

The binocular advantage in visuomotor tasks involving tools

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Abstract. We compared performance on three manual-dexterity tasks under monocular and binocular viewing. The tasks were the standard Morrisby Fine Dexterity Test, using forceps to manipulate the items, a modified version of the Morrisby test using fingers, and a “buzz-wire” task in which subjects had to guide a wire hoop around a 3D track without bringing the hoop into contact with the track. In all three tasks, performance was better for binocular viewing. The extent of the binocular advantage in individuals did not correlate significantly with their stereoaucuity measured on the Randot test. However, the extent of the binocular advantage depended strongly on the task. It was weak when fingers were used on the Morrisby task, stronger with forceps, and extremely strong on the buzz-wire task (fivefold increase in error rate with monocular viewing). We suggest that the 3D buzz-wire game is particularly suitable for assessing binocularly based dexterity.

Keywords: binocular vision, stereoscopic depth perception, visuomotor skills, dexterity, motor coordination.

1 Introduction

Humans, like many other predators, have front-facing eyes which allow a substantial binocular overlap at the cost of reducing the breadth of the visual field. A major advantage of this arrangement is that it permits depth perception from small disparities between the two eyes' images. Binocular stereopsis offers a number of different advantages. For example, it can break camouflage, i.e. detect object boundaries which are invisible or hard to detect monocularly, with benefits for efficient scene segmentation as well as predation (Julesz, 1971; Pettigrew, 1991). In “man, a sophisticated toolmaker” (Barlow, Blakemore, & Pettigrew, 1967), a second key advantage may be that stereo depth perception aids manual dexterity (Fielder & Moseley, 1996). Performance under binocular and monocular viewing conditions has been tested in a variety of tasks (Jones & Lee, 1981; Joy, Davis, & Buckley, 2001; Marotta, Perrot, Nicolle, Servos, & Goodale, 1995; Melmoth & Grant, 2006), and has consistently shown an advantage of binocular viewing. Conversely, a range of studies have found that people lacking stereopsis are impaired on manual tasks (Grant, Melmoth, Morgan, & Finlay, 2007; Murdoch, McGhee, & Glover, 1991; O'Connor, Birch, Anderson, & Draper, 2010; Sachdeva & Traboulsi, 2011; Suttle, Melmoth, Finlay, Sloper, & Grant, 2011; Webber, Wood, Gole, & Brown, 2008), suggesting that restoring binocular function and stereopsis may be functionally important.

Most of these studies have used prehension tasks in which objects are grasped directly with the fingers. We speculated that the binocular advantage should be greater in tasks using tools. Proprioceptive information is not available directly from the tool. Proprioceptive information is available from the fingers holding the tool, but some transformation then needs to be applied in order to obtain the location of the relevant part of the tool. This transformation has to account for movements of the tool in the fingers, especially if the grip needs to change as pressures on the tool vary during the task. A more direct form of proprioceptive information becomes available when the tool comes into contact with an object or surface, as one can “feel” via the tool tip (Burton, 1993). While this information may be helpful in providing feedback on errors, it cannot help the user bring the tool efficiently into

contact with the surface in the first place. For that, one must rely on visual information. Thus, it seems plausible that proprioceptive information will be subject to more effective noise in manual tasks which use tools, resulting in a greater weight being placed upon visual cues such as binocular disparity. To demonstrate this informally, we invite the reader to hold their hands out with each forefinger extended, and bring the tips of the two forefingers rapidly together. This task is easier to perform accurately with both eyes open, but can still be performed quite well with one or indeed no eyes open. Now repeat the task with two pens of diameter similar to the fingers. With only one eye open, it is quite possible to miss completely.

To investigate the role of binocular vision in tasks using tools, we compared binocular versus monocular performance on three tasks: the Morrisby Fine Dexterity Test performed with fingers and with forceps, and a “buzz-wire” task in which a wire hoop is guided around a track. Joy et al. (2001) showed that participants with one eye occluded took longer to complete this task than those viewing with both eyes, while Murdoch et al. (1991) showed that participants with poor stereoacuity performed less accurately. There is no published work relating the Morrisby Fine Dexterity Test to either stereopsis or binocularity.

