Is Vergence an Absolute Distance Cue?

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Abstract

Since Kepler (1604) and Descartes (1638), 'vergence' (the angular rotation of the eyes) has been thought of as one of our most important absolute distance cues. But vergence has never been tested as an absolute distance cue divorced from obvious confounding cues such as binocular disparity. In this article we control for these confounding cues for the first time by gradually manipulating vergence, and find that observers fail to accurately judge distance from vergence. We consider a number of different interpretations of these results, and argue that rather than adopt an ad-hoc reinterpretation of vergence as blind to gradual changes, or ineffective when static, the most principled response to these results is to question the general effectiveness of vergence as an absolute distance cue. cue. Given other absolute distance cues (such as motion parallax and vertical disparities) are limited in application, this poses a real challenge to our contemporary understanding of visual scale.

Keywords: Distance Perception; Visual Scale; 3D Vision; Vergence; Accommodation

1. Introduction

The closer an object is, the more the eyes have to rotate towards one another to fixate on it (Fig.1). Since Kepler (1604) and Descartes (1637), 'vergence' (this angular rotation of the eyes) has been thought of as one of our most important absolute distance cues (Howard, 2012; Rogers, 2017). In the contemporary literature this is often articulated as an ability to 'triangulate' absolute distance (Parker, Smith, & Krug, 2016; Banks, Hoffman, Kim, & Wetzstein, 2016).

Because the angular rotation of the eyes drops off with the arctan of the viewing distance (Fig.1) vergence's effective range as a distance cue is often thought to be limited to 2-3m (Howard, 2012). However, within reaching space, two studies demonstrate the effectiveness of vergence as an absolute distance cue: First, Mon-Williams & Tresilian (1999) asked subjects to point with a hidden hand to the distance of a point of light after the vergence of the left eye had been manipulated using a prism. They found a strong linear relationship between vergence and perceived distance ($y = 0.86x + 6.5$) for distances between 20cm and 60cm (Fig.1). Second, Viguier, Clément, & Trotter (2001) presented subjects with a 0.57° disc at distances between 20cm and 80cm for 5 seconds, and then after another 5 seconds in darkness, asked subjects to match the

distance with a visible reference. They found subjects were close to veridical for 20cm, 30cm, and 40cm, but increasingly underestimated distances beyond that: 60cm was judged to be 50cm, and 80cm was judged to be 56cm (Fig.1).

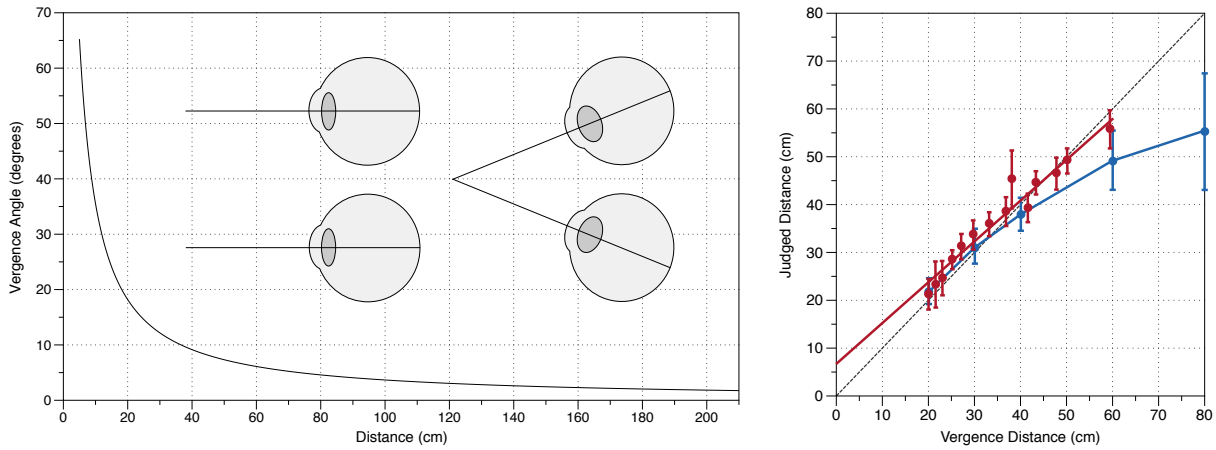

Figure 1. Distance from Vergence. Left panel illustrates how the vergence angle changes with fixation distance. Right panel illustrates the results of distance from vergence in Mon-Williams & Tresilian (1999) (in red, $y = 0.86x + 6.5$), and Viguier, Clément, & Trotter (2001) (in blue), compared to veridical performance (the black dotted line) as plotted by the authors.

Viguier, Clément, & Trotter (2001) conclude: "…in agreement with previous studies (Von Hofsten 1976; Foley 1980; Brenner & van Damme 1998; Mon-Williams & Tresilian 1999; Tresilian et al. 1999) the results of our experiment indicate that vergence can be used to reliably evaluate target distance. This is particularly effective in the near visual space corresponding to arm's length." And, in light of Mon-Williams & Tresilian (1999) and Viguier et al. (2001), the current consensus is that vergence is a highly effective absolute distance cue within reaching space (Howard, 2012; Banks et al., 2016; Scarfe & Hibbard, 2017; and related experimental results in Naceri, Chellali, & Hoinville, 2011; Swan, Singh, & Ellis, 2015; Naceri, Moscatelli, & Chellali, 2015; Campagnoli, Croom, & Domini, 2017).

However, our concern is that studies (such as Mon-Williams & Tresilian, 1999 and Viguier et al., 2001) that appear to confirm vergence as an effective absolute distance cue do not control for three confounding cues.

1. Retinal Disparity (Diplopia): If the observer's vergence is at a resting state, then when the target is initially presented at 20cm it is going to be seen as double. But we know from Morrison

& Whiteside (1984) that diplopia (double vision) can be an effective absolute distance cue. Morrison & Whiteside (1984) found that 90% of performance in estimating the distance of a point of light between 0.5m-9.2m could be attributed to diplopia, since performance was only degraded by 10% when the stimuli were shown for a brief period (0.1-0.2s; too quick for a vergence response) as opposed to an extended period.

