

Stereomotion perception for a monocularly camouflaged stimulus

Kevin R. Brooks

School of Psychology, University of New South Wales,
Sydney, NSW, Australia, &
School of Psychology, University of Plymouth,
Drake Circus, Plymouth, Devon, UK



Barbara J. Gillam

School of Psychology, University of New South Wales,
Sydney, NSW, Australia



Under usual circumstances, motion in depth is associated with conventional stereomotion cues: a change in disparity and differences between object velocities in each monocular image. However, occasionally these cues are unavailable due to the fact that in one eye the object may be occluded by, or camouflaged against appropriately positioned binocular objects. We report two experiments concerned with stereomotion perception under conditions of monocular camouflage. In [Experiment 1](#), the visible half-image of a monocularly camouflaged object translated laterally. In this binocular context, percepts of lateral motion and motion in depth were equally consistent with the stimulus. Subjects perceived an oblique trajectory of 3D motion, compared to the more direct 3D trajectory experienced for binocularly matched stimuli. In [Experiment 2](#), the perceived velocity of stereomotion was assessed. Again, for the stimulus used in [Experiment 1](#), perceived stereomotion speed was lower than that for matched stimuli. However, when additional background objects were present, tightening the ecological constraints, perceived stereomotion velocity was often equivalent to that for matched stimuli. These results demonstrate for the first time that the motion of a monocularly camouflaged object can result in the perception of stereomotion, and that the perceived trajectory and speed are influenced by the ecological constraints of binocular geometry.

Keywords: binocular vision, da Vinci stereopsis, disparity, half-occlusions, motion in depth, stereomotion, unmatched stereopsis

Citation: Brooks, K. R., & Gillam, B. J. (2007). Stereomotion perception for a monocularly camouflaged stimulus. *Journal of Vision*, 7(13):1, 1–14, <http://journalofvision.org/7/13/1/>, doi:10.1167/7.13.1.

Introduction

For many centuries, scholars have appreciated the small differences between the two retinal images that are produced by two distinct monocular viewpoints. Early Greek authors Galen and Euclid described the basics of occlusion geometry, pointing out that when viewing an opaque sphere or cylinder, the two eyes see different portions of the object (see [Figure 1](#)). For example, an area of the stimulus on the extreme left hand side will be visible to the left eye, yet occluded to the right eye by the curvature in depth of the object's surface, and vice versa. More than a millennium later, Leonardo da Vinci observed that foreground objects may occlude the background differently in each eye: a feature of the 3D world that could never be fully captured on a 2D canvas (see [Figure 1](#)). However, none of these authors related their observations on binocular viewing to the derivation of a depth percept. Since this time, much research on stereopsis has concentrated not on the extent to which parts of the retinal images do not match, but instead on the difference in the positions of features which are visible in

both eyes: the well-known depth cue of binocular disparity. Several centuries after da Vinci's observations, Wheatstone (1838) showed that depth perception could be based solely on the disparity in position of matching image components. Despite the dominance of the concept of matching since this discovery, vision scientists have more recently established experimentally that, under certain circumstances, an object visible in one eye but not in the other can produce an impression of depth and have acknowledged the work of Leonardo in naming this phenomenon "da Vinci stereopsis" (Cook & Gillam, 2004; Häkkinen & Nyman, 1996; Nakayama & Shimojo, 1990). In addition to these examples, several related phenomena of unmatched stereopsis have been reported that are not usually referred to as "da Vinci stereopsis," including the sieve effect (Howard, 1995; see also Forte, Peirce, & Lennie, 2002), sequential monocular decamouflage (Brooks & Gillam, 2006b), monocular gap stereopsis (Gillam, Blackburn, & Nakayama, 1999; Grove, Gillam, & Ono, 2002; Pianta & Gillam, 2003a, 2003b), and phantom stereopsis (Gillam & Nakayama, 1999; Häkkinen & Nyman, 2001; see also Anderson, 1994; Grove, Byrne, & Barbara, 2005).

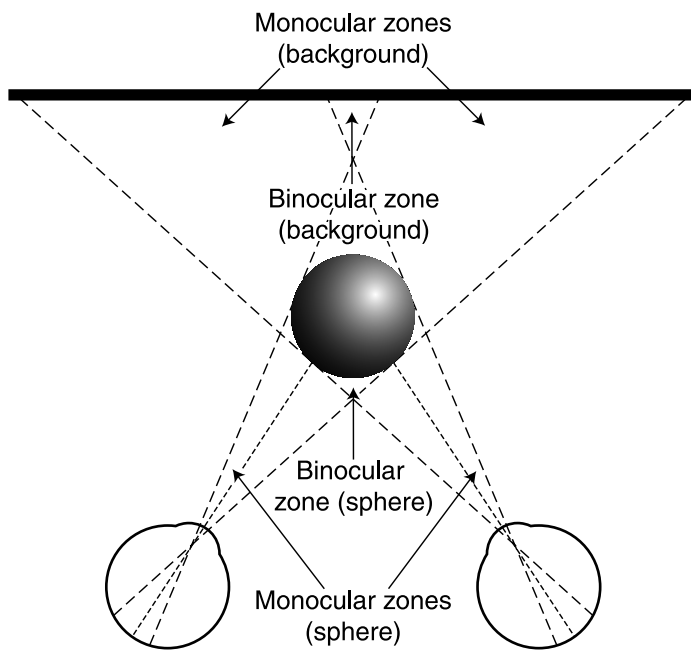


Figure 1. The first descriptions of the details binocular geometry were made by Galen and Euclid who observed that when viewing a sphere, different portions of the object are seen by each eye. Many years later, Leonardo da Vinci described the areas of visibility of a background that are produced by the occlusion “shadow” of a foreground object.

Under the conditions investigated by Cook and Gillam (2004), the observed depth becomes larger as the visible horizontal extent of the monocular object increases, demonstrating the quantitative nature of this cue. One eye views a solid black figure eight with a white surround while the other views a similar black figure eight with a rectangular white “intrusion” in one side (see Figure 2A). In the case illustrated, observers report a white surface with a figure eight shaped aperture through which a black far surface can be seen. The white intrusion is seen as a rectangular object lying in a depth plane between these two surfaces (see Figure 2B). This is consistent with binocular geometry, as the white rectangle is occluded by the nearer surface for one eye, but is visible through the aperture in the other. Systematic shifts in the extent of the intrusion led to corresponding changes in perceived depth.

In addition to occlusion, unmatched images can result from monocular camouflage. Consider the result of reversing the half-images shown in Figure 2A, such that the left, rather than the right eye now views the intruding monocular object (see Figure 3A). This corresponds to a three dimensional situation where the white monocular rectangle stands foremost, as shown in Figure 3B. The white rectangle can be seen by the left eye where it occludes a part of the black figure eight, but is entirely camouflaged against the white background in the right eye. Cook and Gillam (2004) also found quantitative perceived depth for such stimuli, demonstrating that like

monocular occlusion, monocular camouflage can also be a powerful cue to stimulus depth. The authors investigated occlusion and camouflage situations, including them both in the category of “da Vinci stereopsis.”

Although the idea of depth being derived from unmatched stimuli predates the idea of depth signals being derived from matched images, it is perhaps easy to see why researchers have often preferred the latter cue. Unlike binocularly visible features, the depth of half occluded or camouflaged objects is not fully specified by binocular geometry.¹ Instead, the location

