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How simultaneous is the perception of binocular depth and rivalry in plaid stimuli?

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Abstract. Psychophysical experiments have demonstrated that it is possible to perceive both binocular depth and rivalry in plaids (Buckthought and Wilson 2007, *Vision Research* **47** 2543 – 2556). In a recent study, we investigated the neural substrates for depth and rivalry processing with these plaid patterns, when either a depth or rivalry task was performed (Buckthought and Mendola 2011, *Journal of Vision* **11** 1 – 15). However, the extent to which perception of the two stimulus aspects was truly simultaneous remained somewhat unclear. In the present study, we introduced a new task in which subjects were instructed to perform both depth and rivalry tasks concurrently. Subjects were clearly able to perform both tasks at the same time, but with a modest, symmetric drop in performance when compared to either task carried out alone. Subjects were also able to raise performance levels for either task by performing it with a higher priority, with a decline in performance for the other task. The symmetric declines in performance are consistent with the interpretation that the two tasks are equally demanding of attention (Braun and Julesz 1998, *Perception & Psychophysics* **60** 1 – 23). The results demonstrate the impressive combination of binocular features that supports coincident depth and rivalry in surface perception, within the constraints of presumed orientation and spatial frequency channels.

Keywords: Visual cortex, stereopsis, visual attention, spatial vision, spatial channel, dual-task, disparity.

1 Introduction

The possibility that stereoscopic depth may be perceived in the presence of rivalry has been a longstanding controversy in the field of binocular vision. A number of studies have shown that depth and rivalry interfere with one another, and based upon predictions of models of binocular vision we would not usually expect that they can be perceived simultaneously (Blake 1989, 2001; Harrad et al 1994; Hayashi et al 2004). In particular, the assumption is often made that depth cannot be perceived in the presence of rivalry because inhibition of one stereo half-image would prevent a match to the other image (Harrad et al 1994; Hayashi et al 2004).

However, it has also been proposed that distinct spatial frequency channels are involved in binocular depth and rivalry (Julesz and Miller 1975). Moreover, it is actually possible to perceive depth in the presence of rivalry, as long as the components are in different spatial frequency bands (Blake et al 1991). Another study showed recently that it is possible to perceive both depth and rivalry in one spatial location (Buckthought and Wilson 2007). This was observed with binocular plaid patterns in which depth is perceived from the near-vertical components, and rivalry from the oblique components. Moreover, this may be observed even when the depth and rivalry components are at the same spatial frequency, as long as these components are in different orientation bands. The percept of a rivalrous pattern appears to be spatially superimposed on the tilted surface. Recently we investigated the neural substrates for depth and rivalry processing with these plaid patterns, while a depth or rivalry task was performed (Buckthought and Mendola 2011). We documented a similar pattern of activation across cortical areas for both tasks, with some modest differences between the two. Nevertheless, it was not clear to what extent perception of depth and rivalry was truly simultaneous, since subjects were never asked to report both percepts at the same time. One recent psychophysical study reported that it is possible to perceive depth and rivalry simultaneously; however, depth perception with the stimuli used in this study likely reflected second-order processing (Andrews and Holmes 2011). Hence, it still remains an open question whether it is possible to perceive depth and rivalry simultaneously through first-order processing. This is a question of considerable theoretical interest worth revisiting, since current models of binocular vision would not predict that this would be possible (eg, Hayashi et al 2004).

Our work on the coexistence of depth and rivalry fits within a body of literature suggesting that binocular integration and rivalry can occur independently for different stimulus features, including colour, form, and motion (Andrews and Blakemore 1999, 2002; Carney et al 1987; Holmes et al 2006; Hong and Shevell 2009). For example, chromatic integration can occur independently of form rivalry (Holmes et al 2006). Specifically, rival stimuli differing in form and colour can sometimes achieve states of dominance in which the colour information from one eye's image combines with the form of the other eye's image (Holmes et al 2006; Hong and Shevell 2009). In a second example showing separability of motion and colour, the colour information from one eye's image may be suppressed, while the information necessary for motion perception is integrated (Carney et al 1987). In a third example showing separability of form and motion, moving gratings of different orientations were shown to the two eyes, and motion perception was studied during time intervals that one grating was suppressed. Pattern motion was still perceived, indicating that the motion component signals were integrated across the two eyes and the perceptually suppressed grating influenced the perceived motion (Andrews and Blakemore 1999, 2002; see also van Boxtel et al 2008). Collectively, these studies provided evidence that the neural processes involved in integrating information from the two eyes can act selectively on different stimulus features.