2. Motion on the Retina: The second confounding cue is the motion of the target on the retina as it moves from the retinal periphery to the fovea during vergence. When the stimulus is an isolated target viewed in darkness (as it was in Mon-Williams & Tresilian, 1999 and Viguier, Clément, & Trotter, 2001), subjects will literally watch the two targets streak towards each other across the visual field. Given plausible assumptions about our vergence resting state (that our vergence is beyond arms reach when our eyes are relaxed), the motion of the target across the visual field could be used to inform subjects about the absolute distance of the target.

3. Conscious Awareness of our Vergence Eye Movements: If subjects have to make sudden fixational eye movements in a response to a target presented as close as 20cm, they will inevitably be consciously aware of their own eye movements. If subjects have little or no other absolute distance information, they are going to attend to these consciously felt muscular sensations and attach a lot of weight to them. But this is not how we judge distances in everyday viewing (cf. Berkeley, 1709 who argued that it is). Instead, the suggestion is that the visual system unconsciously processes muscle movements that we don't notice (sub-threshold extraocular muscle proprioception) or eye movement plans we don't know about (efference copy). Consequently, it is important to focus on sub-threshold vergence eye movements (eye movements that subjects don't notice) if we are to get a better understanding of how vergence actually contributes to distance perception everyday viewing.

To summarise, the extensive literature on vergence as an absolute distance cue tests vergence in the presence of an obvious confounding cue (binocular disparity) and in a way that is divorced from everyday viewing (conscious awareness of eye movements). The concern binocular disparity might explain the experimental results, is not new: it formed the basis of Hillebrand (1894)'s critique of Wundt (1862). So why, a century on, has this concern yet to be addressed? The answer is that vergence is either driven by disparity or we have to inform the subject about the change in distance in some other way (e.g. tracking their hand whilst observing an after-image: Taylor, 1941; Gregory, Wallace, & Campbell, 1959). Which poses a dilemma: either we test the

effectiveness of vergence as an absolute distance cue in the presence of an obvious confounding cue (binocular disparity), or we inform the subject about the very thing (absolute distance) that we are asking them to judge.

The only alternative is to manipulate vergence gradually so that even the changes in disparity that drive vergence are sub-threshold. This may appear to be an artificial way of manipulating vergence. But since we believe that it is pointless to test the effectiveness of vergence in the presence of an obvious confound, we choose to pursue this option in Experiment 1 and Experiment 2, and then explain in the Discussion why we think that the gradual manipulation of vergence still provides us with a valid insight into everyday viewing.

Experiment 1

Methods

The purpose of Experiment 1 was to replicate Mon-Williams & Tresilian (1999) (by having subjects point to the distance of a point of light between 20cm and 50cm) whilst controlling for retinal disparity and the conscious awareness of eye movements by gradually changing vergence between trials whilst observers were looking at a fixation target. The apparatus consisted of a viewing box similar to Mon-Williams & Tresilian (1999)'s (45cm high, 28cm wide, and 90cm long) (Fig.2). The inside of the box was painted with blackout paint mixed with sand (a standard technique for optical equipment: see Gerd Neumann Jr in bibliography).

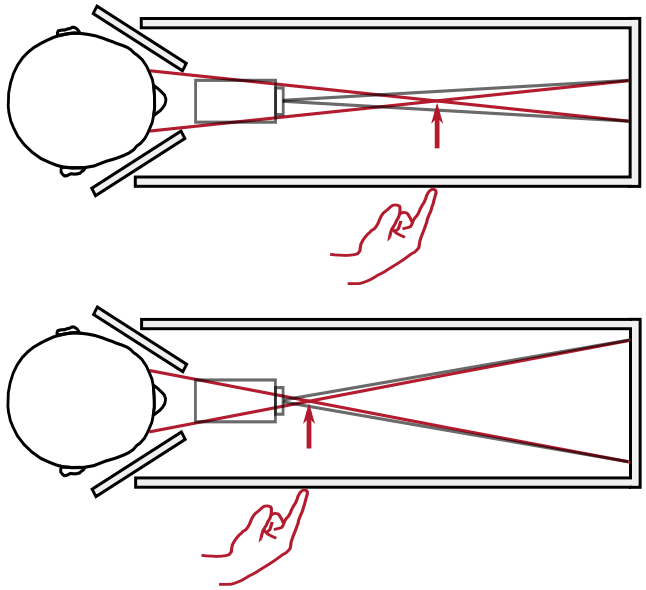

Figure 2. Apparatus for Experiment. Laser projector (in grey) projects two stimuli onto a black metal plate at the end of the apparatus (grey lines). Occluders either side of the head ensure left eye only sees right stimulus, and right eye sees left stimulus (red lines). Vergence specified distance (indicated by red arrow) is manipulated by increasing / decreasing the distance between the two stimuli (compare the upper and lower panels).

Mon-Williams & Tresilian (1999)'s experimental set-up is altered in two fundamental ways:

1. Stimulus alignment: Mon-Williams & Tresilian (1999) align their stimuli with the subject's right eye, and only vary the vergence demand of the left eye. This approach has two shortcomings: First, it leads to an asymmetric vergence demand. For a 20cm target aligned with the right eye, the vergence demand is 17.75° for the left eye and 0° for the right eye, rather than 8.81° for each eye. In normal viewing conditions such extreme asymmetries are eradicated by head rotation. Second, the stimulus is liable to be perceived as drifting rightwards as it gets closer: at 50cm a stimulus aligned with the right eye is offset from the subject's midline by 3.5°, whilst at 20cm it is offset by 8.8°.

2. Stimulus presentation: We use a laser projector (Sony MP-CL1A), fixed 25cm in front and 5cm below the line of sight, to project the stimuli onto the back wall of the apparatus. In piloting we found that this was the only cost-effective way to ensure that the stimulus was viewed in perfect darkness (lasers emit no light for black pixels, eradicating the residual luminance of CRTs and LED displays). The stimuli were presented at eye level using PsychoPy (Peirce, 2007;

2009; Peirce et al., 2019). They comprised of (a) a fixation target (300 green dots located within a 1.83° circle, with the dots randomly relocating every 50ms within the circle) (Fig.3), and (b) a single green dot that subjects had to point to. The fixation target changed in size sinusoidally between 1.83° and 0.91° at 1Hz. The shimmering appearance and constantly changing size of the fixation target ensured that as the vergence demand was varied, any residual motion-in-depth from retinal slip would be hard to detect.