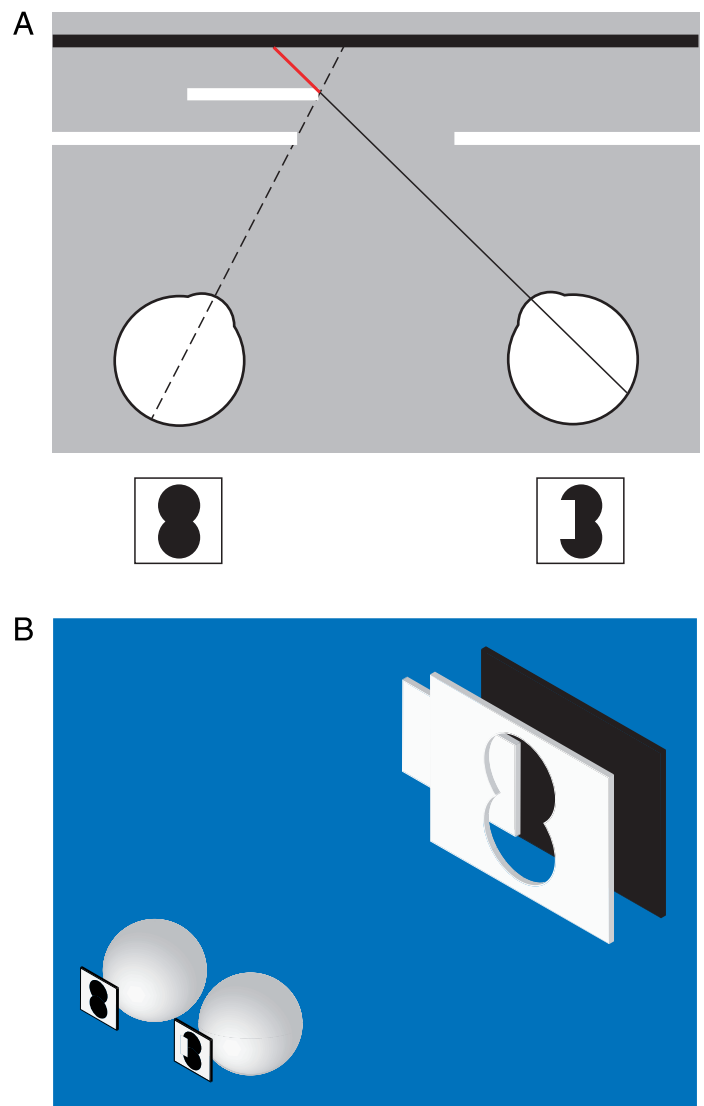


Figure 2. Da Vinci stereopsis: Monocular occlusion situation. (A) Plan view of Cook and Gillam (2004) stimulus. Although the location of the target’s right edge is known in the right eye (solid line), in the left eye it can only be assumed to lie to the left of the dotted line. The intersection of these two lines represents the minimum depth constraint, although the edge may lie anywhere along the extent marked in red. (B) Monocular occlusion depicted in isometric projection.

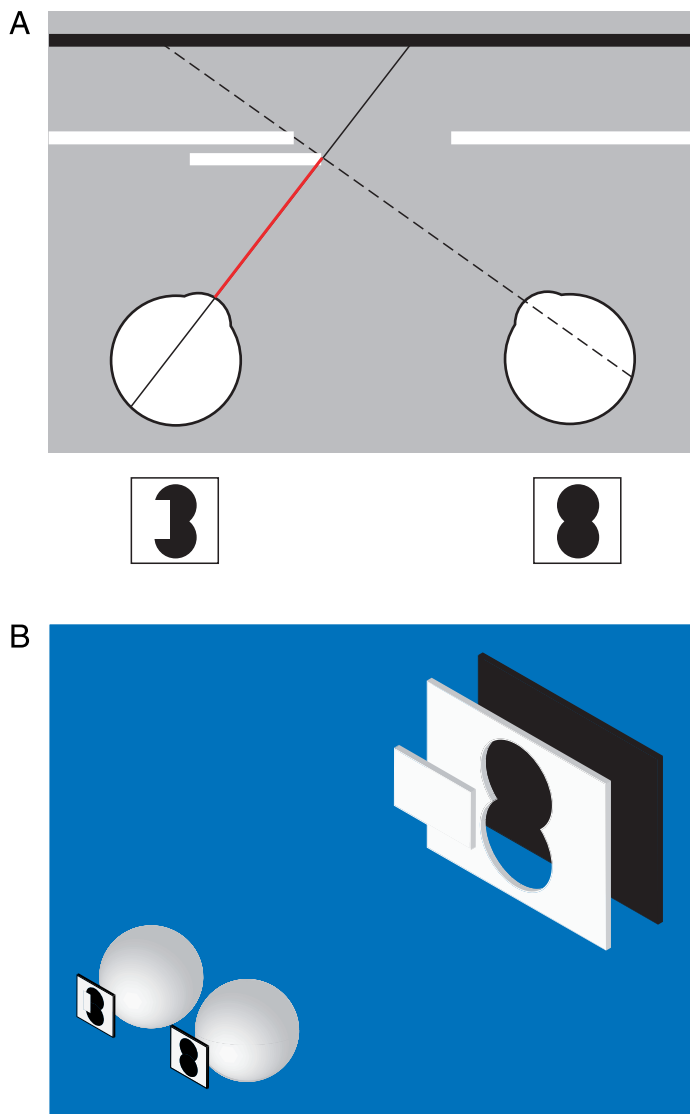


Figure 3. Da Vinci stereopsis: Monocular camouflage situation. (A) Plan view of Cook and Gillam (2004) stimulus. While the location of the target's right edge position is known in the left eye (solid line), it can only be assumed to lie to the left of the dotted line in the right eye. The intersection of these two lines represents the minimum depth constraint, although the edge may be located anywhere along the red line. (B) Monocular camouflage depicted in isometric projection.

of the monocular image and the binocular context in which it is embedded can only provide loose constraints as to the actual 3D location of the object. For example, in Figure 3A, the visual direction of the monocularly camouflaged white rectangle (or more accurately, its left edge) is known for the left eye and is represented by the solid line. In the other eye, it can only be assumed to lie somewhere to the left of the dotted line that represents the projection of the left edge of the figure eight. The converse situation applies in the case of monocular occlusion

(Figure 2A). In either case, the minimum possible depth between the white rectangle and the figure eight is specified by the intersection of the object's image projection in one eye and the projection of the occluding or camouflaging object's edge in the other eye, although the depth could be any number of values larger than this. Despite the fact that actual object depth is not completely specified, the depth percept often adheres to this "minimum depth constraint" (Cook & Gillam, 2004; Pianta & Gillam, 2003b).

As for the derivation of a static depth signal, the motion in depth (in terms of trajectory and velocity) of a binocularly matched stimulus is also fully specified. When an object approaches or recedes from an observer, there is a change in the disparity signal relative to other visible objects (known as the changing disparity, or CD cue) and a concomitant difference in monocular velocity signals (known as the interocular velocity difference, or IOVD cue). These stereomotion cues, according to the geometry of binocular vision, uniquely specify the rate and trajectory of motion throughout, and have been found to be effective in signaling the speed and trajectory of motion in depth (Brooks, 2001, 2002a, 2002b; Brooks & Mather, 2000; Brooks & Stone, 2006b; Cumming & Parker, 1994; Fernandez & Farrell, 2005, 2006; Gray & Regan, 1996; Harris & Watamaniuk, 1995; Portfors-Yeomans & Regan, 1996; Regan, 1993; Shioiri, Saisho, & Yaguchi, 2000). However, for a binocularly unmatched stimulus, a particular lateral translation of the visible monocular image could result from a range of possible trajectories, rates, and extents of motion in depth. Despite this ambiguity, the visual system can derive a vivid percept of motion in depth from half-occluded objects under the correct circumstances (Brooks & Gillam, 2006a). When the half-images shown in Figure 4A are binocularly fused, subjects report a percept of two slanted vertical planes, approximately parallel to each other, and separated by a central depth discontinuity as shown in plan view in Figure 4B (e.g., Gillam et al., 1999; Pianta & Gillam, 2003a, 2003b). When the central gap in one image expands and then shrinks, subjects note a change in the perceived slant of the two planes, such that they appear to swing in depth around their outer edges (Brooks & Gillam, 2006a). Stereomotion was perceived despite the fact that neither a change in disparity nor an interocular velocity difference was available for the inner edges, there being no matching binocular features. Again, the minimum depth constraint appears to be applied in this example.

In this study, we investigate the phenomenon of motion in depth perception in the context of monocular camouflage. In two experiments, we establish that a percept of motion in depth can be elicited by a purely lateral translation of the visible monocular image in a monocular camouflage situation. While Experiment 1 concerns the perceived trajectory of stereomotion, Experiment 2

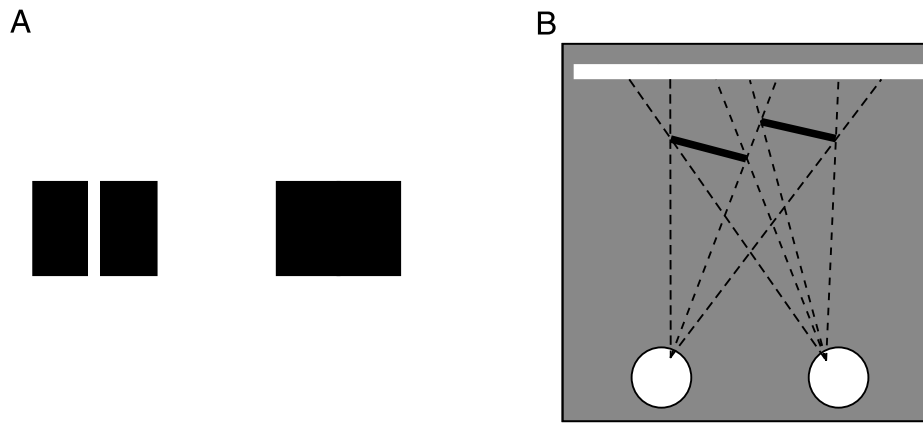


Figure 4. Stimulus from Brooks and Gillam (2006a). (A) Monocular half images intended for crossed fusion. (B) Plan view. A change in the size of the monocular gap (A) causes a sensation of stereomotion in the inner edges of the 3D stimuli (B).

measures perceived velocity in the depth dimension and extends the investigation to include a more tightly constrained binocular situation.

