correlated on an individual basis across different forms of perceptual rivalry.

2.2 *Experiment 2*

In experiment 2 (N = 23) we manipulated experimental instructions, as we were worried that our failure to replicate a previous finding might have been due to instructional differences. Our BR instructions for experiment 1 ("Press left button when you can *only* see vertical bars, and the right when you can *only* see horizontal bars. Don't press either button if you are either unsure or you can see *both* orientations"—henceforth the standard instructions) differed from those used in a previous study, wherein participants had been told to press a third button when they experienced both orientations "for more than a transition period" (Carter & Pettigrew, 2003—henceforth the replication instructions). In experiment 2 we replicated the BR and MIB conditions of experiment 1, and we also included conditions where we replicated the instructions from the previous study. Both the standard and the replication instructions were each applied to one of two BR conditions and to one of two conditions in which participants reported on the unambiguous alternation dynamics of a physical nonrivalrous stimulus (see section 4 for further details).

A paired *t*-test showed that instructional set had a significant effect on reported BR dynamics, with reported dynamics slowed for the replication instructions (experiment 2a, BR: $M = 0.27 \pm 0.11$ Hz) relative to standard instructions (experiment 2b, BR: $M = 0.33 \pm 0.12$ Hz; $t_{22} = 3.37$, p = 0.003). The instructional set had a qualitatively matched impact on reporting physical nonrivalrous alternations, with fewer changes reported for replication instructions (experiment 2a: $M = -9.30 \pm 11.23$) relative to our standard instructions (experiment 2b: $M = -0.48 \pm 5.57$; $t_{22} = 3.68$, p = 0.001). However, results of experiment 2 provided no evidence for a robust correlation between BR and MIB. This was true both for BR with replication instructions (r = -0.05, p = 0.821; see figure 1, experiment 2a) and for BR with standard instructions (r = -0.09, p = 0.683; see figure 1, experiment 2b). These correlations were not qualitatively impacted by the removal of participants who had reported outlying dynamics relative to the sample mean for any form of perceptual rivalry (experiment 2a: N = 22, r = -0.13, p = 0.555; experiment 2b: N = 21, r = -0.11, p = 0.626). We also observed a weak and statistically nonsignificant correlation between MIB and misreports regarding the number of physical alternations in a nonrivalrous stimulus (r = 0.26, p = 0.231), but found



Figure 1. For each experiment we correlated the reported dynamics of two perceptual rivalries. We computed Cronbach's α as an internal consistency measurement for each perceptual rivalry. We also measured the Pearson correlation coefficient between the two perceptual rivalries and the reported alternation rate of the physical nonrivalrous stimulus. (a) Left: mean switch rates for binocular rivalry (BR) and motion-induced blindness (MIB) correlation in experiment 1; right: all internal consistency measures (α) and correlations (r) in experiment 1. (b) Left: mean switch rate in experiment 2a for BR with replication instructions correlated with mean switch rate for MIB; right top: all internal consistency measures (α) and correlations (r) in experiment 2a; right bottom: all internal consistency measures (α) and correlations (r) in experiment 2a; right bottom: all internal consistency measures (α) and correlations (r) in experiment 2a; right bottom: all internal consistency measures (α) and correlations (r) in experiment 2a; right bottom: all internal consistency measures (α) and correlations (r) in experiment 2a; right bottom: all internal consistency measures (α) and correlations (r) in experiment 3.

no evidence for such a correlation involving BR regardless of instructional set (standard instructions, r = 0.01, p = 0.963; replication instructions, r = 0.04, p = 0.856).

2.3 Experiment 3

The reported dynamics of any form of perceptual rivalry are broadly impacted by three factors—neural interactions within the substrate(s) that bring about perceptual changes, physical stimulus characteristics that can modify the dynamics of neural activity, and subjective response criteria. Consequently, one possible reason for there being only weak correlations between the reported dynamics of diverse forms of rivalry would be if one of the two forms of rivalry were determined primarily by physical stimulus characteristics. Of the forms of rivalry in experiments 1 and 2, we felt that MIB might be most susceptible to this criticism because it has a high degree of stimulus specificity, in that it does not occur in response to equiluminant motion (see Wallis & Arnold, 2008) and evidently involves temporal masking, rather than being driven by motion per se (see Wallis & Arnold, 2008). In sum, MIB would seem to involve interplay between dorsal and ventral stream activations (see also Donner, Sagi, Bonneh, & Heeger, 2008), which depends on a stimulus containing both dynamic and static elements—a precondition that is not necessary for other forms of perceptual rivalry.