In the current study, we carried out psychophysical experiments in order to determine whether it is possible for subjects to report depth and rivalry percepts concurrently with plaid patterns. For the sake of comparison, we also tested performance for grating stimuli that only contained depth or rivalry. We were also interested in determining whether these two tasks differ in attentional demand, as this would be relevant to the interpretation of both psychophysical and fMRI results with these plaids. We relied on methodology used previously in concurrent task paradigms (Braun and Julesz 1998). We asked subjects to perform five different tasks with the same plaid stimuli: (1) depth alone; (2) rivalry alone; (3) both depth and rivalry tasks with equal priority; (4) both tasks, but depth had a higher priority than rivalry; (5) both tasks, but rivalry had a higher priority than depth. We assumed that during the simultaneous task conditions (3–5) a drop in performance would be evident in making more wrong or missing responses for depth, or making fewer key presses for rivalry. We compared the performance when both tasks were carried out to performance with each of the single tasks. If depth and rivalry have similar attentional demands, then the performance levels for these tasks in the simultaneous condition (3) should be similar.

2 Methods

2.1 Subjects

An author (AB) and five other subjects, who were naïve as to the hypotheses of the study, participated. The subjects (which included four women) were students or postdoctoral fellows (mean age 29 years). All were right-handed and had normal or corrected-to-normal acuity and stereoacuity thresholds better than 30 s arc, measured using the Titmus stereo test (Stereo Optical Co, Chicago, IL). The subjects provided written consent and were remunerated for their time. The experiments were carried out in accordance with the World Medical Association Helsinki Declaration (October, 2008) and approved by the Research Ethics Board (REB) of McGill University (Protocol NEU-08-03).

2.2 Stimuli

Plaids in which it is possible to perceive both depth and rivalry were produced by adding together near-vertical (±2.5 or ±3.5 deg) and oblique (±30 deg) sinusoidal 6.4 cpd grating components, at 80% Michelson contrast (Figure 1). Similar gratings that contained only depth or rivalry were also used for comparison.

2.3 Display

Stimuli were presented on a MacBook Pro Laptop (Intel Core 2 Duo) Macintosh computer with 1024 X 768 resolution, 120 Hz refresh rate with 8 bit/pixel greyscale, which was gamma-corrected using a colour look-up table. Stimuli were displayed using Matlab and Psychtoolbox Version 3 (PTB-3) software. A Matrox (Dual Head 2Go Analogue Edition) splitter graphics card was used to create two channels for dichoptic displays. Dual LCD (InFocus LP 540) projectors and linear polarizers were used for dichoptic projection (Thompson et al 2008). The subjects wore linear polarizers with complementary polarization on their eyepieces. The stimuli were back-projected from the LCD projectors onto a polarization preserving screen at a viewing distance of 134 cm. Each stimulus was projected through an opaque circular aperture (3.8 deg diameter), which minimized any edge disparities. Viewed through the polarizers, the stimulus had a mean luminance of 30 cd/m^2 and peak luminance of 60 cd/m^2. The same display apparatus and viewing distance was used as had been used previously for fMRI experiments (Buckthought and Mendola 2011).

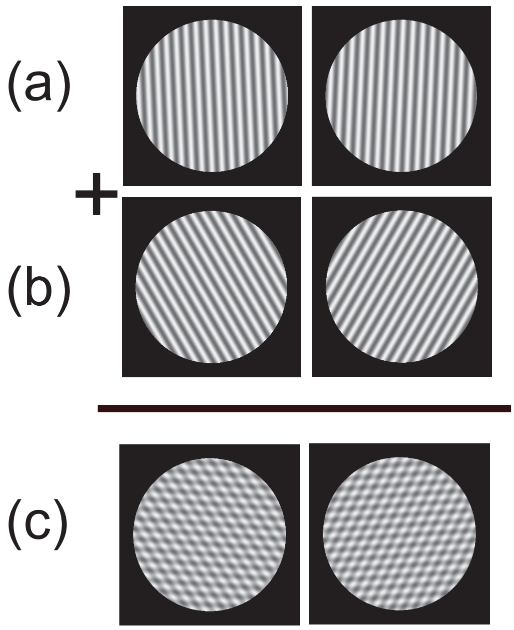

Figure 1. Stimulus patterns. (a) Depth alone and (b) rivalry alone. (c) These components were added to produce plaids in which both depth and rivalry may be perceived simultaneously.