Experiment 1

In Experiment 1, we extended the work of Cook and Gillam (2004) using their monocular camouflage stimuli, as shown in Figure 3. Cook and Gillam established that certain objects that are camouflaged in one eye, yet revealed or “decamouflaged” in the other eye can appear in depth, and that the apparent depth corresponds to the minimum depth constraint. This applies to monocular targets that are attached to the edge of the decamouflaging figure eight (see intrusion stimuli, Figure 5, left column) but not to monocular targets that are unattached (see bar stimuli, Figure 5, right column). We asked whether motion in depth would be perceived in similar stimuli where the monocular white rectangle gradually changed position in one eye while remaining fully camouflaged in the other. If a continuously changing minimum depth constraint were enforced as the visible edge of the intrusion translates laterally, a large degree of motion in depth would be expected, with a trajectory of motion aimed directly at the eye to which the white rectangle is entirely camouflaged (see Movie 1). Alternatively, given that the motion signal for this monocular stimulus can only be lateral translation, the perception of changing depth may be elusive. No matchable contours are available² to form a changing disparity or IOVD cue, and hence conventional stereomotion information cannot be derived. In addition, given the constant height of the stimulus, looming information explicitly signals no motion in depth. Indeed, a percept of purely lateral motion would be perfectly consistent with the binocular geometry of these images. It is also possible that the visual system might consider the entire motion sequence and apply a

single minimum depth constraint throughout the target’s oscillation. If this were the case, the only consistent minimum depth constraint would be the largest of the sequence (corresponding to the moment of maximum target intrusion). In this instance, we would predict that lateral motion would be observed throughout the sequence, as shown in Movie 2. In addition, a large range of alternative perceived trajectories are possible given the fundamental ambiguity of the binocular information.

We measured apparent trajectory for this unmatched stimulus and for stimuli that featured (A) a moving target in one eye and a matchable stationary edge in the other, presenting conventional cues to motion in depth, (B) synoptic stimulation, where each eye viewed identical

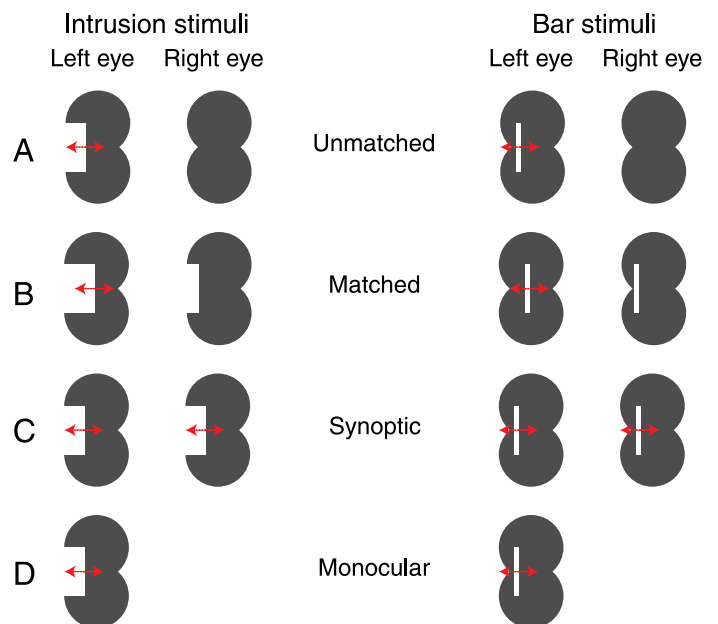
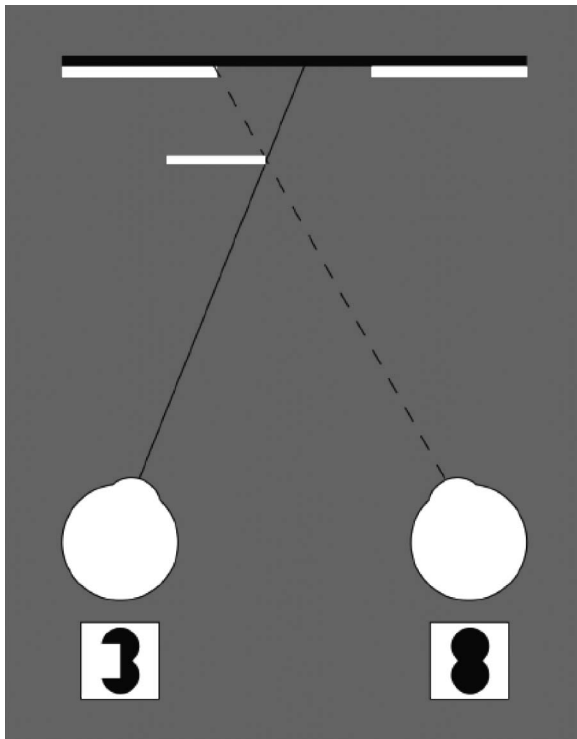


Figure 5. Schematics of stimuli for Experiment 1: (A) Unmatched, (B) Matched, (C) Synoptic, (D) Monocular. Left column: intrusion; right column: bar.



Movie 1. A possible percept of motion in depth during viewing of the Unmatched intrusion of [Experiment 1](#): Motion in depth. Not drawn to scale.

stimuli including a moving target, and (C) monocular stimulation (left eye only). In the case of the unmatched stimulus, our configuration ensured that the application of the minimum depth constraint on each frame would yield a motion in depth trajectory identical to that expected for the fully specified motion in the matched condition.

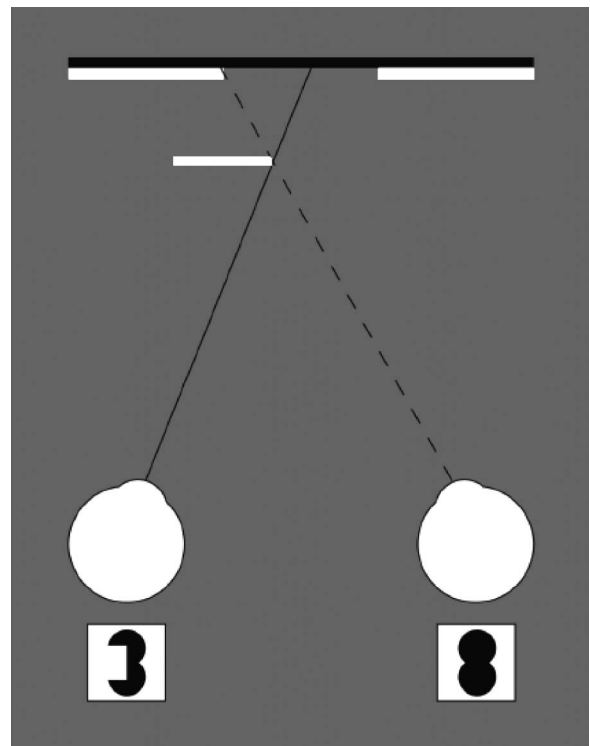
Methods

Stereoscopic stimuli were presented on two Samsung SynchMaster 957DF CRT monitors driven by an ATI Radeon 8500 dual-head video board and synchronized at a rate of 60 Hz. The gamma nonlinearity of each monitor was corrected using the look-up table. Images were superimposed using a modified Wheatstone stereoscope with convergence distance adjusted to match the optical distance of 86 cm, while maintaining perpendicular lines of sight to the screens. At this distance each screen subtended $24.3 \text{ deg} \times 19 \text{ deg}$. Subpixel resolution was achieved by anti-aliasing edge positions to 1/60th of a 0.62-arcmin wide pixel.

The basic test stimulus always included a stationary gray figure eight (37.8 cd/m^2), presented on a white surround (114.9 cd/m^2). The white (114.9 cd/m^2) target was visible against the figure eight (toward the left side) in

either one or both half-images, moving laterally. These luminance levels ensured that the Michelson contrast of any moving edge was 50%. The gray figure eight consisted of two partially overlapping gray ellipses presented in a vertical arrangement, as in Cook and Gillam (2004). Each ellipse measured 60 arcmin in width, and 61.1 arcmin in height, and overlapped the other by 20% of its vertical extent, producing a figure eight 110 arcmin in height. The white rectangular target measured 49 arcmin in height with its centre aligned vertically with that of the gray figure eight. The target moved laterally in a periodic fashion with a 0.5-Hz triangular displacement waveform, maintaining a constant lateral speed (0.312 deg/s). The size of all elements of the display was held constant.³

The target stimulus in each of four conditions could be of one of two types: either a “Bar” or an “Intrusion.” While Bar stimuli featured a target with a fixed width of 3.75 arcmin, whose right and left edges were always fully visible, Intrusion stimuli extended toward the centre of the gray figure eight from the white surround on the left by an amount that changed continuously throughout the motion sequence. Only the right edge of the Intrusion target was ever revealed, meaning that its precise width remained undefined throughout.