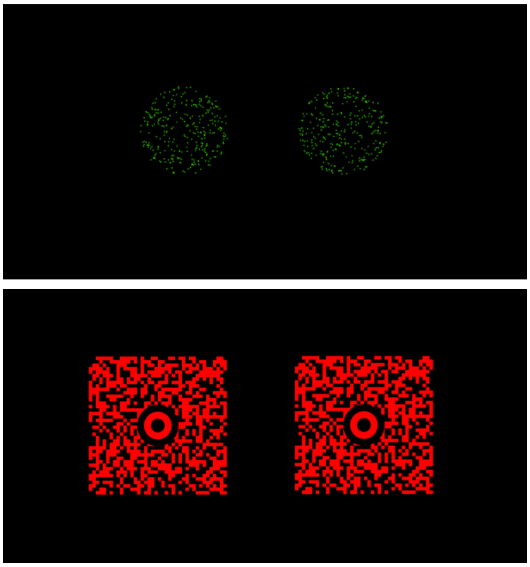

Figure 3. Fixation Targets for Experiment 1 (top) and Experiment 2 (bottom).

The experimental protocol set the initial vergence distance to 50cm. During the first trial, that was longer than the subsequent trials, the vergence distance was varied over 32 seconds from 50cm to 29cm (the centre of the range) as the subjects looked at the fixation target. After 32 seconds, a point was presented at 29cm and the subject had to point to its distance on the side of the box. In each subsequent trial the vergence distance was stepped up or stepped down over 15 seconds by one step in a pseudo-random walk that covered 7 vergence-specified distances (20cm, 22cm, 25cm, 29cm, 34cm, 40cm, and 50cm). Each subject completed 96 trials, with the pseudo-random ensuring that each of the 7 distances was tested at least 10 times.

All subjects were naïve as to the purpose of the experiment, and subjects were completely naïve about the experimental set-up. They did not see the room or apparatus beforehand, which was sealed off by a curtain, and they were wheeled into the experimental room wearing a blindfold. Their hand was guided to a head and chin rest, and they had to ensure their head was in place, with

a further hood of blackout fabric pulled over their head, before they could take the blindfold off. This procedure, coupled with the fact that the box was sealed, and the illumination in the room outside the box was reduced to a low-powered LED, ensured that the stimulus was viewed in perfect darkness.

After the main experiment was complete, a control study was run in full-cue conditions to confirm Mon-Williams & Tresilian (1999)'s and Swan et al. (2015)'s findings that hidden hand pointing is a good reporting mechanism for perceived distance. The control replicated the head and chin rest, and right-hand wall, of the original apparatus, but removed the top, back, and left-hand wall, enabling a familiar object (a 510g Kellogg's Rice Krispies box) to be seen in full-cue conditions. Subjects pointed to the front of the cereal box with a hidden hand in 3 sets of trials that ensured 10 trials in total for each of the 7 distances (20cm, 22cm, 25cm, 29cm, 34cm, 40cm, and 50cm). One subject (SM) was unable to return to complete the control.

The observers were 12 acquaintances of the author (9 male, 3 female; ages 28-36, average age 31.2) who indicated their interest to volunteer for the study in response to a Facebook post. Observers either did not need visual correction or wore contact lenses (no glasses). All observers gave their written consent, and the study was approved by the School of Health Sciences Research Ethics Committee, City, University of London in accordance with the Declaration of Helsinki. Three preliminary tests were performed to ensure that (a) the subjects' arm reach was at least 60cm, (b) their convergence response was within normal bounds (18D or above on a Clement Clarke Intl. horizontal prism bar test), and (c) that their stereoacuity was within normal bounds (60 sec of arc or less on a TNO stereo test).

Results

The results in Experiment 1 are reported in Figure 4.