In experiment 3 (N = 32) we therefore examined the dynamics of two forms of perceptual rivalry that each involve static inputs—BR and the NC. However, in agreement with the results of experiments 1 and 2, we did not find any evidence for a strong correlation between the reported dynamics of BR and the NC (r = 0.04, p = 0.828; see figure 1c). Results of an analysis that excluded participants who reported outlying dynamics for either form of perceptual rivalry were qualitatively matched (r = 0.17, p = 0.369). In experiment 3 there was a positive correlation between the dynamics of BR and misreports regarding number of physical alternations in a nonrivalrous stimulus (r = 0.42, p = 0.017; see figure 1), but there was no correlation between dynamics reported for the NC and misreports regarding number of physical alternations (r = 0.07, p = 0.703; see figure 1).

3 Discussion

Across three experiments, involving a total of 109 participants, we have failed to find evidence for a robust correlation between the reported dynamics of diverse forms of perceptual rivalry. This was true for both combinations of BR and MIB (experiments 1 and 2) and for BR and the NC (experiment 3). Our results highlight the importance of subjective criteria when measuring the dynamics of perceptual changes, as the strongest correlation we measured in any experiment was between the dynamics of BR and misreports concerning the number of stimulus changes in a physical nonrivalrous stimulus (experiment 3; r = 0.42, p = 0.017). Even this relationship was, however, weak, having failed to reach significance in experiments 1 and 2. Overall, our results suggest that the dynamics of any particular form of perceptual rivalry are primarily determined by factors specific to that form of perceptual rivalry.

In addition to diverse forms of rivalry being correlated on an individual basis, other researchers have emphasised the tendency for dominance durations in diverse forms of perceptual rivalry to conform to a gamma distribution as being evidence for a common causal mechanism (Andrews & Purves, 1997; Carter & Pettigrew, 2003; Kovács, Papathomas, Yang, & Fehér, 1996; Logothetis et al., 1996; Murata, Matsui, Miyauchi, Kakita, & Yanagida, 2003). A gamma distribution for perceptual rivalry dominance periods is characterised by a relative few dominance periods reportedly persisting for very brief durations, a small number persisting for variable longer periods, and most persisting for intermediate durations—in sum producing a distribution with a marked right skew. We believe this constitutes very weak evidence for a common causal link—first, because if one asks a person to press a

button randomly, the distribution of times for which they depress the button can conform to a gamma distribution (see Edwards & Li, 2002); and, second, because distributions of obviously unrelated phenomena also conform to a gamma distribution (such as the distribution of rainfall over time; see Barger & Thorn, 1949).

Other researchers have pointed to modulations of the neurotransmitter gammaamino-butyric acid (GABA) as being involved in driving the dynamics of diverse forms of perceptual rivalry (see van Loon et al., 2013). This was suggested by slower rivalry dynamics being reported when participants were administered a sedative, lorazepam, which is a GABA agonist. However, it is unclear on the basis of these data if there is a direct effect of GABA levels on rivalry dynamics, or if being more relaxed results in people being less slavish when reporting on the dynamics of ambiguous perceptual changes. Unfortunately, the authors of this study did not report on individual correlations between baseline measures of diverse forms of perceptual rivalry, so this study does not provide data that are directly comparable to measures in this study. It is also unfortunate that sedated participants in this study were unable to complete BR tasks, as they were unable to maintain vergence to facilitate binocular fusion.

While some evidence suggests commonalities between diverse forms of perceptual rivalry, other evidence highlights the probability of independent causes. For instance, in a previous study participants simultaneously tracked diverse forms of perceptual rivalry above and below a central binocular fixation point. The dynamics of identical forms of BR were well correlated in different positions, but there were only chance correlations between the dynamics of diverse forms of BR (house/face vs orthogonal grating rivalry) and between BR and changes in the direction of perceived rotation in an ambiguous display (Quinn & Arnold, 2010). Similarly, other studies have shown that BR is less susceptible to volitional control via selective attention relative to other multistable phenomena (Meng & Tong, 2004; van Ee, van Dam, & Brouwer, 2005).