Movie 2. A possible percept of motion in depth during viewing of the Unmatched intrusion of [Experiment 1](#): Lateral motion only. Not drawn to scale.

Unmatched stimuli presented a binocular gray figure eight, on which a white target (either Bar or Intrusion as described above) was superimposed in the left eye alone (see Figure 5A). This target moved a total extent of 18.7 arcmin throughout its motion, moving from a position where its right edge intruded 9.4 arcmin into the figure eight to an intrusion of 28.1 arcmin. The Matched condition involved a binocularly visible target (see Figure 5B), and as such, contained conventional cues to motion in depth (changing disparity and IOVD). In the right eye, the target was stationary with its right edge located 15 arcmin from the left edge of the figure eight. In the left eye, the target's right edge moved from 24.4 to 43.1 arcmin. These positions correspond to conventional crossed disparities of 9.4 to 28.1 arcmin. The depths produced by such disparities are equal to those predicted if the minimum depth constraint were applied throughout the motion sequence of the Unmatched stimulus. In the Synoptic condition, the same half-image—the one featuring the target in motion—was presented to each eye (see Figure 5C). In the Monocular condition, while one eye viewed the target in motion over the gray figure eight, the other eye viewed the white surround alone (see Figure 5D).

Subjects were asked to match the white rectangular target's apparent trajectory of motion in depth with that of the probe. The probe stimulus took the same form as the equivalent stimulus from the Matched condition but was presented 1 deg below the target. The probe's apparent trajectory could be manipulated using the cursor keys. This was achieved by altering the probe's monocular velocities and the location of one of the extremes of the 3D motion path, with the other extreme always occurring at a disparity of 9.4 arcmin. A simultaneous increase in the speed of one of the probe's half-images and decrease in the other was effected whenever subjects depressed either the left or right cursor keys. In view of concerns that when asked to make judgments on some aspects of three-dimensional motion perception, subjects instead respond on the basis of the rate or extent of lateral translation (Harris & Drga, 2005, but see also Brooks, 2002b; Brooks & Stone, 2006a), the speed of lateral motion (the average of the velocities of each half-image) remained constant at 0.156 deg/s regardless of the trajectory setting. There were 36 possible values of probe trajectory angle β , calculated as in Equation 1 below, given left and right monocular (signed) image velocities, ω_L and ω_R , respectively, the interpupillary distance, I , and the viewing distance, d .

$$\beta \approx \tan^{-1} \left[\frac{I(\omega_L + \omega_R)}{2d(\omega_L - \omega_R)} \right] \quad (1)$$

Here 0° represents motion directly toward the observer's cyclopean eye, 90° represents purely lateral motion to the right, and 180° represents motion directly away from the observer from the fixed 9.4 arcmin disparity point.

Subjects were able to manipulate the probe trajectory between 177.8° , representing motion directly away from the left eye, and 1.6° , representing motion aimed between the right eye and the nose. These trajectories represent left:right monocular image velocities from 0:0.3 to 0.36:−0.05 deg/s, respectively.

The initial β value of the probe at the beginning of each trial could have any of the possible β values (randomized with uniform distribution). To account for vergence eye movements, the motion of the probe oscillated in phase with the target in half of the trials, and in antiphase in the other half. The relative phase of the target and probe was not under subjects' control. Subjects performed 12 matches in each of the eight conditions (6 in-phase, 6 antiphase). There were no appreciable differences in settings for these two subconditions, and so data from the two were combined before being subjected to further analysis.

In this experiment, author B.G. was joined by two other observers (B.S. and B.A.), each of whom had knowledge of stereoscopic vision, but were naïve as to the specific purpose, details, and conditions of this experiment. All had good stereoscopic vision, as measured with the Titmus Fly test.

Results

The results of probe matching are shown in Figure 6 for all three subjects. As expected, trajectory settings near the frontoparallel plane ($\beta = 90^\circ$) were made for the Synoptic and Monocular comparison conditions, using either Bar or Intrusion stimuli. For Matched binocular conditions, far smaller settings were made for both bars and intrusions, representing a vivid percept of oblique motion in depth approaching the eye that sees no image motion (here, the right eye). These values are close to 2.2° : the prediction of the conventional stereomotion cues with which this stimulus is replete. For the Unmatched condition, the results differed between the two stimulus types. While settings were near frontoparallel for Bar stimuli, the Intrusion stimuli show far smaller settings, despite a degree of individual differences. For unmatched intrusion stimuli, subjects B.G. and B.A. observed a large excursion in depth and show trajectory settings with a low β value—almost as low as those for Matched stimuli—while the results of subject B.S. represent more oblique perceived trajectories.

Statistical analyses were performed in the form of seven planned linear contrasts for each subject. Contrasts were assessed between Unmatched Bar stimuli and all three other versions of Bar stimuli; between Unmatched Intrusion stimuli and all three other Intrusion stimuli; and between Unmatched Intrusion and Unmatched Bar stimuli. The critical significance level for each comparison was adjusted to $\alpha = .00714$ to reflect the multiple comparisons and to maintain a per-subject α level of .05.

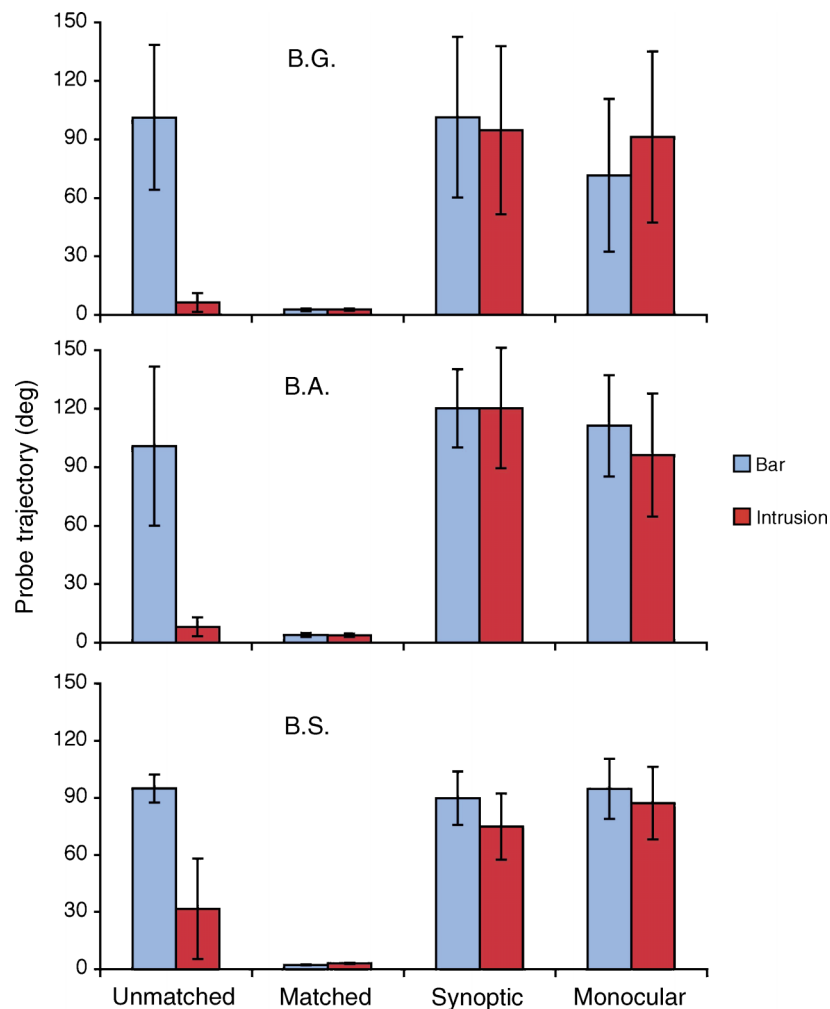


Figure 6. Results of probe matches to stimulus trajectory for Experiment 1. Pale blue and red bars represent responses to Bar and Intrusion stimuli, respectively. Error bars represent ± 1 SEM.

For each comparison of conditions, only the statistical values closest to our critical significance level are reported.