2 Methods

2.1 Participants

The participants were recruited at public science events at the Newcastle Centre for Life Science Centre and the Newcastle Literary and Philosophical Society. They included equal numbers of males and females, and ranged in age from 7 to 82 years. They had no experience of previous psychophysical experiments. Thirty participants completed the Morrisby test and 40 the buzz-wire game. Experiments were carried out in accordance with institutional regulations and the Declaration of Helsinki.

2.2 Monocular and binocular viewing

Participants were asked to perform each experiment three times: with binocular vision, or with vision in the left or right eye only. The order of the three conditions was randomised. In each condition, participants wore laboratory safety spectacles over their normal refractive correction, if any. In the monocular conditions, a sheet of 2-mm-thick opaque foam was inserted into one lens. In the binocular condition, foam was inserted at the periphery of each lens, so that the angular extent of the field of view was approximately the same as in the monocular condition, but symmetric about the midline.

2.3 Morrisby Fine Dexterity Test

The Morrisby Fine Dexterity Test (The Morrisby Organisation, www.morrisby.com/pages/public/dexterity-tests.aspx) is a commercial test used to assess candidates for tasks such as assembly of electronic components. Participants are presented with an array of small metal pegs and a dish of metal collars and washers. The task is to put a collar and two washers, in that order, onto each peg, completing as many pegs as possible within 2 minutes. Subjects first performed the “fingers task,” picking up the collars and washers with their fingers. Subjects then performed the “forceps task,” in which they used forceps in order to manipulate the collars and washers, rather than touching the items directly. (The commercial Morrisby test requires the use of forceps.) In each task, subjects used their dominant/preferred hand, and were given a 20-second practice session to familiarise them with the task before completing the task proper in the three viewing conditions (in a randomised order). Data were collected by author SFB.

2.4 Buzz-wire test

This is based on the children’s toys in which one must guide a wire loop around a complicated wire track without touching the loop to the track. A buzzing noise indicates whenever contact is made. In commercial versions of this toy, the wire track lies in a plane, which is typically oriented frontoparallel to the observer (Joy et al., 2001). To make the task more challenging and make stereopsis more useful, we used a custom-made track which followed a convoluted path in three dimensions (Figure 1 and Murdoch et al., 1991). To enable quantitative measurements, we also used an electronic timer, custom-made by author JT, which measured current through the wire and output the total time spent buzzing and the total number of separate contacts made with the wire (the number of hits). Total time spent on performing the task was recorded manually with a stopwatch. Data were collected by author AM.



Figure 1. Stereopair of the buzz-wire game used in the study. The image pair is suitable for cross-fusing, i.e. the left eye's view is on the right. The wooden base is 35 cm long.

2.5 Eye dominance

Participants were asked to report which was their dominant eye by viewing a distant object through a small hole formed by holding their hands up at arm's length. They closed each eye in turn and reported when the object jumped out of sight. The dominant eye was the one that was closed when this occurred.

2.6 Stereoacuity

Stereo thresholds were measured informally using the Randot Stereotest (Stereo Optical Co. Inc., www.stereooptical.com). Participants older than 10 performed the "Circles" test. This enables measurements of stereoacuity down to 20 arcsec. Six children younger than 10 performed the "Animals" test. All six scored the best available score of 100 arcsec, the other possible scores being 200 and 400 arcsec (or stereonegative).

3 Results

3.1 Morrisby Fine Dexterity Test

[Figure 2](#) shows results of the Morrisby Fine Dexterity Test for our 30 participants. [Figures 2\(a\)](#) and [\(b\)](#) show the mean number of pegs successfully completed in the 2 minutes, averaged across subjects, in each of the three different conditions: binocular viewing ("Binoc") and monocular viewing with the