Our data are inconsistent with the dynamics of diverse forms of perceptual rivalry being strongly shaped by a common high-level process (Andrews & Purves, 1997; Carter & Pettigrew, 2003; Miller et al., 2000). They are more consistent with diverse forms of perceptual rivalry having diverse causal mechanisms (see Arnold, 2011). Note that this does not dictate that the activity that determines a particular rivalry's dynamics (Donner et al., 2008; Tong, 2003) cannot possibly be modulated via interactions with substrates that are involved in generalised operations, such as attention and object recognition (Arnold, Grove, & Wallis, 2007; Arnold, James, & Roseboom, 2009; Kang, Heeger, & Blake, 2009; van Boxtel, Alais, & van Ee, 2008a; van Boxtel, Knapen, Erkelens, & van Ee, 2008b; Watson, Pearson, & Clifford, 2004), or decision making (see Einhauser, Stout, Koch, & Carter, 2008). However, our data suggest that any such interaction fails to exert a strong personalised dynamic across diverse forms of perceptual rivalry.

To summarise, our results challenge the proposition that diverse forms of perceptual rivalry have well-correlated dynamics due to the influence of a common causal mechanism. On the basis of the strength of the relationship between the reported dynamics of BR and MIB in a previous study (r = 0.69; Carter & Pettigrew, 2003), we should have been able to detect such a relationship given our sample sizes (estimated required N = 9, experiment 1 actual N = 54, experiments 2a and 2b actual N = 23). Obvious explanations for this discrepancy would involve type-1 errors in the previous report (Carter & Pettigrew, 2003), or type-2 errors in this study. We would therefore strongly encourage other researchers to reexamine this issue, and to publish the results of their studies in order to elucidate this conceptual conundrum.

4 Methods

Stimuli were generated using Matlab 7.5 software to drive a ViSaGe MKII Visual Stimulus Generator and were presented on a 21-inch Samsung SyncMaster 1100p monitor (120 Hz refresh rate and 1024×768 pixel resolution). Stimuli were viewed from a distance of 57 cm with the participant's head restrained by a chin-rest. Each experiment contained three experimental conditions: (1) BR, (2) either MIB or NC, and (3) a physical nonrivalling stimulus. There were 5 stimulus presentations per participant for each rivalry condition, and 2 presentations per participant for nonrival conditions. Each presentation lasted 60 s. Interrivalry correlations were calculated by obtaining the mean alternation rate in Hertz (dominance periods in BR, disappearances in MIB, and reported switches in the nonrival task) for each participant in each task. Alternation rates were then compared using a Pearson's correlation coefficient, which indicated the degree to which perceived alternation rates within an individual were consistent across tasks.

4.1 Stimuli

4.1.1 *Binocular rivalry (experiments 1–3).* BR stimuli consisted of superimposed green (CIE coordinates x = 0.29, y = 0.61) horizontal and red (CIE coordinates x = 0.63, y = 0.33) vertical gratings (sinusoidal modulations of luminance contrast) with a peak luminance of 22 cd m⁻². Gratings had a spatial frequency of 4 cycles deg⁻¹ at the retina and a diameter subtending 1 deg. In our standard BR instructions participants were asked to report when they could see only vertical bars by pressing and holding down the left mouse button, and to report when they could see only horizontal bars by pressing down and holding the right mouse button. Participants actively reported only piecemeal rivalry in experiment 2a, by pressing down and holding the middle mouse button, if piecemeal rivalry persisted for more than about 1 s. In all other conditions participants were asked not to press any buttons if they experienced piecemeal rivalry, or if they were uncertain what they were seeing.

4.1.2 Motion-induced blindness (experiments 1 and 2). Participants fixated a red central cross hair (CIE coordinates x = 0.63, y = 0.33, Y = 22; height/width = 0.4 deg) positioned between two (experiment 1) or three (experiment 2) peripheral static yellow discs (diameter subtending 0.5 deg) centred 5.5 deg into the periphery. Static yellow discs were positioned either to the left and right of fixation (experiment 1) or above and at angular positions of 120° and 240° from above (experiment 2). Some 30 smaller (diameter = 0.1 deg) blue (CIE coordinates x = 0.63, y = 0.33, Y = 22) discs each translated in a random linear direction at a retinal speed of 24 deg s⁻¹. These were initially randomly distributed about the 4.5 deg diameter circular display region, and were wrapped to the opposite side if they translated beyond the display region. There was a 1.2 deg diameter exclusion zones around each yellow disc. If blue discs entered these regions, they disappeared until they emerged from the other side.