For all subjects, data for Unmatched Bar stimuli and Unmatched Intrusion stimuli were quite different (B.G.: $F(1, 11) = 27.802$, $p < .0005$; B.A.: $F(1, 11) = 25.181$, $p < .0005$; B.S.: $F(1, 11) = 23.284$, $p = .001$), with the intrusion stimulus eliciting a greater impression of motion in depth, and hence smaller settings. For Unmatched Bar stimuli, settings were significantly different from those for Matched Bars (B.G.: $F(1, 11) = 33.618$, $p < .0005$; B.A.: $F(1, 11) = 28.072$, $p < .0005$; B.S.: $F(1, 11) = 787.947$, $p < .0005$) but did not differ significantly from those for either Synoptic Bars (all subjects: $F(1, 11) < 1$) or Monocular Bars (B.G.: $F(1, 11) = 1.405$, $p = .261$; B.A., B.S.: $F(1, 11) < 1$). These results confirm that no motion in depth was seen for Bar stimuli. However, a statistically significant difference between Unmatched Intrusion stimuli and both Synoptic Intrusions (B.G.: $F(1, 11) = 19.065$, $p = .001$; B.A.: $F(1, 11) = 70.107$, $p < .0005$; B.S.: $F(1, 11) = 11.882$, $p = .005$) and Monocular

Intrusions (B.G.: $F(1, 11) = 19.015$, $p = .001$; B.A.: $F(1, 11) = 38.569$, $p < .0005$; B.S.: $F(1, 11) = 19.076$, $p = .001$) was shown. In contrast to the results for bar stimuli, intrusion stimuli appear quite different in trajectory to the lateral motion produced by synoptic or monocular stimuli. In addition, the comparison of Unmatched Intrusion and Matched Intrusion stimuli lacked significance for observers B.G. and B.A. (B.G.: $F(1, 11) = 3.232$, $p = .1$; B.A.: $F(1, 11) = 3.139$, $p = .1$). For subject B.S., this comparison ($F(1, 11) = 5.765$, $p = .035$) may have appeared significant in an uncorrected test, although it failed to achieve significance at our more conservative corrected alpha level of .00714.

Discussion

It is clear that a percept of motion in depth can occur with a monocularly camouflaged stimulus, despite a lack of any conventional cues to motion in depth, such as the stereoscopic cues of changing disparity and IOVD.

Although Unmatched Intrusion stimuli were, for the majority of subjects, successful in eliciting a motion in depth percept, this was not the case for Unmatched Bar stimuli. This mirrors the results for static depth perception, where a quantitative depth percept was shown for Intrusion, but not Bar stimuli—a phenomenon attributed to the existence of “cyclopean T-junctions” in the former, but not the latter stimulus type (Cook & Gillam, 2004). It might be suggested that looming is responsible for the sensation of motion in depth in the intrusion stimulus. However, the expansion of the stimulus is not isotropic. Furthermore, if the changing width were responsible for the percept of changing depth, a percept of motion in depth should have been evident in the Synoptic and Monocular conditions, yet this was not the case. Hence, the stimulus appears to move in depth despite its constant height, rather than because of its changing width.

For each observer, trajectory settings showed a higher β value for Unmatched than for Matched stimuli containing conventional stereomotion cues, although this difference did not achieve statistical significance, in part because of the number of comparisons performed. Probe settings reflected a percept of lateral motion accompanying the sense of motion in depth, which corresponded to subjects’ informal descriptions of the stimuli during debriefing. Although changing depth is seen, the minimum depth constraint does not appear to be applied throughout the motion sequence. The imposition of such a constraint would have led to probe settings equal to those made in the Matched stimuli. As described earlier, the stimulus is relatively unconstrained, and is geometrically consistent with a range of possible trajectories, with only a constraint on the smallest depth that should be seen at any one instant. This may help to explain the oblique trajectories seen by our subjects. In Experiment 2, we reused the Unmatched Intrusion stimulus from Experiment 1, and introduced a second stimulus with additional geometrical constraints in an attempt to elicit more robust perception of motion in depth.

Experiment 2

In the experiment above, although the position of the Unmatched Intrusion target’s edge is known for one eye, it is undefined in the other, due to the fact that it is camouflaged. Given that the target cannot lie in the same position with respect to the gray figure eight in each half image, the target must lie in a different depth plane. The minimum possible depth would occur if the camouflaged half-image of the target were to abut the gray figure eight on the same side as the visible intrusion in the other half-image. This situation is depicted in Figure 3A. Since the white target rectangle is camouflaged against a white background that extends to the edge of the display, its

position could be anywhere in this expanse, and as such its maximum binocularly defined depth is effectively unconstrained. In static depth perception, Cook and Gillam (2004) showed that the minimum depth constraint appears to be applied to this stimulus. However, for motion in depth, this constraint does not appear to apply throughout the duration of the display, as this would lead to equivalent motion in depth for Matched and Unmatched targets. By introducing new objects adjacent to the stimulus that are not occluded by the target in either eye, we can more strictly constrain the inferred position of the camouflaged target in an attempt to produce a more robust impression of motion in depth. We hypothesize that for those subjects experiencing a smaller magnitude of motion in depth for unmatched stimuli, the tightening of constraints by the addition of new decamouflaging objects will produce enhanced perception of motion in depth reflected in larger probe settings.

The new display used in this experiment was formed by introducing a second gray figure eight alongside the display, as shown in Figure 7A. The white rectangular intrusion moved from a central position into the right figure in the left eye only, before retreating until no part of either figure was occluded. Following this, the target intruded from the centre into the left figure in the right eye alone, before retreating once more. This sequence continued in a periodic fashion. Crucially, the horizontal gap between the two background figures eight was exactly equal to the maximum intrusion of the white target.

During a monocular intrusion in the left eye, the target’s right edge is revealed while the corresponding edge in the right eye remains camouflaged just as before. Although the location of the camouflaged feature was completely unconstrained in Experiment 1, it is constrained to lie within a narrow expanse in the new, more elaborate stimulus. These additional constraints restrict the possible trajectories and velocities of motion in depth to a narrow range. During maximum intrusion—a situation depicted in Figure 7B—the 3D location of the target edge must lie somewhere along the extent AB, since its monocular visual direction is known in the left eye, although is it not visible (due to camouflage against the white background) in the right eye. In the limit that the intrusion tends to zero the edge must lie along extent DC. Some degree of motion in depth is inevitable in transition between the two. The same analysis can be applied in mirror image during an intrusion in the right eye. Furthermore, if observers were to assume that the target is frontoparallel with a constant shape,⁴ then the positions of both edges of the target would be fully defined. At each instant, the depth is certain, as the target can only have one possible position in each eye. At the moment of largest intrusion, it entirely fills the gap between the gray figures in one eye, and in the other it intrudes to the point where its trailing edge almost becomes decamouflaged. As the target retreats to the point where it is momentarily camouflaged in both eyes, its only possible position is the plane of the white background.

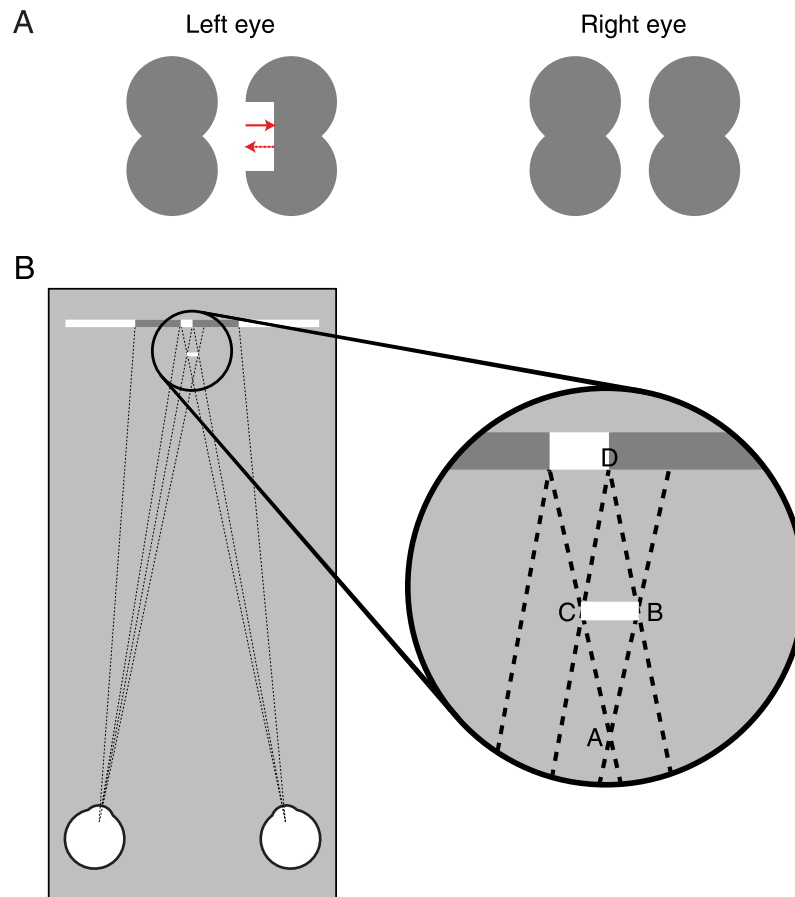


Figure 7. The constraints of binocular geometry for Unmatched Double stimuli.