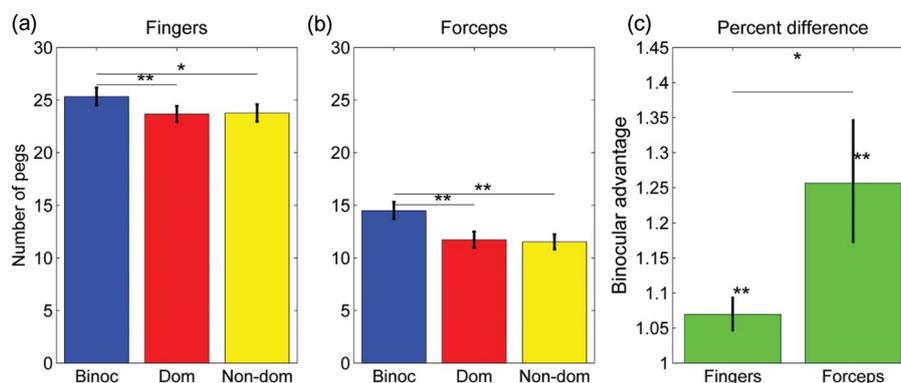


Figure 2. Performance on the Morrisby manual dexterity task, for monocular versus binocular viewing. (a–b) Number of pegs successfully completed within the 2-minute time period, averaged over all 30 subjects, with binocular viewing ("Binoc"), or monocular viewing with the dominant eye ("Dom") or non-dominant eye ("Non-dom"). (a) Using fingers; (b) using forceps. In each case, performance is significantly better with binocular viewing than with monocular viewing using either eye. Bar height shows the mean; error bars show ± 1 standard error on the mean. (c) The binocular advantage, i.e. ratio of number of pegs completed with binocular viewing to that for monocular viewing with the dominant eye, calculated for each subject individually and then averaged over all 30 subjects. Bar heights show geometric mean of the binocular advantage (equivalent to mean of $\log_{10}(\text{Binoc}/\text{Dom})$, raised to power 10); error bars mark ± 1 standard error on $\log_{10}(\text{Binoc}/\text{Dom})$.

dominant or non-dominant eye (“Dom” or “Non-dom”). All subjects completed each condition once. There was no difference between the two monocular conditions: subjects performed equally well whether they were viewing with their dominant or non-dominant eye. Similarly, subjects performed equally well with either left or right eye (data not shown). However, subjects completed more pegs when viewing with both eyes than with only one.

We used the paired-sample *t*-test to assess the significance of this difference. The *t*-test assumes the differences are normally distributed. The Jarque–Bera normality test (Matlab function JBTEST) did not reject the null hypothesis that the differences are normally distributed, indicating that a paired-sample *t*-test is appropriate. The difference in mean performance between binocular and monocular viewing was highly significant (asterisks in [Figures 2a](#) and [b](#)). [Figure 2\(c\)](#) examines the within-subject change, expressed as binocular advantage, i.e. ratio of number of pegs completed with binocular viewing to that for monocular viewing with the dominant eye. This shows that on average subjects performed about 7% better on the fingers task, and 25% better on the forceps task, when viewing binocularly. Both these binocular advantages were highly significant ($p = 0.004$ for fingers task; $p = 0.003$ for forceps task; *t*-test on log binocular advantage). Additionally, the binocular advantage was significantly greater for forceps ($p = 0.015$, paired *t*-test on log binocular advantage).

There was no clear evidence relating performance to stereoacuity. For example, we found no significant correlation between stereoacuity and percentage difference in performance between binocular versus monocular viewing. A median split analysis on stereo threshold did find a larger increase in performance with binocular viewing for subjects with good stereoacuity, especially on the forceps task, but this was not significant.

3.2 Buzz-wire task

[Figure 3](#) shows results of the buzz-wire task for our 40 subjects. In this task, we considered four different performance metrics: the total time taken to guide the hoop from start to finish, in seconds ([Figure 3a](#)); the time spent in contact with the wire, in seconds ([Figure 3b](#)) and as a percentage of total time ([Figure 3c](#)); and the number of separate occasions on which the hoop came into contact with the wire, irrespective of how long these lasted ([Figure 3d](#)). Since the distribution of some of these metrics was highly non-normal, we assessed significance with bootstrap resampling as described in the Appendix. Once again, there was no difference in performance for monocular viewing with the dominant versus non-dominant eye. However, on all four metrics, performance was very significantly better with binocular viewing.

[Figure 3\(e\)](#) expresses this improvement as binocular advantage. This time, since the metrics are such that higher numbers indicate worse performance, binocular advantage has to be defined as the ratio of the metric with monocular viewing to that with binocular viewing. Again, the improvement was very significant for all four metrics ($p < 0.0025$ for all four metrics, whether assessed by bootstrap resampling or *t*-test on log binocular advantage). The smallest change was in total time, where on average the time taken to do the task increased by one-third when participants could use only one eye. The largest time was in contact time, which increased on average nearly fivefold.