2.4 Psychophysical tests

2.4.1 *Rivalry task*

Alternation rates were measured during binocular rivalry with the plaids or, for the sake of comparison, with left/right oblique grating stimuli. Subjects reported perceptual alternations continually over each trial. Subjects pressed one key when the left image predominated (over at least two-thirds of the stimulus) and another key when the other image predominated, using the same criterion. Subjects were tested a second time with the meaning of the keys reversed.

2.4.2 *Depth task*

For the depth task, subjects reported whether the top or bottom of the plaid stimulus pattern appeared to be tilted forward (or for the sake of comparison, with depth alone grating stimuli). The orientation disparity was 5 deg. The depth changed every 3 s (this interval was chosen based on pilot studies, so that it was not significantly different from the mean time interval between key presses in the rivalry task, averaged across subjects). In order to prevent the task from being too easy, there was one catch trial chosen randomly at every 20 s interval in which the disparity did not switch to the opposite percept but was changed to a slightly different orientation disparity (7 deg). Subjects were not told how many catch trials there were.

2.4.3 *Concurrent task conditions*

Subjects performed five different task conditions with identical plaid images in which there was both rivalry and depth changes every 3 s: (1) depth alone; (2) rivalry alone; (3) both depth and rivalry tasks with equal priority; (4) both tasks, but depth had a higher priority than rivalry; and (5) both tasks, but rivalry had a higher priority than depth. Subjects made responses for the two tasks using four different keys, two keys for rivalry appearance and two other keys for depth appearance. The length of each trial was 90 s. Subjects were instructed to make key presses only when they were able to clearly perceive a rivalry alternation, or a depth percept. Subjects were given a practice set of trials, then tested four times at each condition. For the depth task, we compared the performance in terms of percentage correct under the different task conditions, while for rivalry we used alternation rates. The order of the psychophysical testing for all of the different task conditions was counterbalanced to avoid the effects of practice or learning.

One additional control test was subsequently used. After the main testing sessions, three subjects (AB, LA, JH) were also tested a second time in versions of these tests in which the time interval between switches in depth was jittered randomly, so that the interval varied unpredictably, but with a mean of 3 s (the following time intervals were used with equal probability: 1.5, 2, 2.5, 3, 3.5, 4, 4.5 s). This was a better match to the temporal dynamics of rivalry, and also made guessing more difficult.

3 Results

Our first comparison between the rivalry rates for the plaid and sinusoidal grating patterns (when the rivalry task alone was performed), shows that mean rivalry rates are decreased by the addition of depth cues ($f_{df=5} = 2.77$, $p = 0.039$). There was also a significant difference in the distribution of time intervals between key presses (Kolmogorov-Smirnov Z = 2.49, $p =$ 0.013). This confirms results from our previous experiments that there is some interference at the perceptual level resulting from the addition of the depth cue in the plaids (Buckthought and Mendola 2011; see Buckthought and Wilson 2007).