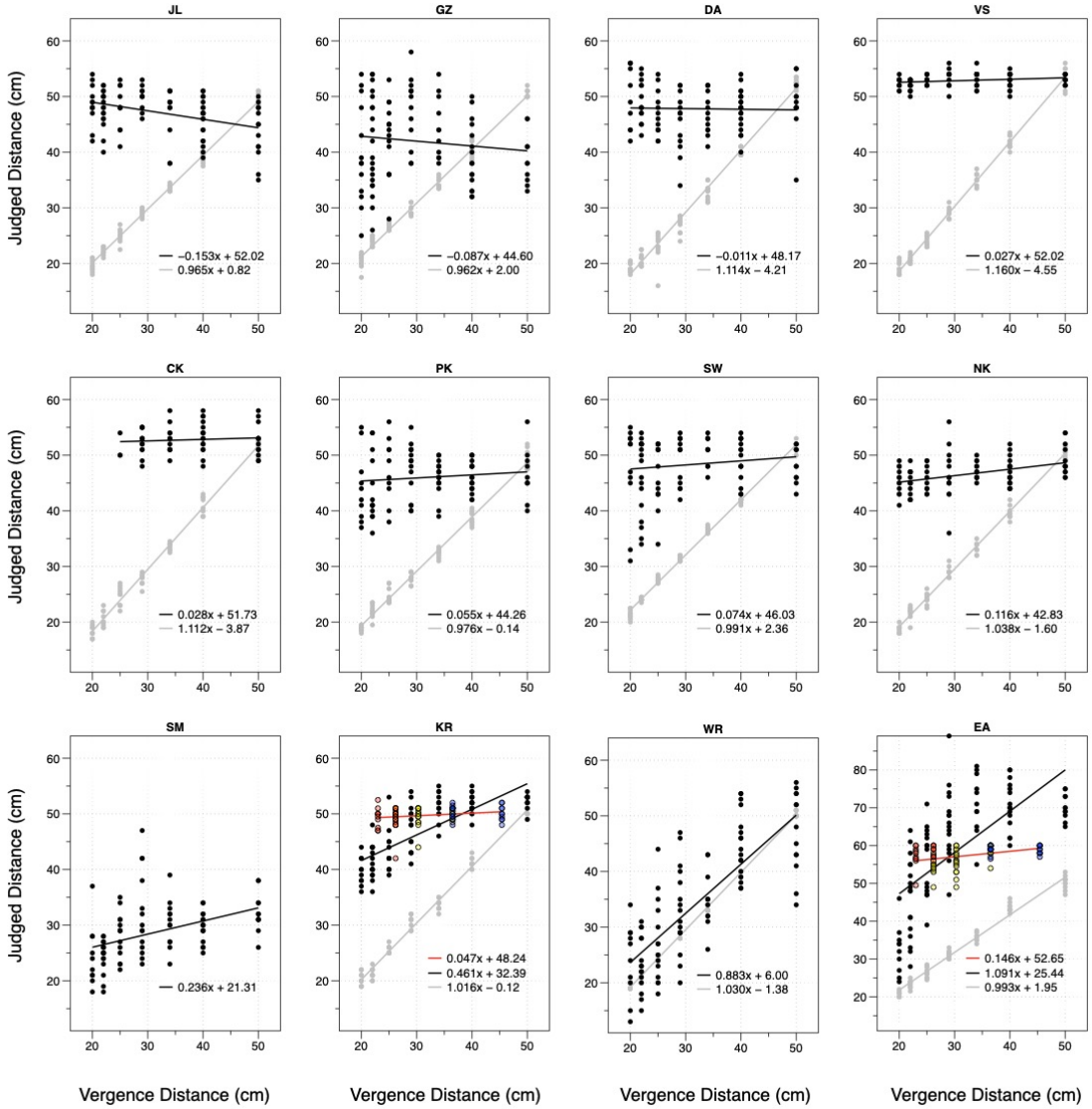

Figure 4: Individual Results for 12 Subjects in Experiment 1. Grey dots and grey line indicate performance in full-cue condition. Black dots and black line indicate performance in vergence-only condition. Coloured dots and red line for subjects KR and EA indicate revised performance in Experiment 2 (the colour of the dots indicates accommodative demand: ● = –4.15D, ● = –3.15D, and ● = –2.15D).

The data were analysed using a linear mixed-effects model (Pinheiro & Bates, 2000) in R (R Core Team, 2012) using the lme4 package (Bates, Maechler, & Bolker, 2012), with pointed distance (y) a combination of a fixed-effect of vergence distance (x), and a random-effect of each participant

(x | Subject), so that: $y \sim x + (x \mid \text{Subject})$. All data and analysis scripts are accessible in an open access repository: https://osf.io/2xuwn/

As expected, hidden-hand pointing in full-cue condition is close to veridical: $y = 1.032x - 0.76$ (with 95% confidence intervals of 0.992 to 1.071 for the slope, and –2.36 to 0.73cm for the intercept). However, it is a different story when vergence is the only cue. We clustered a histogram of the slopes in Fig.4 using the mclust5 package (Scrucca, Fop, Murphy, & Raftery, 2017), and found that the results were best explained by two populations of equal variance:

1. 10 out of the 12 subjects had a slope indistinguishable from 0 ($y = 0.074x + c$). Using a linear mixed-effects model we estimated the slope and intercept for these 12 observers to be $y = 0.075x + 43.52$ (with 95% confidence intervals of –0.035 to 0.183 for the slope, and 37.12 to 49.70 for the intercept).

2. 2 out of the 12 subjects (EA and WR) had a slope indistinguishable from 1 ($y = 0.983x + c$). Using a linear mixed-effects model we estimated the slope and intercept for these 2 observers to be $y = 0.987x + 15.72$ (with 95% confidence intervals of 0.747 to 1.219 for the slope, and –3.94 to 36.13 for the intercept).

Vergence is an ineffective absolute distance cue for the vast majority of our subjects. However, how do we explain the performance of WR and EA? Both of them, along with the subject with the third highest gain (KR), reported symptoms consistent with vergence-accommodation conflict: EA and KR reported using the change in size of the dot with defocus as a cue to distance, whilst WR complained of significant eye strain, describing the experiment as "exhausting" for his eyes (and abandoned a revised version of the experiment as being "painful" and "quite exhausting for his eyes" after just six trials). We hypothesised that the performance of these three subjects relied on vergence-accommodation conflict, rather than vergence being an effective absolute distance cue. The purpose of Experiment 2 was to test whether their performance would disappear once vergence-accommodation conflict had been controlled for, as well as testing 12 new participants using our revised experimental paradigm that controlled for vergence-accommodation conflict.

Experiment 2

Methods

In Experiment 2, vergence / accommodation conflict was kept within reasonable bounds (+/–1D, within the 'zone of clear single binocular vision': Hoffman, Girshick, Akeley, & Banks, 2008) by dividing the trials into Near (23cm to 30cm), Middle (23cm to 45.5cm), and Far (30cm to 45.5cm) trials, and testing each of these with different lenses to ensure that:

- Near: Accommodation set at 24cm (–4.15D) was used to test vergence at 23cm, 26cm, and 30cm.

- Middle: Accommodation set at 32cm (–3.15D) was used to test vergence at 23cm, 26cm, 30cm, 36.5cm, and 45.5cm.

- Far: Accommodation set at 47cm (–2.15D) was used to test vergence at 30cm, 36.5cm, and 45.5cm.

In addition the fixation target (Fig.3) was made larger (2.4° x 2.4°) and higher contrast in order to aid accommodation. Rather than changing in angular size, the fixation target now varied in luminance (between 100% and 50% of its initial luminance, at 2Hz). To increase contrast, stimuli were projected onto a white screen 156cm away from the observer, rather than a black metal plate 90cm away. To ensure this increase in illumination did not also illuminate the apparatus, black fabric was added to ensure a narrow viewing window, and red filters from red-cyan stereo-glasses (blocking ≈100% green light, ≈90% blue light) were added in front of each eye. In a separate preliminary experiment using an autorefractor, these filters were found to have no impact on accommodation.

The experimental protocol set the initial vergence distance to 50cm. During the first trial, that was longer than the subsequent trials, the vergence distance was varied over 50 seconds from 50cm to the centre of the range (26cm for Near trials, 30cm for Middle trials, and 36.5cm for Far trials) as the subjects looked at the fixation target. In each subsequent trial the vergence distance was stepped up or stepped down over 30 seconds by one step in a pseudo-random walk that covered

the vergence-specified distances. The 12 new participants completed 7 sets of 20 trials (2 Near, 3 Middle, and 2 Far) that ensured that each combination of accommodation and vergence was tested at least 10 times. For the subjects from Experiment 1 a reduced version of the experiment was constructed: 4 sets of 20 trials (1 Near, 2 Middle, and 1 Far) with 23cm and 26cm tested in Near; 26cm, 30cm, and 36.5cm tested in Middle; and 36.5cm and 45.5cm tested in Far. Subject WR from Experiment 1 was unable to return, but subjects KR and EA returned to complete this experiment.