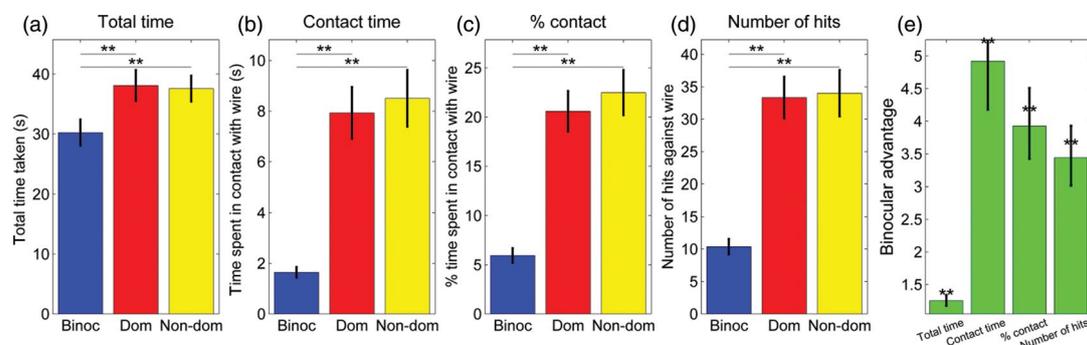


Figure 3. Performance on the buzz-wire task, for monocular versus binocular viewing. (a–d) Performance on four different metrics, with binocular viewing (“Binoc”), or monocular viewing with the dominant eye (“Dom”) or non-dominant eye (“Non-dom”). In every case, binocular performance is significantly better than either monocular condition. (e) Binocular advantage, i.e. ratio of the metric in the monocular-dominant condition to that in the binocular condition, calculated for each subject individually and then averaged over all 40 subjects. Other details are as in [Figure 2](#).

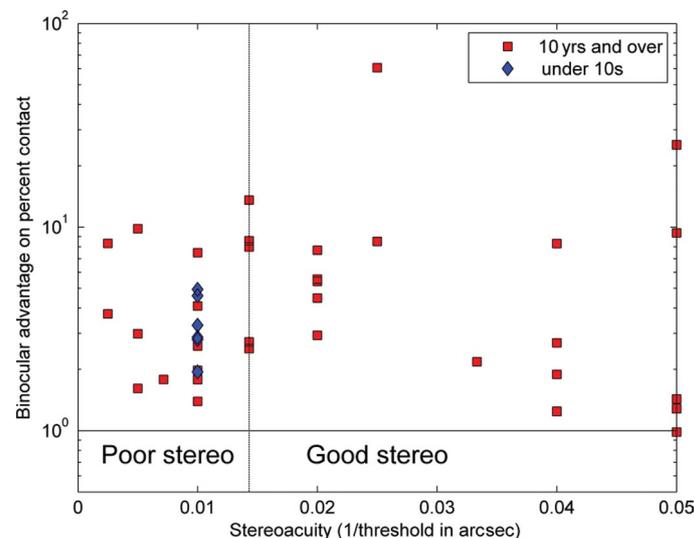


Figure 4. Binocular advantage on the buzz-wire task, % contact time metric, plotted against stereoacuity (reciprocal of stereo threshold in arcsec). The horizontal line shows a ratio of 1 (performance same in both conditions, no binocular advantage); the vertical dashed line shows the median stereoacuity, corresponding to a threshold of 70 arcsec. The mean stereoacuity corresponded to a threshold of 49 arcsec, and the upper and lower quartiles were 100 and 34 arcsec. Data for the six young children who were tested on the “Animals” stereotest are shown with blue diamonds. There was no significant correlation ($r = 0.12$, $n = 40$).

Again, we looked for a relationship with stereo thresholds. We found that subjects with below-median stereoacuity showed slightly worse performance in both monocular and binocular conditions (data not shown), and also a slightly smaller binocular advantage (Figure 4). However, these differences were small and not significant.