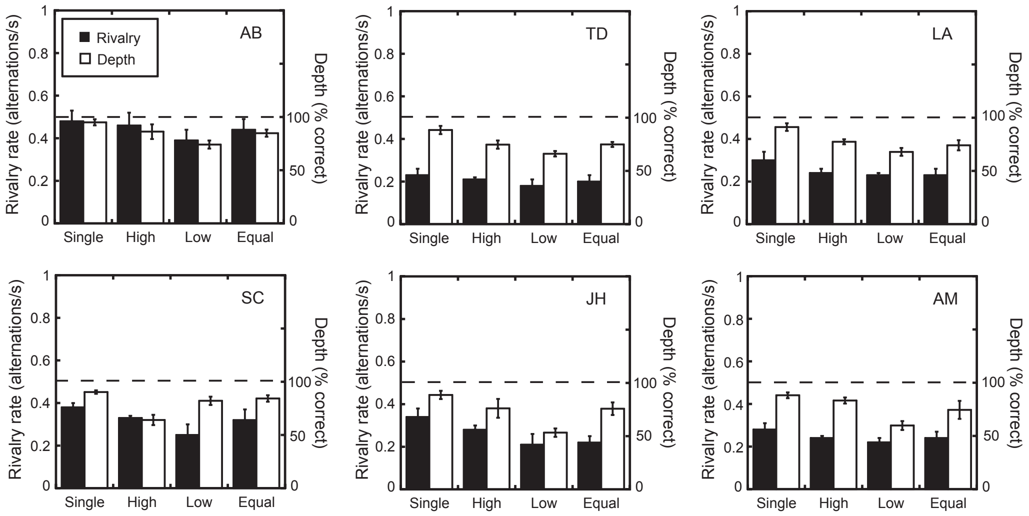

Figure 2. Depth perception judgments (% correct) and alternation rates for binocular rivalry for all six subjects. Performance is shown for the single task and concurrent task conditions, in which the task had high, low or equal priority. Subjects were able to perform both the depth and rivalry tasks in the concurrent conditions, although performance was lower than the single task conditions. Error bars show ±1 standard errors.

In our next manipulation, we compared performance on the five task conditions for identical plaid stimuli in which both rivalry and changing depth cues were present. Depth perception and rivalry alternation rates are shown for all six subjects in Figure 2. The performance is shown for either depth or rivalry in the single task, or for the concurrent task conditions when it had the high, low or equal priority. Although absolute levels of performance could be quite different, all subjects showed a similar pattern of results when comparing performance on the single task relative to the other task conditions. In particular, the baseline rate of rivalry differed across subjects (Figure 2, left-sided y-axis). Nevertheless, all of the subjects were able to perform both the depth and rivalry tasks under all of the different concurrent task conditions, lending support to the hypothesis that these percepts were indeed simultaneous. For example, in the simultaneous condition when the two tasks had equal priority all subjects were able to perform the depth task, since performance levels ranged from 74.1% to 84.8% and were above chance for all subjects (chance performance is 50%). Nevertheless, it can be seen for each subject that the performance decreased somewhat in all of the concurrent conditions compared with the single task conditions.

In Figure 3a, the individual results have been averaged across subjects and show the same trends. In Figure 3b, the performance for the concurrent task conditions have been normalized relative to the single task condition, where a value of one would indicate equal performance (again, averaged across all subjects). Overall, the similar results for depth and rivalry indicated that the attentional demand did not differ for the two tasks. There was clearly a performance deficit for either depth or rivalry during both the low and high priority simultaneous task conditions, relative to the condition in which either task was performed alone. But interestingly, this symmetrical performance deficit was always similar for either depth or rivalry, implying that they required equal attention.

Statistical analyses were carried out to confirm these trends. A two-way repeated measures ANOVA was significant for the differences between the single and simultaneous task conditions with equal priority for the two tasks ($F_{1,5} = 44.4$, $p = 0.001$) but was not significant for depth versus rivalry ($F_{1,5} = 1.85$, $p = 0.23$) nor the interaction ($F_{1,5} = 1.85$, $p = 0.23$).

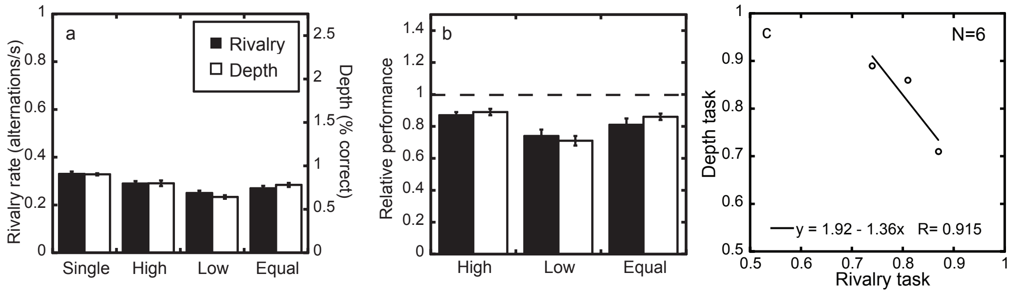

Figure 3. (a) Depth perception judgments (% correct) and alternation rates for binocular rivalry as in Figure 2, but averaged across all six subjects. Error bars show ±1 standard errors. (b) The psychophysical data has been normalized to performance in the single task condition, which is assigned a value of one (mean of all subjects). Again, subjects were able to perform both the depth and rivalry tasks in the concurrent conditions, but there was a symmetric drop in performance for either depth or rivalry. Performance for either depth or rivalry did not differ significantly in either the high, low, or equal priority conditions. Error bars show ±1 standard errors. (c) Attention operating characteristic (AOC). The performance levels from (b) have been plotted as a scatter plot. As performance on one task increases, performance on the other decreases.