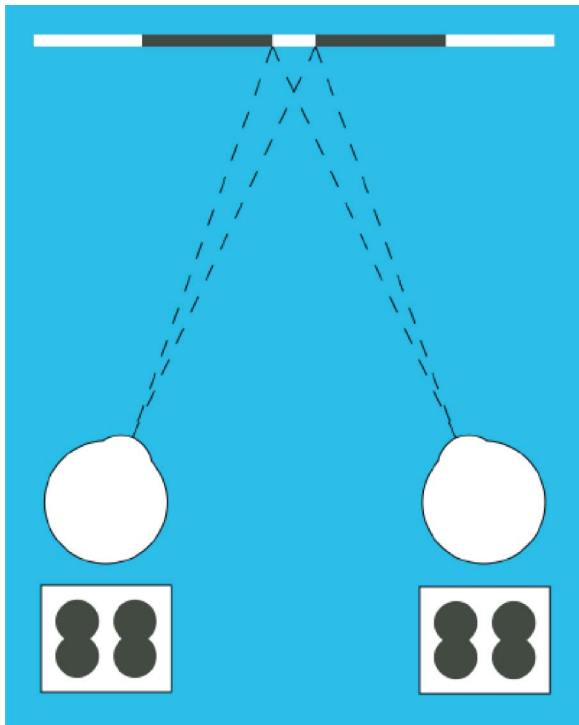
[Movie 3](#) demonstrates the V-shaped motion in depth trajectory that would be predicted given these constraints.

Methods

Schematics of the stimuli used in this experiment are provided in [Figure 8](#). We again used the Unmatched Intrusion stimulus, this time allowing the monocular intrusion to range from zero to 10 arcmin at a rate of 0.167 deg/s. As no Bar stimuli were used in this experiment, this is referred to as the Unmatched Single stimulus. In a second stimulus, referred to as Unmatched Double, two gray figure eights were displayed side-by-side, 10 arcmin apart, to introduce further geometrical constraints on the predicted motion in depth percept. Two other conditions were included, where the motion in depth of the target was fully specified by conventional stereomotion cues. Stimuli in these conditions, entitled Matched Single and Matched Double, were identical to their unmatched counterparts except that the target was black (12.6 cd/m^2), and hence was visible at all times and included conventional stereomotion cues, specifying a rate of disparity change of 0.167 deg/s. These luminance levels ensured that the Michelson contrast of any moving edge, either white-gray or black-gray was fixed at 50%. While

the target in one eye moved in the same manner as the white target in the Unmatched conditions, in the other eye it was stationary, located in the gap between the two figures eight. Target width remained constant at 10 arcmin, equal to the separation of the two gray figure eights in the Double conditions. In each stimulus configuration, motion was always present. In the Single conditions, target stimuli simply reversed their direction along a single trajectory axis, as in [Experiment 1](#). In the Double conditions, the target followed a symmetrical “V-shaped” path in depth (i.e., the same trajectory as the Single condition, plus its mirror image).

Subjects were asked to consider the apparent motion in depth of the target and to adjust the velocity of a binocular probe, presented 12.4 arcmin below, to match. The speed and the sign of the probe stimulus’ phase could be manipulated by the subject; increases and decreases being effected with a pair of keys, and a phase-reversal being effected with a separate key. One extreme of the probe’s motion was anchored to lie at a near disparity of 2.5 arcmin to prevent subjects from simply matching the depths or disparities at the extremes of the motion sequence. The initial speed and sign of motion in depth was randomized. The probe was a vertical black bar, identical in size to the target, which oscillated in opposite directions at equal speeds in each eye, simulating a direct



Movie 3. A possible percept of motion in depth during viewing of the Unmatched intrusion of Experiment 2: V-shaped motion in depth. Not drawn to scale.

($\beta = 0^\circ$) trajectory of motion in depth. A row of short vertical lines were provided above and below the probe, providing the necessary stereoscopic reference points to ensure a vivid impression of motion in depth. Twelve matches were made per condition by each of four subjects, two of whom had contributed data in Experiment 1. On this occasion, subjects B.G. and B.S. were joined by naïve observers D.B. and S.L., who had no knowledge of the mechanisms of binocular vision or of the aims of the experiment.

Results

Here, all subjects perceived a significant magnitude of motion in depth, although the apparent speed varied between subjects and between conditions, as shown in Figure 9. As expected, all subjects made high probe settings to matched stimuli featuring conventional stereomotion cues. As in Experiment 1, the Unmatched Single stimulus produced different sensations of motion in depth for different subjects, ranging from the large settings made by subject D.B. to the near-zero settings made by subject S.L., who reported no motion in depth percept for this stimulus. However, in the Unmatched Double stimulus, where the constraints of binocular geometry are far tighter and an increased perceived speed of motion in depth was predicted, all subjects reported a clear percept of motion

in depth. All subjects made higher mean settings for the Unmatched Double compared to the Unmatched Single condition.

Statistical significance was assessed using 2×2 ANOVAs for each subject. In addition, one planned

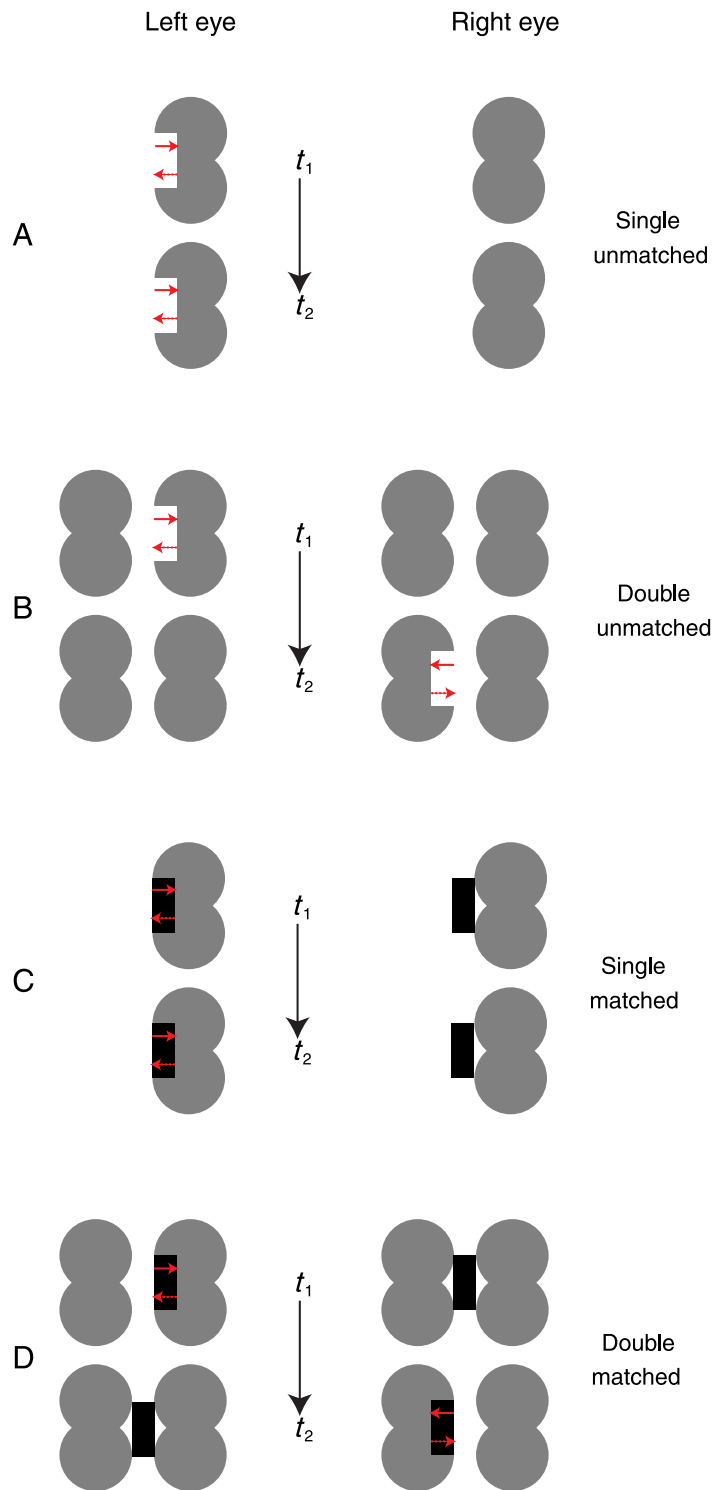


Figure 8. Schematics of stimuli for Experiment 2: (A) Single Unmatched, (B) Double Unmatched, (C) Single Matched, (D) Double Matched.