4 Discussion

On all tasks, individuals performed significantly better with binocular vision than with monocular. The difference was particularly pronounced when participants were using a tool to perform the task. On the Morrisby task where participants grasped the manipulanda directly with their fingers, the within-subjects difference was 5%. Where they used a tool (forceps), it was 15%. The binocular advantage was still more pronounced in the buzz-wire task. When subjects were viewing with both eyes, they held the hoop in contact with the track for only 6% of the time taken to complete the task (Figure 3c). When they were viewing with only their dominant eye, this increased to 21%: a massively significant 3.5-fold increase in error rate. This was not the result of a speed-accuracy trade-off, since the total time taken to complete the task also increased. In fact, performance was worse on all four metrics when subjects viewed monocularly. The longer time required with monocular viewing agrees with Joy et al. (2001), who compared performance in 6 binocular with 12 monocular participants (6 temporarily wearing an occluder over the non-dominant eye, and 6 who lacked binocular single vision long term). The ratio of the mean time taken in their occluded group to that in the binocular group was 1.3 (their Table 2), which is exactly the same value as in our data (Figures 3a and e). However, Joy et al. (2001) found no significant difference in accuracy, whereas we found even greater effects on accuracy than on time taken (Figure 3e). There are several differences between the two studies which may contribute to this difference. First, we made a within-subjects measurement of the effect of monocular versus binocular viewing, whereas Joy et al. measured differences between participants assigned to different conditions. Second, they have 6 participants in each condition, while we have 40. Both of these increase our effective statistical power and thus our chances of finding a significant relation. Finally and perhaps most significantly, the wire track shown in Joy et al. (their Figure 1) appears to lie in a plane, whereas ours and that of Murdoch et al. (1991) was in three dimensions. A 3D track requires the subject to move the loop in depth as well as in the frontoparallel plane, which could plausibly increase the need for accurate depth perception. This could be why we and Murdoch et al. found that monocular viewing and poor stereoacuity were associated with reduced accuracy, whereas Joy et al. did not.

Why is the binocular advantage greater on the buzz-wire task than on the Morrisby task? A key feature of the former task was that it required subjects to use their vision to avoid touching the wire,

removing haptic feedback. In the Morrisby task, although depth perception was impaired, subjects could still “feel their way” around, using proprioceptive information from the tool (Burton, [1993](#)). They were aiming to position the hole in the washer squarely over the peg, but if initially the edge of the washer was on the peg, they could still slide it into place with only minimal delay. In contrast, any haptic feedback of this kind was counted as an error in the buzz-wire task. Thus, the buzz-wire game represents a more demanding test of depth perception. Subjects also tended to move their body more while doing the buzz-wire task, and this may also have contributed to the difference.

Binocular viewing provides several possible advantages over monocular. These can be divided into two broad classes: depth cues which require comparison between the two eyes (disparity and vergence) and “bi-ocular” cues which simply require monocular information to be combined.

If the main advantage of binocular viewing were stereo depth from disparity, we might have expected a relationship between stereoacuity and either binocular advantage or absolute performance. Murdoch et al. ([1991](#)), using their version of the buzz-wire test, found that stereo-blind participants performed very significantly worse than those with normal stereoacuity. We also found that people with below-median stereoacuity performed worse, but this was not significant. One explanation could be that people with poor stereoacuity have learnt to compensate for this. Marotta et al. ([1995](#)) found that patients in whom one eye had been enucleated generate more head movements than binocular control subjects during a visually guided grasping task, presumably in order to exploit retinal motion parallax, while Shah et al. ([2003](#)) report that surgeons learn to reduce their reliance on stereopsis while performing endoscopic surgery where these cues are not present. We would then expect that people with poor stereoacuity would perform similarly under binocular and monocular conditions, while people with good stereoacuity would be relatively more impaired in the monocular condition. O’Connor et al. ([2010](#)) report exactly this effect for stereo-blind participants. Again, in our data the tendency was the same, but not significant. This may be because our data set included no participants who were completely stereo-blind.

Binocular viewing also offers a vergence cue. Previous work suggests that this may aid manual tasks independently of stereo disparity, especially at near distances such as used here (Bradshaw et al., [2004](#); Melmoth, Storoni, Todd, Finlay, & Grant, [2007](#); Mon-Williams & Dijkerman, [1999](#); Mon-Williams, Tresilian, McIntosh, & Milner, [2001](#); Tresilian & Mon-Williams, [2000](#); Tresilian, Mon-Williams, & Kelly, [1999](#); Viguier, Clement, & Trotter, [2001](#)). However, this work also indicates that vergence is a relative imprecise cue. Given that our tasks, especially the buzz-wire game, required accurate judgment of small distances, it seems unlikely that vergence cues alone would have provided fine enough information to reduce the error rate so substantially.