Crucially, the lack of significant difference between the performance for either depth or rivalry in the simultaneous condition suggests the two tasks are comparable in attentional demand ($t_5 = 1.36$, $p = 0.23$). Furthermore, when either the depth or rivalry task was performed with higher priority, the performance did not differ ($t_5 = 0.643$, $p = 0.55$). Also, when either the depth or rivalry task had lower priority, again the performance levels did not differ ($t_5 = 1.25$, $p = 0.27$).

Another interesting feature of the results was that the subjects were able to increase their performance on either the depth or rivalry task by giving it higher priority, and this also caused a drop in performance for the other task. A two-way repeated measures ANOVA on the whole data set was significant for the differences between the five task conditions ($F_{3,15} = 50.0$, $p = 0.001$) but not the differences between depth and rivalry ($F_{1,5} = 0.361$, $p = 0.57$) nor the interaction ($F_{3,15} = 1.98$, $p = 0.16$). Since the differences between depth and rivalry were not significant, the results were averaged together to compare the different task conditions. The differences in performance in the high, low, and equal priority task conditions were all statistically significant (high versus low: $t_5 = 3.67$, $p = 0.014$; high versus equal: $t_5 = 3.20$, $p = 0.024$; low versus equal: $t_5 = 3.59$; $p = 0.016$). These results are also shown in the form of the Attention Operating Characteristic (AOC) (Figure 3c), in which performance levels for the three concurrent task conditions are plotted as a scatter plot (Sperling and Melchner 1978). These lie on a straight line, indicating that performance on the depth task increases while that on the rivalry task decreases and vice versa. The AOC scatter plots for individual subjects (Figure 4) show some intersubject variability, but all subjects showed the same overall trend. This further confirms that the two tasks did not differ in attentional demand and that performing the two tasks concurrently results in symmetrical declines in performance (Braun and Julesz 1998; Sperling and Melchner 1978).

Following the main experiment, three subjects were retested on a control experiment with the same five main task conditions with identical plaids, but with the time intervals between depth changes jittered. This was done in order to discount the possibility that the subjects were only able to perform the original depth task by allocating their attention to the task just after depth changes. For comparison, the subjects were also retested on versions in which the depth changes were exactly 3 s. A three-way repeated measures ANOVA comparing the two data sets was not significant for the effect of jitter ($F_{1,2} = 1.04$, $p = 0.42$) or differences between the depth or rivalry tasks ($F_{1,2} = 0.271$, $p = 0.66$), but was significant for the differences between the task conditions ($F_{3,6} = 16.0$, $p = 0.003$). None of the interactions were significant (depth/rivalry by jitter, $F_{1,2} = 0.160$, $p = 0.73$; depth/rivalry by task, $F_{3,6} = 1.42$, $p = 0.33$; jitter by depth/rivalry by task $F_{3,6} = 0.073$, $p = 0.97$). Since there were no significant differences between these two different versions of the tests, subjects were not likely relying on a strategy of predictably allocating their attention in the temporal domain.