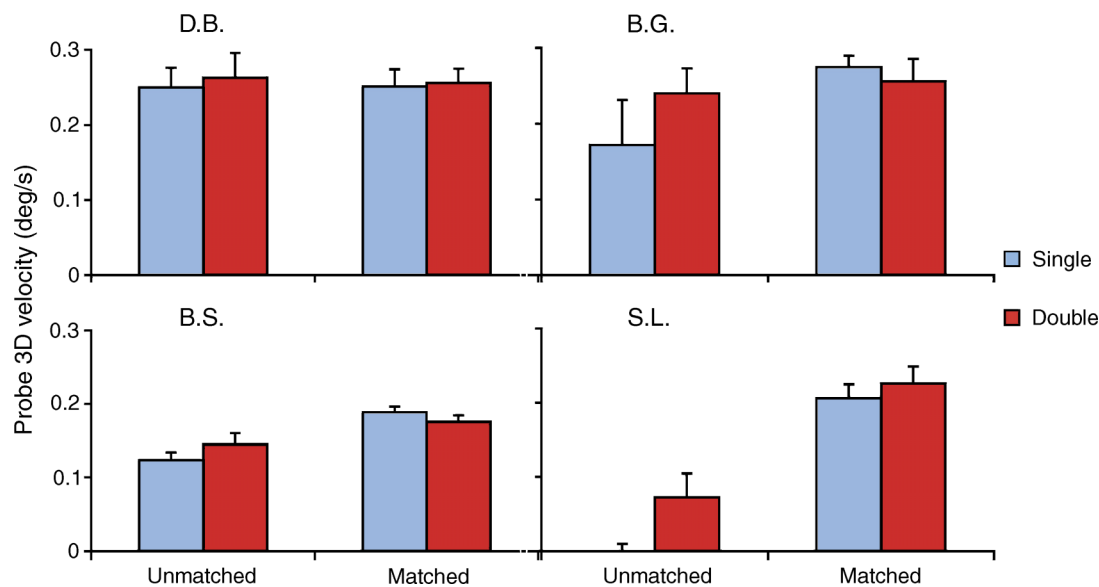


Figure 9. Results of probe matches to stimulus velocity in depth for Experiment 2. Pale blue and red bars represent responses to Single and Double figure conditions, respectively. Error bars represent ± 1 SEM.

contrast was performed to specifically assess the difference between settings for the Unmatched Single and the Unmatched Double conditions. For subject D.B., all settings were near the value predicted by the minimum depth constraint, precluding the emergence of significant differences in statistical comparisons. Despite this, there can be no doubt that for this subject Unmatched stimuli produce a vivid impression of motion in depth, regardless of the extent to which the display is constrained. For the remaining three subjects, a significant main effect emerged, indicating that in general, Unmatched displays produced smaller settings than their Matched equivalents (B.G.: $F(1, 11) = 11.084$, $p = .007$; B.S.: $F(1, 11) = 62.125$, $p < .0005$; S.L.: $F(1, 11) = 264.056$, $p < .0005$). A significant effect of number of figure eights was present only for one subject (S.L.: $F(1, 11) = 21.588$, $p = .001$). A significant interaction was present for the three subjects not performing at ceiling, indicating that moving from a single to a double stimulus had a greater effect on unmatched than matched stimuli (B.G.: $F(1, 11) = 10.524$, $p = .008$; B.S.: $F(1, 11) = 27.39$, $p < .0005$; S.L.: $F(1, 11) = 8.66$, $p = .013$). Confirming our original hypothesis that the addition of a second decamouflaging figure would increase probe settings the planned contrast between Unmatched Single and Double displays was significant for all three subjects not performing at ceiling (B.G.: $F(1, 11) = 10.054$, $p = .009$; B.S.: $F(1, 11) = 8.56$, $p = .014$; S.L.: $F(1, 11) = 71.588$, $p = .002$).

Discussion

In this experiment, all observers experienced a percept of motion in depth for displays lacking conventional stereomotion cues. This was indicated by the large

settings shown by all observers in the Unmatched Double condition. Although individual differences remain for both unmatched conditions, the tightening of constraints was successful in strengthening the impression of motion in depth, and producing settings closer to the levels shown for stimuli that contain conventional stereomotion cues. The presence of two gray figure eights in our double display acts to more tightly constrain the size, and hence the monocular edge locations of the intruding white object. It would seem that for our observers, this additional constraining information has helped to enhance the percept of motion in depth. The influence of the constraints of binocular geometry on the perceived motion in depth of stimuli in the absence of conventional stereoscopic matches is clear.

It is also noteworthy that in this experiment, the probe speed setting for matched stereomotion stimuli is often higher than the predicted value of 0.167 deg/s. This may be explained by the fact that although all of our test stimuli appeared to move obliquely through stimulus space, our probe moved directly toward and away from the cyclopean eye along the midline. It has been shown previously that oblique motion in depth generally appears faster than otherwise equivalent direct stereomotion defined by the CD and IOVD cues (Brooks & Stone, 2006a; Lages, 2006). Here, oblique motion again appears faster, and hence a higher speed of direct probe motion is required to achieve a subjective match. Interestingly, the same seems to be the case for our unmatched stimuli, at least for the robust motion in depth perception evoked by our Double Unmatched stimulus. Although a full explanation for this effect has not yet been made, the possibility remains that it is related to the compression of space (or of velocity) representation in the depth plane (see Brooks & Stone, 2006a).

General discussion

We have demonstrated the perception of motion in depth for stimuli that lack any of the conventional cues to approaching and receding motion. Although motion in depth perception has not previously been demonstrated for objects that are monocularly camouflaged, similar effects have recently been reported. Brooks and Gillam (2006a) established a third stereomotion cue (dynamic half-occlusion) using the monocular gap stereogram (Gillam et al., 1999)—a stimulus configuration quite different from the one used here. In a monocular gap stereogram, the white background is visible to the observer through one eye, yet is occluded in the other eye (see Figure 4). It has been argued that the presence of the background in one eye allows a different depth signal to be attributed to each of the two foreground objects. This situation is different from the present case where the monocular stimulus itself appears in depth (for a discussion, see Pianta & Gillam, 2003b). Furthermore, the stimulus in this experiment involves camouflage and not occlusion. Occlusion and camouflage are intrinsically related, representing complimentary situations of monocularity. However, differences are found in the luminance prerequisites for each type of depth signal due to the fact that a monocularly occluded object may have any surface properties, while a monocularly camouflaged object must be indistinguishable from the background against which it is presented in one eye. With these differences in mind, it may be that motion in depth elicited by changes in the extent of monocular camouflage results from a separate process from motion in depth by occlusion. Alternatively, depth signals from monocular camouflage and monocular occlusion may both be calculated in a similar way, with an additional processing stage that could veto a near depth signal when the luminance conditions are invalid for camouflage.

Few studies have investigated temporal factors in the perception of depth or motion in depth through unmatched stereopsis. In the matched context, it has been shown that a stimulus with an oscillating disparity is perceived as moving in depth at frequencies up to approximately 1 Hz, after which the sense of stereomotion is diminished or abolished (Norcia & Tyler, 1984; Regan & Beverley, 1973; Tyler, 1971). For this reason, we used a stimulus that oscillated in depth at only 0.5 Hz. Although recent research has shown similarities in some temporal aspects such as the variation of performance with exposure duration (Pianta & Gillam, 2003a; Sachtler & Gillam, 2007), and the rate of recovery from adaptation (Pianta & Gillam, 2003a), it remains possible that unmatched stereomotion processing breaks down at a lower frequency than matched stereomotion. If this were the case, our results might reflect a breakdown of unmatched stereomotion perception at an oscillation frequency where

matched stereomotion perception remains intact. We do not believe that this is the case, as Experiment 2 clearly demonstrated that a large and robust percept of motion in depth—equivalent to that shown for matched stimuli—is quite possible using unmatched displays at this frequency. Whatever the specific reason for the differences here, it seems that the processing of matched and unmatched stereomotion is distinct.

Although it may be tempting to think that the perception of motion in depth shown in this study may simply be the result of combining static depth percepts from each frame of our motion sequence, the data suggest that the two processes are, at least to some extent, distinct. It has been shown that for stationary stimuli, subjects perceive quantitative depth in the target stimulus in line with the predictions of the minimum depth constraint (Cook & Gillam, 2004). If these depth percepts were simply combined over time through our motion sequence, the single unmatched stimuli would be expected to evoke a 3D motion trajectory and velocity equal to those in the corresponding matched conditions for both experiments. However, this was not the case. Although all subjects saw these unmatched stimuli as having a depth distinct from that of the white surround throughout the motion sequence, this depth did not change at the rate predicted by the minimum depth constraint. Instead, a considerable degree of lateral motion was seen unless this was rendered inconsistent with the binocular stimulus layout. Our results show that for perceived depth satisfying the minimum depth constraint in monocular camouflage stimuli, additional complementary constraints are required in the motion in depth case compared to the static case. Thus, the motion case is not merely an integration of a succession of static signals. The strong effect of the additional constraint in Experiment 2 reinforces the fact that binocular depth perception involves not only combining monocular and binocular information but doing so both locally and globally in space and time. However, at this stage we are unable to say whether unmatched stereo depth perception and motion in depth perception involve entirely parallel processes, or whether they are computed in series, with motion in depth perception incorporating static depth perception modulated by additional factors specific to motion stimuli.

Acknowledgments

Support: ARC DP0211698 to B. Gillam.

Commercial relationships: none.

Corresponding author: Kevin R. Brooks.

Email: kbrooks@psy.mq.edu.au.