Binocular viewing also offers “bi-ocular” cues, which do not require information to be compared between eyes. First, it simply offers a wider field of view. Although we tried to equalise the total extent of the field of view, in our experiments the temporal limit of the visible field was smaller in the occluded eye in the monocular condition, and this may have affected performance. It is also possible that the conflict between visual information from the viewing and occluded eyes in our monocular condition may have artefactually impaired performance.

Finally, binocular viewing offers improved signal-to-noise simply by providing two copies of the same information, even where each eye’s information is processed separately. This results in better performance on a range of visual tasks, especially in poor lighting conditions (reviewed by Blake, Sloane, & Fox, [1981](#)). van Mierlo, Brenner, and Smeets ([2011](#)) recently showed that three stereo-blind observers performed substantially better on a complex structure-from-motion task when binocular information was available, even when the two eyes’ images were not correlated. This cannot be due to the “true binocular” cues of vergence and disparity, since disparities were not available in the uncorrelated condition and could not guide vergence. Thus, there is compelling evidence that bi-ocular cues can give an advantage on purely visual tasks. For visuomotor tasks, Jones and Lee ([1981](#)) argue that it is also due to a poorly defined “binocular concordance” between the eyes. Bradshaw et al. ([2004](#)) compared performance on a prehension task binocularly, monocularly and bi-ocularly (both eyes seeing identical views, providing the benefits of additional signal while removing disparity as a useful cue). They found that performance in the monocular and bi-ocular conditions was similar (and worse than for the binocular condition), and concluded that the binocular advantage was due to disparity. Other studies have argued that the visuomotor system integrates many cues in a statistically optimal way, and that the binocular advantage is due to a general reduction in uncertainty rather than to a critical role of specifically binocular cues (Keefe, Hibbard, & Watt, [2011](#); Loftus, Servos, Goodale, Mendarozqueta,

& Mon-Williams, 2004). Thus, while our data do not permit us to identify the source of the binocular advantage, the existing literature suggests that many cues probably contribute, notably but not exclusively binocular disparity.

Our original thesis was that the binocular advantage would be greater on tasks involving tools than in those simply involving prehension. Our results generally support this idea. The binocular advantage was significantly greater on the Morrisby test when that was completed with forceps than with fingers. However, this is not conclusive, as our results may suffer from a ceiling effect. That is, monocular performance with fingers may already have been so close to the limits imposed by non-visual constraints (maximum acceleration, etc.) that there was limited scope for improvement with binocular viewing.

The buzz-wire task lacks a tool-free control for comparison. Comparisons with previous studies are complicated by the fact that most previous comparisons of monocular and binocular performance on motor tasks have looked at differences in parameters such as grip aperture, rather than errors as such (Loftus et al., 2004; Marotta et al., 1995; Melmoth & Grant, 2006). Bradshaw et al. (2004) do have an error metric: when subjects knocked the object over instead of successfully grasping it. Monocular (or bi-ocular) viewing doubled the rate of such errors. O'Connor et al. (2010) report a 30% increase in time taken to complete a manual bead-threading task with monocular viewing. Schiller et al. (2012) compared monocular and binocular performance on two tasks involving tools: a "thread the needle" task and a task in which rods had to be inserted into tubes. Both are similar to the Morrisby task, in that haptic feedback from the tool is available at some cost in time. The time taken to complete the needle task nearly doubled with monocular viewing. Joy et al. (2001), using a 2D version of the buzz-wire task, found that participants viewing binocularly completed the task more quickly than those with one eye occluded, although they found no difference in accuracy. In our study, monocular viewing increased the time spent in contact with the wire by a factor of 4.8, while the percentage of contact time and the number of hits more than tripled. Thus, performance on the 3D buzz-wire game is uniquely sensitive to the loss of information associated with monocular viewing. This makes it particularly suitable for research into the function of binocular vision.