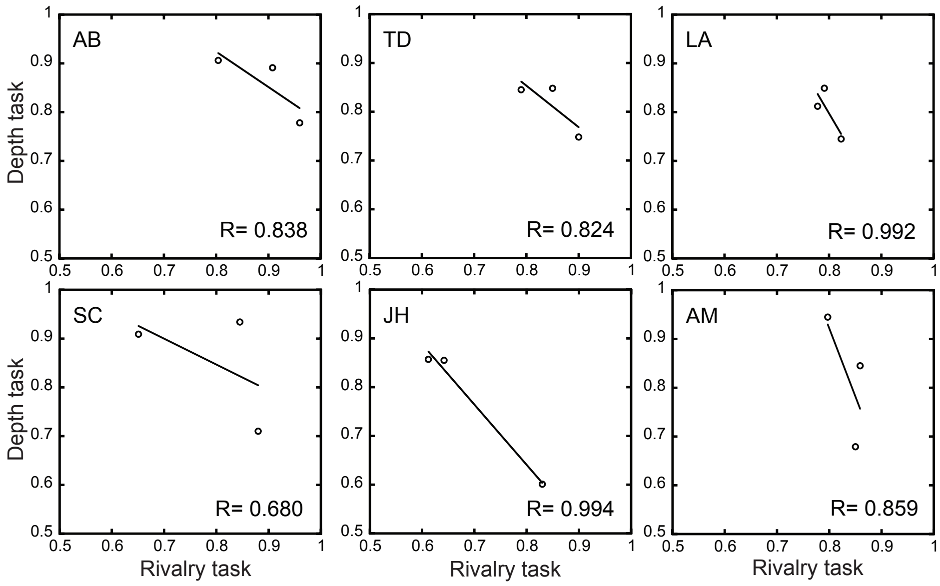

Figure 4. Attention operating characteristic (AOC) as shown in Figure 3, but for all six subjects. The performance levels (normalized to performance on the single task) have been plotted as a scatter plot for each individual. As performance on one task increases, performance on the other decreases.

4 Discussion

Our main finding is that the depth and rivalry tasks could be performed concurrently, which is consistent with the interpretation that depth and rivalry are perceived simultaneously. This is also in agreement with subjects' subjective reports that the rivalrous percept was spatially superimposed upon the tilted pattern. Although these tasks could be performed concurrently, there were symmetrical drops in performance for depth and rivalry relative to the single task conditions. The drop in performance could be due to a number of factors, including a limit on low level binocular visual perceptual encoding, a bottleneck at the stimulus selection stage or access to visual short-term memory for these different visual perceptual changes, or interference at the motor response stage (Braun and Julesz 1998; Klingberg and Roland 1997; Marois et al 2006; Schubert and Szameitat 2003; Wolfe et al 2006). A number of previous studies of dual-task interference have noted that the bottleneck in processing often occurs at the stimulus selection stage (Marois et al 2006; Sigman and Dehaene 2008), or at the motor stage, given the difficulty in making motor responses and in mapping the responses to the appropriate key (Herath et al 2001). Alternatively, limitations in visual short-term memory have been invoked to explain the failure of subjects to identify visual perceptual changes which are well above contrast thresholds and difficulty to recall the status of recently attended items (eg Wolfe et al 2006). This was studied in paradigms using arrays of simple objects in which subjects were asked to report the colour or orientation of cued items just after they were removed or masked. The ability to report the features correctly was generally poor, but improved if attention had been recently directed to that object. Subjects have a very limited ability to detect changes that happen after attention has been directed away from an object and before attention returns to that object (Wolfe et al 2006). Selective attention in the concurrent task conditions is also related to a mechanism by which task-relevant information impacts on ongoing processing, while task-irrelevant information is excluded (Roberts and Thiele 2008).

An important point to consider when interpreting the current data is whether the deficit in the concurrent tasks could be simply due to the motor demands of making two sets of responses. In considering this issue, we note that previous studies have found that a number of different detection tasks are performed in a parallel fashion, so that the required viewing time is not prolonged by additional display elements (Braun and Julesz 1998). Generally, the detection of two sets of stimulus features occurs in parallel when a simple feature (eg, luminance, colour, motion, disparity, orientation, size and presence of line terminators) distinguishes the target from other display elements (Braun and Julesz 1998). For example, Braun and Julesz (1998) found that discrimination of the hues of two targets in the periphery entailed little or no attentional cost (ie, the hues of two targets were discriminated and reported just as reliably and quickly as the hue of one target). The colour targets were presented simultaneously, and subjects were required to make two sets of button press responses for the two tasks. The fact that some perceptual tasks can be performed in parallel with no apparent deficit in performance due to added motor demands suggests that the deficits that we observed here were more likely perceptual than motor. Nevertheless, the difficulty in confirming this issue does not detract from our main conclusion that the depth and rivalry tasks can be performed concurrently, with approximately equal demands on attention.