The 12 new participants were 12 City, University of London undergraduate students (8 female, 4 male; age range 18-27, average age 20.8) recruited through flyers and Facebook posts. All subjects were naïve as to the purpose of the experiment. The same exclusion criteria as Experiment 1 were applied, with the additional requirement that subjects' accommodative responses (tested with a RAF near-point rule) were within normal bounds. The study was approved by the School of Health Sciences Research Ethics Committee, City, University of London in accordance with the Declaration of Helsinki, and all subjects gave their written consent. The undergraduate students were paid £10/hr + a £20 completion bonus.

Results

The results for the two subjects from Experiment 1 (KR and EA) are reported alongside their Experiment 1 performance in Figure 4. We find a dramatic reduction in their performance once vergence / accommodation conflict has been controlled for: EA's previous performance of $y = 1.091x + 25.44$ drops to $y = 0.146x + 52.65$, whilst KR's previous performance of $y = 0.461x + 32.39$ drops to $y = 0.047x + 48.24$ (both drops in performance are significant to $p < 0.001$). This confirms the hypothesis that their performance in Experiment 1 was driven by vergence-accommodation conflict, rather than vergence being an effective absolute distance cue.

The results for the 12 new participants are summarised in Figure 5, with individual results reported in Figure 6.

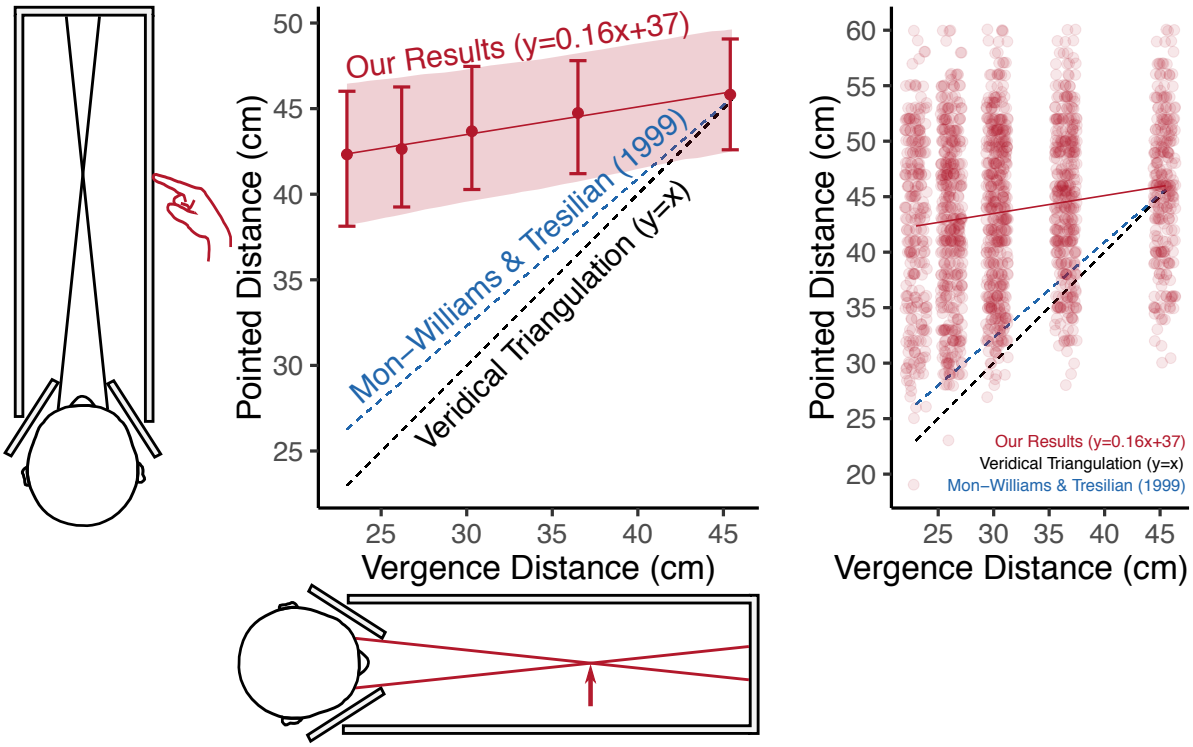

Figure 5. Summary of Results from Experiment 2 when Vergence and Accommodation are the only cues to Distance. On the x-axis is the vergence-specified distance, and on the y-axis the pointed distance. The left panel illustrates averaged results. The error bars represent bootstrapped 95% confidence intervals across observers. The error band represents the bootstrapped 95% confidence interval of the linear mixed-effects model. The right panel plots the raw trial data across observers as a jitter plot.