4.1.3 *Necker cube (experiment 3).* The cube consisted of two white (CIE coordinates x = 0.28, y = 0.30, Y = 113) square frames (width/height = 3.5 deg, frame width = 0.3 deg), with corners linked by 45° lines (width = 0.3 deg, length = 1.5 deg), with the right frame centred above the left frame. The display background was black. Participants fixated a small red crosshair (width/height = 0.4 deg) positioned in the middle of the cube configuration. The ambiguous nature of this stimulus allowed for two perceptual interpretations (left frame in front/right frame in front) that stochastically changed. Participants reported when the left frame seemed to be in front by holding down the left mouse button, and when the right frame seemed to be in front by holding down the right mouse button. Each participant completed five 1 min presentations.

4.1.4 Nonrival stimulus (experiments 1-3). The stochastic physical stimulus consisted of achromatic vertical and horizontal Gabors, each subtending 10 deg in diameter, in a spatial envelope with an SD of 1.67 deg and a spatial frequency of 0.5 cycle deg⁻¹ (see figure 2). The phase of the Gabor waveforms drifted, from left to right or bottom to top, at 0.25 Hz. This, and foveal presentation, ensured that neither stimulus component faded from view due to Troxler fading.

During 1 min presentations the luminance contrast of either Gabor was physically modulated to mimic BR dynamics reported by the second author during a matched 1 min stimulus presentation. The vertical Gabor was set to a Michelson contrast of 1.0 (and the horizontal to 0.0) to mimic epochs during which the author had reported vertical dominance, and this relationship was reversed to mimic periods of reported horizontal dominance. Piecemeal rivalry was mimicked by setting each component to a contrast of 1.0, producing a plaid with pattern motion drifting up to the left. Instructions for this stimulus were as for BR. For each experimental condition with this stimulus, each participant completed two 1 min trials, which mimicked BR dynamics reported by the second author during two 1 min presentations. All participants viewed these same physical dynamics.



Figure 2. Left: physical nonrivalling stimuli presented during experiments consisting of vertical, horizontal, and plaid Gabor patches. Right top: Necker cube used in experiment 3. Bottom: 'physical' plot depicting how the contrasts of the vertical and horizontal components of the physical nonrivalling stimulus changed during a 1 min stimulus presentation during experiments 1-3. A value of 1 signifies that the vertical component was full contrast and the horizontal contrast was 0; a value of -1 signifies the reverse. A value of 0 signifies that both components had full contrast, to mimic piecemeal rivalry. The dynamics of this presentation were based on reports from the last author during a 1 min binocular rivalry presentation. 'Reported' plot showing a participant's reports on the appearance of this stimulus in real time. Reports of 1 signify that the participant could see only vertical, -1 that they could see only horizontal, and 0 that they could see both components.

4.1.5 *Procedures.* In experiment 1, for BR and nonrivalrous physically alternating stimulus presentations, participants were instructed to report their current perceptual experience in real time using mouse buttons. Participants reported when they perceived a horizontal (left mouse button) or vertical (right mouse button) stimulus; or if they were unsure what they were seeing (due to mixed dominance or piecemeal rivalry), participants were instructed to not press a button. For MIB presentations participants were instructed to report the disappearance of any of the static yellow stimuli by pressing the left mouse button, and to keep the button depressed for so long as they were experiencing blindness. If all static stimuli were perceptually apparent, then participants did not press any buttons.

In experiment 2 BR and physically changing stimulus presentation conditions were repeated using our standard instructions, as per experiment 1. Physically matched stimulus presentations were also conducted, with participants instructed to report periods of mixed dominance using the middle mouse button. To allow for periods of transition, participants were instructed to report mixed dominance only if they occurred for longer than a transition period (Carter & Pettigrew, 2003). For ease of interpretation, we instructed participants to report mixed dominance periods if they lasted for more than about 1 s. Details concerning MIB presentations were as for experiment 1.

Details concerning BR and physically changing nonrivalrous stimulus presentations in experiment 3 were as for experiment 1. For NC presentations, participants were instructed to report the change in apparent perspective from above the cube (right mouse button) to below the cube (left mouse button)—alternately described as left panel toward the observer (left mouse button) or right panel toward the observer (right mouse button).

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