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References

- Barlow, H. B., Blakemore, C., & Pettigrew, J. D. (1967). The neural mechanisms of binocular depth discrimination. *Journal of Physiology*, *193*, 327–342. doi:10.1109/TBC.2005.846190
- Blake, R., Sloane, M., & Fox, R. (1981). Further developments in binocular summation. *Perception & Psychophysics*, *30*(3), 266–276. doi:10.1037/0096-1523.3.2.251
- Bradshaw, M. F., Elliott, K. M., Watt, S. J., Hibbard, P. B., Davies, I. R., & Simpson, P. J. (2004). Binocular cues and the control of prehension. *Spatial Vision*, *17*(1–2), 95–110. doi:10.1167/iovs.08-3229
- Burton, G. (1993). Nonneural extensions of haptic sensitivity. *Ecological Psychology*, *5*(2), 105–124. doi:10.1207/s15326969eco0502_1
- Fielder, A. R., & Moseley, M. J. (1996). Does stereopsis matter in humans? *Eye*, *10*(Pt 2), 233–238. doi:10.1007/s00221-004-1926-x
- Grant, S., Melmoth, D. R., Morgan, M. J., & Finlay, A. L. (2007). Prehension deficits in amblyopia. *Investigative Ophthalmology & Visual Science*, *48*(3), 1139–1148. doi:10.1167/iovs.06-0976
- Jones, R. K., & Lee, D. N. (1981). Why two eyes are better than one: the two views of binocular vision. *Journal of Experimental Psychology: Human Perception and Performance*, *7*(1), 30–40. doi:10.1136/bjo.85.5.619
- Joy, S., Davis, H., & Buckley, D. (2001). Is stereopsis linked to hand-eye coordination? *The British Orthoptic Journal*, *58*, 38–41. doi:10.1167/iovs.09-4434
- Julesz, B. (1971). *Foundations of cyclopean perception*. Chicago, IL: University of Chicago Press. doi:10.1002/bs.3830170307
- Keefe, B. D., Hibbard, P. B., & Watt, S. J. (2011). Depth-cue integration in grasp programming: No evidence for a binocular specialism. *Neuropsychologia*, *49*(5), 1246–1257. doi:10.1016/j
- Loftus, A., Servos, P., Goodale, M. A., Mendarozqueta, N., & Mon-Williams, M. (2004). When two eyes are better than one in prehension: Monocular viewing and end-point variance. *Experimental Brain Research*, *158*(3), 317–327. doi:10.1007/s00221-004-1905-2
- Marotta, J. J., Perrot, T. S., Nicolle, D., Servos, P., & Goodale, M. A. (1995). Adapting to monocular vision: Grasping with one eye. *Experimental Brain Research*, *104*(1), 107–114. doi:10.1007/BF00229860

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- Melmoth, D. R., & Grant, S. (2006). Advantages of binocular vision for the control of reaching and grasping. *Experimental Brain Research*, 171(3), 371–388. doi:10.1007/s00221-005-0273-x
- Melmoth, D. R., Storoni, M., Todd, G., Finlay, A. L., & Grant, S. (2007). Dissociation between vergence and binocular disparity cues in the control of prehension. *Experimental Brain Research*, 183(3), 283–298. doi:10.1007/s00221-007-1041-x
- Mon-Williams, M., & Dijkerman, H. C. (1999). The use of vergence information in the programming of prehension. *Experimental Brain Research*, 128(4), 578–582. doi:10.1007/s002210050885
- Mon-Williams, M., Tresilian, J. R., McIntosh, R. D., & Milner, A. D. (2001). Monocular and binocular distance cues: Insights from visual form agnosia I (of III). *Experimental Brain Research*, 139(2), 127–136. doi:10.1007/s002210000657
- Murdoch, J. R., McGhee, C. N., & Glover, V. (1991). The relationship between stereopsis and fine manual dexterity: Pilot study of a new instrument. *Eye*, 5(Pt 5), 642–643.
- O'Connor, A. R., Birch, E. E., Anderson, S., & Draper, H. (2010). The functional significance of stereopsis. *Investigative Ophthalmology & Visual Science*, 51(4), 2019–2023. doi:10.1167/iovs.09-4434
- Pettigrew, J. D. (1991). Evolution of binocular vision. In J. R. Cronly-Dillon & R. L. Gregory (Eds.), *The evolution of the eye and visual system* (pp. 271–283). Boca Raton, FL: CRC Press. doi:10.1242/jeb.032615
- Sachdeva, R., & Traboulsi, E. I. (2011). Performance of patients with deficient stereoacuity on the EYESi microsurgical simulator. *American Journal of Ophthalmology*, 151(3), 427–433.e1.
- Schiller, P. H., Kendall, G. L., Kwak, M. C., & Slocum, W. M. (2012). Depth perception, binocular integration and hand-eye coordination in intact and stereo impaired human subjects. *Journal of Clinical & Experimental Ophthalmology*, 3(2). doi:10.4172/2155-9570.1000210
- Shah, J., Buckley, D., Frisby, J., & Darzi, A. (2003). Depth cue reliance in surgeons and medical students. *Surgical Endoscopy and Other Interventional Techniques*, 17(9), 1472–1474. doi:10.1007/s12262-010-0118-0
- Suttle, C. M., Melmoth, D. R., Finlay, A. L., Sloper, J. J., & Grant, S. (2011). Eye-hand coordination skills in children with and without amblyopia. *Investigative Ophthalmology & Visual Science*, 52(3), 1851–1864. doi:10.1167/iovs.10-6341
- Tresilian, J. R., & Mon-Williams, M. (2000). Getting the measure of vergence weight in nearness perception. *Experimental Brain Research*, 132(3), 362–368. doi:10.1007/978-3-540-73055-2_42
- Tresilian, J. R., Mon-Williams, M., & Kelly, B. M. (1999). Increasing confidence in vergence as a cue to distance. *Proceedings of the Royal Society B: Biological Sciences*, 266(1414), 39–44. doi:10.1117/12.790387
- van Mierlo, C. M., Brenner, E., & Smeets, J. B. (2011). Better performance with two eyes than with one in stereo-blind subjects' judgments of motion in depth. *Vision Research*, 51(11), 1249–1253. doi:10.1007/BF00155209
- Viguiet, A., Clement, G., & Trotter, Y. (2001). Distance perception within near visual space. *Perception*, 30(1), 115–124. doi:10.1068/p3119
- Webber, A. L., Wood, J. M., Gole, G. A., & Brown, B. (2008). The effect of amblyopia on fine motor skills in children. *Investigative Ophthalmology & Visual Science*, 49(2), 594–603. doi:10.1167/iovs.07-0869