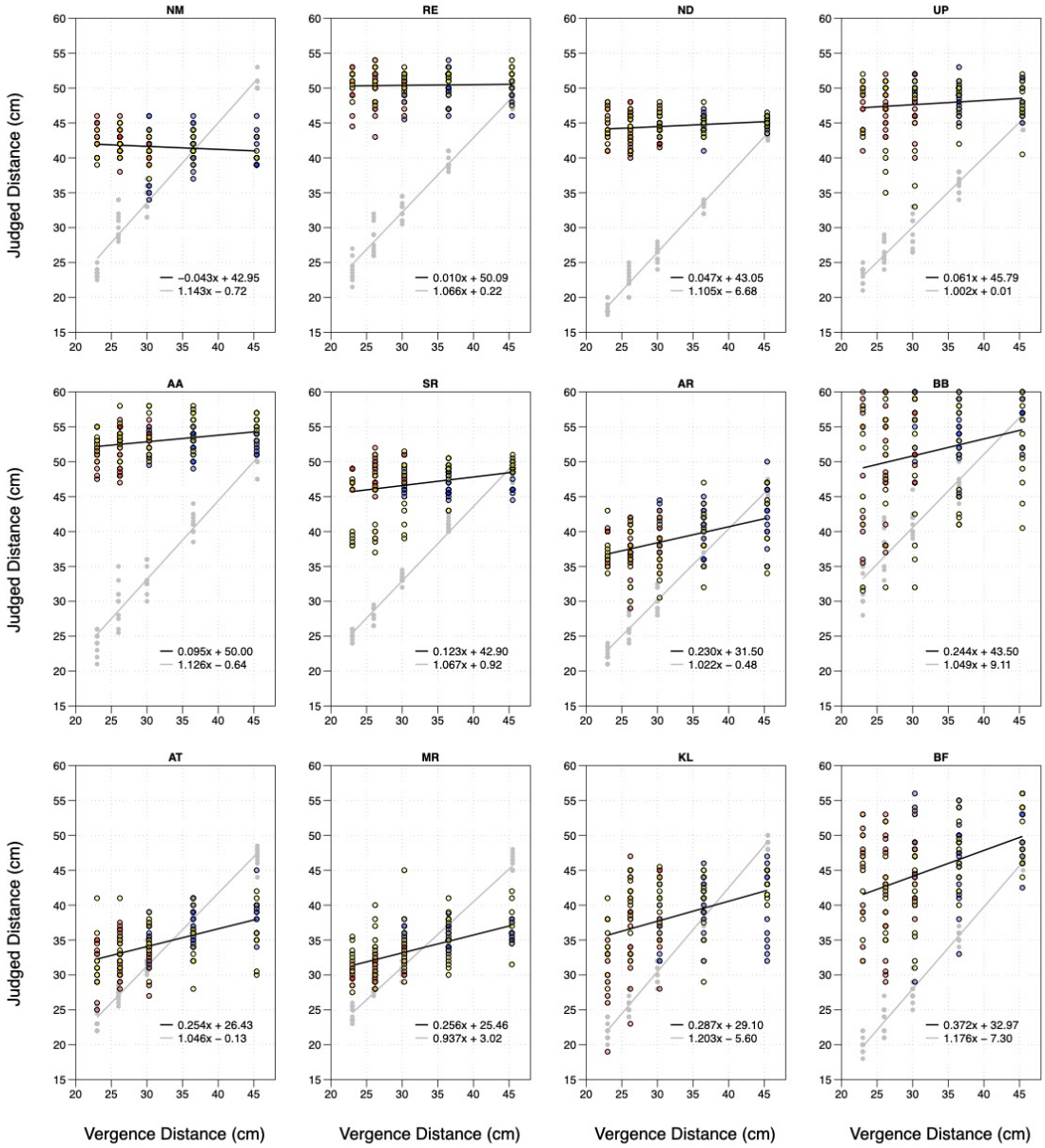

Figure 6: Individual Results for 12 Subjects in Experiment 2. Grey dots and grey line indicate performance in full-cue condition. Coloured dots and black line indicate performance in vergence and accommodation-only condition (colour of the dots indicates accommodative demand: ● = –4.15D, ● = –3.15D, and ● = –2.15D).

As expected, the 12 new subjects were also close to veridical in the full-cue control condition: $y = 1.078x - 0.69$ (with 95% confidence intervals of 1.036 to 1.122 for the slope, and –3.19 to 1.81 for

the intercept). By contrast, when vergence and accommodation were the only cues to absolute distance their performance had three defining features: 1. Low gains, 2. High variability, and 3. No benefit from accommodation:

1. Low Gains: We clustered the slopes in Fig.6 using the mclust5 package and found that a single population with an average slope of $y = 0.161x + c$ best fits the data (although this was only marginally better than two populations with equal variance). Using a linear mixed-effects model we estimate the slope and intercept to be $y = 0.161x + 38.64$ (with 95% confidence intervals of 0.090 to 0.239 for the slope, and 33.43 to 43.36cm for the intercept). This confirms similar findings for 11 of the 12 participants in Experiment 1 (when we include KR and EA's revised results), with the 12th participant unable to return. On the basis of these results we are confident that this is a highly replicable finding.

2. High Variability: The high degree of variance in the results is best illustrated by the raw data of the 12 subjects (Figure 5, right panel). There is little evidence of a specific distance tendency (Gogel, 1969). Instead, subjects appear to be effectively guessing.

Indeed, we were struck by the high degree of variance in the results of the 6 subjects with above average slopes. To quantify this variance we estimated the standard deviation of the residual error (i.e. how much each of those 6 subjects departed from their own line of best fit in Figure 6), after correcting for motor error (assuming that perceptual error and motor error are independent). We did this by attributing all of the variance in the full-cue control condition to motor error (an intentional overestimate) in order to produce a conservative estimate of the residual error using the following formula:

$$\sigma_{residual} = \sqrt{{\sigma_{vergence}}^2 - {\sigma_{control}}^2}$$

Limiting ourselves to ± 2 standard deviations from the slope of best fit to rule out any outliers, we find an average residual error for those 6 subjects of 17cm. Given the range of the experiment itself was 22.5cm, one is left questioning just how functionally useful an absolute distance cue with this degree of variance could be.

3. No Benefit from Accommodation: It has been shown that accommodation can contribute absolute distance information, although it is subject to a high degree of variance (Fisher &

Ciuffreda, 1988; Mon-Williams & Tresilian, 2000). But we found no effect on absolute distance of varying accommodation by two dioptres. We compared the line of best fit when (a) accommodation was varied in line with vergence for 23cm, 30cm, and 45.5cm, to the line of best fit when (b) accommodation was fixed at 30cm for all three distances. We found a slight reduction in performance when accommodation was varied ($y = 0.147x + 38.91$) vs. when accommodation was fixed ($y = 0.176x + 38.02$), but this effect was not statistically significant. We certainly didn't find the improvement in performance that one would expect if accommodation were a complementary absolute distance cue to vergence.

4. Discussion

We believe that these results show that vergence and accommodation are ineffective absolute distance cues once confounding cues have been controlled for. The key criticism of this conclusion is that vergence was gradually manipulated in an artificial way during our experiments. But this is inevitable if we are to test vergence in the absence of confounding cues such as retinal disparity. And we can have no confidence that vergence is an absolute distance cue if it is only effective when it is tested in the presence of confounding cues.

The distance estimates of some of the participants in Experiment 2 were biased by vergence. But this is not evidence of unconscious processing of the vergence signal. Instead, the subjects with the highest gains reported responding to consciously felt muscular sensations from intense sustained near fixation. For instance BF, the subject with the highest gain, reported that the experiment was "messing up my accommodation":

> "I could feel my eye are working, my eyes are focusing then relaxing then focusing."
>
> "I really had to focus to stop them going two … the target started to separate when I didn't really focus on it."
>
> "I usually get the same sensation when I'm up too late and doing some studies – a slight strain in the eye, it's not too bad, it's just that you really have to focus."

Similarly KL, the subject with the second highest gain, reported that with near targets she felt her "eyes accommodating a lot to get them to work." So, whilst our experimental paradigm effectively controlled for the conscious muscular sensations that accompany eye movements (kinaesthesia), it failed to control for the conscious muscular sensation of sustained near fixation (proprioception).