Address: Department of Psychology, Macquarie University, NSW 2109, Australia.

Footnotes

¹That the location of an object is fully specified by binocular geometry should not be taken to imply that the perceived depth is unambiguous to an observer. Although such information may be considered a prerequisite to accurate binocular depth perception, a host of other factors can influence apparent 3D position even for a fully visible binocular object. An exhaustive discussion of these factors is beyond the scope of this paper.

²The target in the Unmatched condition constituted the only continuously vertical contour in the display. Although it is in principle possible that this straight vertical edge could be fused with the curved contours of the figure eight this outcome was ruled out by Cook and Gillam in control experiments.

³Although in the natural environment a change in depth is often accompanied by a change in image size, we adopted this simplification for several reasons. Firstly, any expansion of our target stimulus over the range of depths concerned here would be small (less than 0.4 of an arcmin in width). For small targets such as ours, monocular cues to motion in depth are known to be less influential than binocular cues (Regan & Beverley, 1979). Furthermore, it has been repeatedly shown that binocular and looming cues can independently lead to a percept of motion in depth, even when the remaining cue explicitly signals no such motion. Throughout this study, all images retain the same size throughout whether matched or unmatched, in both target and probe.

⁴It should be noted that along with the possible rigid motions associated with this stimulus, there also exist many possible nonrigid motions that could be consistent with our display. As none of our subjects reported a percept of target deformation, and for the sake of simplicity, we restrict our discussion to rigid motions.

References

- Anderson, B. L. (1994). The role of partial occlusion in stereopsis. *Nature*, *367*, 365–368. [PubMed]
- Brooks, K. (2001). Stereomotion speed perception is contrast dependent. *Perception*, *30*, 725–731. [PubMed]
- Brooks, K., & Mather, G. (2000). Perceived speed of motion in depth is reduced in the periphery. *Vision Research*, *40*, 3507–3516. [PubMed]
- Brooks, K. R. (2002a). Interocular velocity difference contributes to stereomotion speed perception. *Journal of Vision*, *2*(3):2, 218–231, <http://journalofvision.org/2/3/2/>, doi:10.1167/2.3.2. [PubMed] [Article]
- Brooks, K. R. (2002b). Monocular motion adaptation affects the perceived trajectory of stereomotion. *Journal of Experimental Psychology: Human Perception and Performance*, *28*, 1470–1482. [PubMed]
- Brooks, K. R., & Gillam, B. J. (2006a). Quantitative perceived depth from sequential monocular decamouflage. *Vision Research*, *46*, 605–613. [PubMed]
- Brooks, K. R., & Gillam, B. J. (2006b). The swinging doors of perception: Stereomotion without binocular matching. *Journal of Vision*, *6*, 685–695, <http://journalofvision.org/6/7/2/>, doi:10.1167/6.7.2. [PubMed] [Article]
- Brooks, K. R., & Stone, L. S. (2004). Stereomotion speed perception: Contributions from both changing disparity and interocular velocity difference over a range of relative disparities. *Journal of Vision*, *4*(12):6, 1061–1079, <http://journalofvision.org/4/12/6/>, doi:10.1167/4.12.6. [PubMed] [Article]
- Brooks, K. R., & Stone, L. S. (2006a). Stereomotion suppression and the perception of speed: Accuracy and precision as a function of 3D trajectory. *Journal of Vision*, *6*(11):6, 1214–1223, <http://journalofvision.org/6/11/6/>, doi:10.1167/6.11.6. [PubMed] [Article]
- Brooks, K. R., & Stone, L. S. (2006b). Spatial scale of stereomotion speed processing. *Journal of Vision*, *6*(11):9, 1257–1266, <http://journalofvision.org/6/11/9/>, doi:10.1167/6.11.9. [PubMed] [Article]
- Cook, M., & Gillam, B. (2004). Depth of monocular elements in a binocular scene: The conditions for da Vinci stereopsis. *Journal of Experimental Psychology: Human Perception and Performance*, *30*, 92–103. [PubMed]
- Cumming, B. G., & Parker, A. J. (1994). Binocular mechanisms for detecting motion-in-depth. *Vision Research*, *34*, 483–495. [PubMed]
- Fernandez, J. M., & Farrell, B. (2005). Seeing motion in depth using inter-ocular velocity differences. *Vision Research*, *45*, 2786–2798. [PubMed] [Article]
- Fernandez, J. M., & Farrell, B. (2006). Motion in depth from interocular velocity differences revealed by differential motion aftereffect. *Vision Research*, *46*, 1307–1317. [PubMed] [Article]
- Forte, J., Pierce, J. W., & Lennie, P. (2002). Binocular integration of partially occluded surfaces. *Vision Research*, *42*, 1225–1235. [PubMed]
- Gillam, B., Blackburn, S., & Nakayama, K. (1999). Stereopsis based on monocular gaps: Metrical encoding of depth and slant without matching contours. *Vision Research*, *39*, 493–502. [PubMed]
- Gillam, B., & Nakayama, K. (1999). Quantitative depth for a phantom surface can be based on cyclopean occlusion cues alone. *Vision Research*, *39*, 109–112. [PubMed]
- Gray, R., & Regan, D. (1996). Cyclopean motion perception produced by oscillations of size, disparity and location. *Vision Research*, *36*, 655–665. [PubMed]

- Grove, P. M., Byrne, J. M., & Barbara, J. G. (2005). How configurations of binocular disparity determine whether stereoscopic slant or stereoscopic occlusion is seen. *Perception*, *34*, 1083–1094. [PubMed]
- Grove, P. M., Gillam, B., & Ono, H. (2002). Content and context of monocular regions determine perceived depth in random dot, unpaired background and phantom stereograms. *Vision Research*, *42*, 1859–1870. [PubMed]
- Häkkinen, J., & Nyman, G. (1996). Depth asymmetry in da Vinci stereopsis. *Vision Research*, *36*, 3815–3819. [PubMed]
- Häkkinen, J., & Nyman, G. (2001). Phantom surface captures stereopsis. *Vision Research*, *41*, 187–199. [PubMed]
- Harris, J. M., & Drga, V. F. (2005). Using visual direction in three-dimensional motion perception. *Nature Neuroscience*, *8*, 229–233. [PubMed]
- Harris, J. M., & Watamaniuk, S. N. (1995). Speed discrimination of motion-in-depth using binocular cues. *Vision Research*, *35*, 885–896. [PubMed]
- Howard, I. P. (1995). Depth from binocular rivalry without spatial disparity. *Perception*, *27*, 67–74. [PubMed]
- Lages, M. (2006). Bayesian models of binocular 3D motion perception. *Journal of Vision*, *6*(4):14, 508–522, <http://journalofvision.org/6/4/14/>, doi:10.1167/6.4.14. [PubMed] [Article]
- Nakayama, K., & Shimojo, S. (1990). da Vinci stereopsis: Depth and subjective occluding contours from unpaired image points. *Vision Research*, *30*, 1811–1825. [PubMed]
- Norcia, A. M., & Tyler, C. W. (1984). Temporal frequency limits for stereoscopic apparent motion processes. *Vision Research*, *24*, 395–401. [PubMed]
- Pianta, M. J., & Gillam, B. J. (2003a). Monocular gap stereopsis: Manipulation of the outer edge disparity and the shape of the gap. *Vision Research*, *43*, 1937–1950. [PubMed]
- Pianta, M. J., & Gillam, B. J. (2003b). Paired and unpaired features can be equally effective in human depth perception. *Vision Research*, *43*, 1–6. [PubMed]
- Portfors-Yeomans, C. V., & Regan, D. (1996). Cyclopean discrimination thresholds for the direction and speed of motion in depth. *Vision Research*, *36*, 3265–3279. [PubMed]
- Regan, D. (1993). Binocular correlates of the direction of motion in depth. *Vision Research*, *33*, 2359–2379. [PubMed]
- Regan, D., & Beverley, K. I. (1973). Some dynamic features of depth perception. *Vision Research*, *13*, 2369–2379. [PubMed]
- Regan, D., & Beverley, K. I. (1979). Binocular and monocular stimuli for motion in depth: Changing-disparity and changing-size feed the same motion-in-depth stage. *Vision Research*, *19*, 1331–1342. [PubMed]
- Sachtler, W. S., & Gillam, B. (2007). The stereoscopic sliver: A comparison of duration thresholds for fully stereoscopic and unmatched versions. *Perception*, *36*, 135–144. [PubMed]
- Shioiri, S., Saisho, H., & Yaguchi, H. (2000). Motion in depth based on inter-ocular velocity differences. *Vision Research*, *40*, 2565–2572. [PubMed]
- Tyler, C. W. (1971). Stereoscopic depth movement: Two eyes less sensitive than one. *Science*, *174*, 958–961. [PubMed]
- Wheatstone, C. (1838). Contributions to the physiology of vision. I. On some remarkable and hitherto unobserved, phenomena of binocular vision. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *2*, 371–393.