Appendix: Bootstrap resampling

Since many of the metrics under investigation are distributed non-normally, the statistical significance of differences between conditions was evaluated using bootstrap resampling. The precise procedure was as follows.

Let B_j and M_j represent the performance of subject j in the binocular and monocular conditions, respectively, and let $D_j = B_j - M_j$ be the difference in performance for this subject. The mean within-subjects difference is $W_o = \langle D_j \rangle$, where the angle brackets represent the mean over all N subjects. We evaluate the significance of this mean difference by resampling. The null hypothesis is that there is no difference in the distribution of X in monocular versus binocular viewing. Under this hypothesis, individual values of D_j are as likely as $-D_j$. The set used for resampling is therefore $R = \{D_j - D_j\}$. We generated each set of resamples by picking N values, with replacement, from the set R . The mean of these N values, W_k , is the mean within-subjects difference for the k th resampling run. We repeat this process $n = 10,000$ times, and see what fraction of the resampled W_k exceeds the magnitude of the original W_o . This is the (two-tailed) significance of the difference, i.e.

$$p = \frac{1}{n} \sum_{k=1}^n H(|W_k| - |W_o|),$$

where H is the Heaviside step function: $H(x) = 1$ if $x \geq 0$, and 0 otherwise. This procedure was used to test the significance of differences between the conditions in [Figures 3\(a–d\)](#). To compute the significance of the mean within-subjects percentage difference, as in [Figure 3\(e\)](#), we followed the same procedure as applied to the percentage differences, $P_j = 100(B_j - M_j)/B_j$, instead of to the differences D_j .



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Shah Farzana Begum participated in the project researching the differences between monocular and binocular viewing, during a 6-week summer placement. Farzana is now in her first year studying Physiology at the University of Liverpool.



Alice McDonald is currently studying History of Art at the University of York. She enjoys many different activities in her spare time including badminton, singing and being a reporter for Radio York. She thoroughly enjoyed doing the research project as it opened her eyes to varying opportunities available within the world of research and allowed her the exciting opportunity to create her own research project and collect data.



Jack Trowbridge lives in Castleside, County Durham, and attends Queen Elizabeth High School in Hexham. Having completed his electronics GCSE a year early, attaining an A*, he is due to complete the rest of his GCSEs in 2013 and has ambitions to do a degree in Mechanical Engineering at Newcastle University. Jack has many interests; he is keen on electronics and has designed and built numerous projects. He is also a keen software programmer and has published mobile phone apps on the Android marketplace.