Such muscular sensations are rarely felt in everyday viewing, and appear to be a shortcoming of manipulating vergence and accommodation as pure optical reflexes (see Charman & Heron, 2015 for similar concerns about Badal systems).

In the remainder of this Discussion we explore two alternative explanations for these results that have been put to us, and explain why we do not find these alternative explanations convincing. Our starting point is that we should be very reluctant to try and construct ex post and ad hoc rationalisations to try and 'save the data' from previous experiments if the data from those previous experiments are collected in the presence of confounding cues. We also believe ex post and ad hoc rationalisations have little cogent value unless they make testable predictions themselves, otherwise they risk simply becoming 'just so' stories to fit the data (Heyes, 2019; Catmur, Press, Cook, Bird, & Heyes, 2014; Kerr, 1998).

1. Absolute Distance from Delta Theta rather than Theta?

The first alternative explanation agrees that our results show that the static vergence angle (vergence angle theta) is an ineffective absolute distance cue, but suggest that the visual system may instead be able to extract absolute distance from changes in the vergence angle (delta theta). First, we would challenge the suggestion that the visual system is able to extract absolute distance from delta theta. Second, we would challenge the suggestion that our results are only concerned with static vergence, and do not account for delta theta as well.

1. Absolute Distance from Delta Theta: Delta theta (the change in the vergence angle) is merely thought be a relative depth cue. As Brenner & van Damme (1998) observe, simply knowing how much the vergence angle has changed "can be of little use for judging distances if we do not know the orientation of the eyes before the change (1 deg of ocular convergence could be due to a shift in gaze from 20 to just over 21 cm or from 2 to approx. 4 m)." This should be sufficient to address the absolute distance from delta theta hypothesis.

By contrast, if the claim is that delta theta (changes in vergence) can scale absolute distance in the presence of other absolute distance cues, that may be true, but it is uninteresting. All it would show is that delta theta is a relative depth cue. Any pretence that vergence is an independent source of absolute distance information would have to be given up.

But sometimes this second (uninteresting) claim is rearticulated to make it sound like the first (interesting) claim. For instance, it has been suggested to us that changes in vergence (delta theta) are combined with a 'specific distance tendency' (Gogel, 1969) to provide an independent source of absolute distance information. But this is still the uninteresting claim that vergence is merely a relative depth cue that is scaled by an independent source of absolute distance information, in this context the 'specific distance tendency'. Furthermore, even articulated in this way, this account suffers from three distinct shortcomings:

a. First, it is a distortion of the traditional relationship between vergence and the 'specific distance tendency' posited in the literature (Mon-Williams & Tresilian, 1999). There the suggestion is that vergence is an independent source of absolute distance information whose measurement of absolute distance is tempered by the 'specific distance tendency'. By contrast, here the suggestion is that 'specific distance tendency' usurps vergence as an independent source of our absolute distance information.

b. Second, we are skeptical that the 'specific distance tendency' actually exists. First, Gogel & Tietz (1973)'s vague assertions of '2-3m' are decidedly unspecific for a specific distance tendency. Second, the distance estimates in Gogel & Tietz (1973) for a point of light 30cm away (mean = 46cm, median = 28cm) and 91cm away (mean = 100cm, median = 91cm) are much better than the 'specific distance tendency' for which the paper is remembered. Third, as we have already observed, there is no evidence for a 'specific distance tendency' in our own results. There is no sense in which the results in Fig.5 cluster around a specific distance. Indeed, one of the defining and surprising features of our results is the very high degree of variance in Fig.5: subjects simply seem to be largely guessing. Interestingly the very same high degree of variance can be found in Gogel (1969)'s own results, where the standard deviation of distance estimates is the same size as the actual distance estimates themselves.

c. Third, even putting these objections to one side, it is very unclear how this proposal would work in practice. Does the absolute distance reset to the 'specific distance tendency' after every vergence eye movement? Or are we stuck in a near infinite regress trying to trace our path back to an original 'specific distance tendency' after multiple changes in vergence? Both are recipes for an absolute distance mechanism that has no correspondence with reality.

2. Our Experiments Merely Static? It is hard to maintain that our experiments are only concerned with static vergence, any more than any experiment that asks subjects to judge the

distance of a non-moving target (such as Mon-Williams & Tresilian, 1999) is concerned with static vergence. Both of our experiments involved very significant changes in vergence: 10.5° in Experiment 1 and 7.6° in Experiment 2. Since we rarely fixate on objects closer than 35cm, 10° is equivalent to the full vergence range in normal viewing conditions (Fig.1). The objection may be that these changes, though significant, were made gradually in our experiments. But this concern, which will be addressed below, is very different from claiming that our experiment is just about static vergence, any more than Mon-Williams & Tresilian (1999) is.

2. Gradual Changes in Vergence Sub-Threshold for the Visual System?

Everyone agrees that the gradual changes in vergence in our experiments are subthreshold for the observer. Indeed, that is their very point. But the remaining point of contention is whether the changes are too gradual even for the observer's visual system to unconsciously process?

1. Effective Vergence Response: First, it is not as if observers in our experiment were unable to make effective vergence eye movements over the course of 90 trials (in Experiment 1) or 140 trials (in Experiment 2) that ranged over close to the whole vergence range (10.5° of vergence in Experiment 1, and 7.6° of vergence in Experiment 2). So a critic of our experimental paradigm is left in the unenviable position of having to maintain that the visual system both does have access to these changes in vergence in order to make them, but doesn't have access to these changes in order to specify absolute distance.

2. Apparent Monocular Motion: Second, whilst observers were subjectively blind to the gradual changes in vergence, they are not subjectively blind to the monocular motion of the stimuli when they close one eye. As an illustration of this point, I was able to judge the correct direction of motion of the stimulus on every trial when I performed our experiment monocularly. This reflects the principle that 'two eyes less are less sensitive than one' when detecting motion in a stereo stimulus (Tyler, 1971). If monocular motion is above threshold for the observer, then it is surely available to the visual system for unconscious processing. And this is all the vergence signal is: two monocular direction signals that are combined. That these monocular motion signals are subsequently suppressed by the visual system when they are combined (Tyler, 1971) in no way challenges this point. Instead, it strengthens it: in order to suppress the equal and opposite signals, the visual system first has to have access to them.