The effects of attention have often been compared to the effects of increasing stimulus contrast, in that objects or features that are attended to are more salient (Boynton 2009; Roberts and Thiele 2008). In neural models, the effects of attention on neuronal responses have been characterized in further detail as reflecting a contrast gain, baseline shift or multiplicative gain (Boynton 2009). The majority of recent studies of attention can be categorised as studies of either spatial attention, feature-based attention, or object-based attention (Boynton 2009; Yantis 2008). In the current study, attention was not cued specifically to a particular location in space or feature, so the depth and rivalry tasks may be more closely related to object-based attention, as in previous studies in which subjects directed attention to transparent surfaces (eg, Ciaramitaro et al 2011). In general, an attention system acts on neural representations of the visual perceptual world, enhancing the processing of the currently attended object at the expense of information about less relevant objects (Yantis 2008). Previous fMRI studies of dual-task interference have proposed that if two tasks make use of the same cortical neural resources, then the two tasks cannot be performed simultaneously ('cortical field hypothesis'; Roland and Zilles 1998). The assumption is made that a particular brain network which is fully engaged in performing one task is not available to perform a concurrent task (Herath et al 2001; Klingberg and Roland 1997).

When considering the current results along with those from recent fMRI experiments, a consistent picture emerges—depth and rivalry are processed in parallel spatial and orientation channels (Buckthought and Mendola 2011). Both depth and rivalry are perceived simultaneously in the binocular plaid patterns because (with the carefully chosen orientation differences used here) they are processed in different orientation channels in early visual cortex. They may also be segregated by being placed in different spatial frequency channels, with spatial frequency differences greater than one octave (eg, 2.5 and 6.4 cpd). The brain activation results indicate that early visual areas V1–V3 support high spatial frequencies (eg, 6.4 cpd) while at the same time MT+ supports lower spatial frequencies (eg, 2.5 cpd; Buckthought and Mendola 2011). Either depth or rivalry could selectively activate V1–V3 when it was at the higher spatial frequency, or could activate MT+ when it was the lower spatial frequency component. Also, other data suggest that the binocular combination of multiple 'cues'—ie depth and rivalry in a coherent binocular percept—selectively recruits an area in lateral occipital cortex. In addition to the mechanism in which the correspondence problem for depth or rivalry is solved, there may be a representation at the surface-level for the grouping of features, in which more than one feature is coded at a spatial location. Furthermore, the psychophysical results also help to interpret greater brain activation in parietal areas (ie, superior and inferior parietal cortex, including temporoparietal junction and intraparietal sulcus) for the depth task than the rivalry task (Buckthought and Mendola 2011). The psychophysical results rule out the possibility that this could be attributed to differences in attention and is more likely explained by differences in binocular perceptual processing.

The results also indicated that these two tasks were not mutually exclusive; the performance levels in the concurrent task conditions were clearly above chance, although they were below best performance in the single task condition. Hence each one of the tasks did not engage all of the available attention. In general, a task would be expected to have a low attentional load in situations in which the task-relevant stimulus is easily detectable, and the task-relevant attributes can be processed in parallel at the level of early vision (Braun and Julesz 1998). The results were also shown in the form of an AOC, which describes how performance on the two tasks varies as a function of the division of attention. This description is designed to make inferences about the performance-resource functions (PRFs) of the tasks, which describe performance as a fraction of the attention devoted to a task (Braun and Julesz 1998; Sperling and Melchner 1978). This description also illustrates that subjects could selectivity raise their performance levels for either depth or rivalry by placing higher priority on that task. A linear and symmetric AOC is consistent with the underlying PRFs being similar for both tasks, and with increments in performance on one task directly related to decrements in the other task (Braun and Julesz 1998). This is consistent with the hypothesis that depth and rivalry may share overlapping neuronal resources. The ability to voluntarily direct attention in accordance with behavioural goals may fit with the conceptualisation of voluntary (ie, top-down) attention, which has been distinguished from involuntary attention (ie, bottom-up or stimulus-driven), which usually relies upon the salience of stimulus features such as contrast or colour (Yantis 2008).

In conclusion, the results indicated that the perception of binocular depth and rivalry was indeed simultaneous in the plaid patterns. This is one of a few examples of simultaneous percepts studied with both psychophysical and physiological methods (eg, Jiang et al 2008). The current work also provides a new paradigm in which binocular visual perceptual changes are reported concurrently, and do not differ in attentional demand.

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