3. Apparent Binocular Motion: Third, Erkelens & Collewijn (1985a) observed that binocular subjects could discriminate the lateral x-axis motion of a large-field (30° x 30°) stimulus using version (conjugate eye movements), but not the z-axis motion in depth of the stimulus using vergence (opposite eye movements). But the only difference between these two scenarios is the sign (direction) of motion of one of the eyes, leading Erkelens & Collewijn (1985a) to conclude that the extra-retinal (vergence vs. version) signal is likely responsible for the stark difference in percepts. Whilst (as we explain below) our experiment stimuli are not analogous to Erkelens & Collewijn (1985a)'s, the same phenomenon is observable: binocular x-axis lateral motion is clearly visible, but z-axis motion in depth is not. But, according to Erkelens & Collewijn (1985a)'s explanation of this phenomenon, this implies that the visual system must have access to the vergence signal in our paradigm in order to suppress one percept (motion in depth from vergence) but not the other (lateral motion from version).

4. Replacing Ineffectiveness with Redundancy? Fourth, arguing that vergence is blind to gradual changes may be just as damaging to the claim that vergence is an important absolute distance cue. If we maintain that vergence is blind to gradual changes, but it later turns out (as one would expect) that subjects are no less accurate in judging absolute distance in full-cue conditions when the distance of the target is gradually manipulated, then even under this alternative account we would have shown that there is no benefit from having vergence as an absolute distance cue when reaching for objects; the very scenario where vergence is thought to be at its most important (Loftus, Servos, Goodale, Mendarozqueta, & Mon-Williams, 2004; Melmoth & Grant, 2006; Melmoth, Storoni, Todd, Finlay, & Grant, 2007).

5. Expanding Room Experiments: In a series of 'expanding room' experiments subjects failed to notice gradual changes in vergence and motion parallax (Glennerster, Tcheang, Gilson, Fitzgibbon, & Parker, 2006; Rauschecker, Solomon, & Glennerster, 2006; Svarverud, Gilson, & Glennerster, 2010; Svarverud, Gilson, & Glennerster, 2012). As Glennerster et al. (2006) observe: "Subjects seem to ignore information both about vergence angle (to overrule stereopsis) and about stride length (to overrule depth from motion parallax)." However, first, it is important to understand just how different our two experimental paradigms are, and second, we argue that these studies actually support the idea that the gradual manipulation of vergence ought to be an effective absolute distance cue. The fact that we don't find this to be the case is therefore a major finding that challenges existing accounts of visual scale.

There are three important ways in which our experimental paradigm differs from the 'expanding room' experiments:

1. Limited Vergence Range: First, although Glennerster et al. (2006) increase the size of their room by a factor of x4, because the distance of the object being tested is 75cm away, the actual vergence manipulation is a mere 3.5° (75cm to 3m). As we see from Fig.1, this is far from vergence's most effective distance range. Contrast this with 10.5° in our Experiment 1 or 7.6° in our Experiment 2. Indeed, Glennerster et al. (2006) interpret their results as merely indicating that the "efficacy of motion and disparity cues is greater at near viewing distances." But near viewing distances (20-50cm) are exactly what our experiments test.

2. Full-field Stimulus: Second, their scene takes up the whole visual field. As Glennerster et al. (2006) themselves recognize, a failure to respond to changing vergence cues is expected in light of Erkelens & Collewijn (1985a; 1985b)'s studies of large-field (30° x 30°) stimuli. But this has nothing to do with gradual changes in vergence: the speed of the stimuli in Erkelens & Collewijn (1985a; 1985b) was far from gradual (up to 13.5°/s), and instead reflects the fact that the large angular size of the stimulus does not change with vergence.

There is no equivalent conflicting size cue in our experiments since subjects were asked to point to the distance of a dot. One suggestion is that the constant 2.4° x 2.4° angular size of the fixation target in Experiment 2 may be a conflicting size cue. We disagree for five reasons:

First, the angular size of the fixation target did change in Experiment 1, where we found similar results.

Second, we asked the subjects in Experiment 2 if they thought the dot was presented at the same distance as the fixation target, and only one subject thought it was. The rest either had no opinion, or positively thought it was not. The key point being that our subjects made no association of identity between the fixation target and the dot.

Third, as you can see from the right panel in Figure 5, the pointing responses were not fixed at the initial presentation distance of the fixation target (50cm), which is what we would expect if we were in an Erkelens & Collewijn (1985a; 1985b) no motion-in-depth scenario.

Fourth, our 2.4° x 2.4° fixation target is much closer in nature to a 2.1° x 2.1° spot where motion-in-depth has been reported from vergence (Howard, 2008) than a 30° x 30° large-field displays where it has not (Erkelens & Collewijn, 1985a; 1985b).

Fifth, this objection is hard to square with the vergence micropsia literature where 20° x 20° after-image has been found to respond consistently with Emmert's Law (Mon-Williams, Tresilian, Plooy, Wann, & Broerse, 1997). We question whether these results are attributable to vergence and are working on new experiments to test this hypothesis. But a critic of our account cannot at one and the same time embrace the vergence micropsia literature whilst criticising our experimental paradigm.

Sixth, in any case we'd expect any fixed angular size effect on a small stimulus to act as a counter-cue to vergence as an absolute distance cue, as it arguably appeared to do in Viguier et al. (2001), not entirely eradicate vergence as a distance cue.

3. Stable Scene: Third, as the title of Glennerster et al. (2006) illustrates, the purpose of their experiment is to convince us that "humans ignore motion and stereo cues in favor of a fictional stable world". But no fictional stable world is presented in our experiment. Furthermore, once the stable scene assumption was disrupted in Glennerster et al. (2006) (for instance, by passing through a door), subjects became surprisingly good at noticing a change in scale. All subjects needed was some indication that the scale of the scene might have changed in order to disrupt the stable scene assumption (something afforded by our experimental paradigm: each trial the subjects were explicitly alerted to the fact that the distance of the dot had changed, and were asked to reevaluate its distance). So Glennerster et al. (2006) provides evidence for the stable scene assumption, not the suggestion that vergence is an ineffective absolute distance cue when gradually manipulated (see also Rogers, 2011).

Instead, Glennerster et al. (2006) actually suggests that the gradual manipulation of vergence ought to be an effective absolute distance cue. Glennerster et al. (2006) gradually manipulated three potential absolute distance cues: vergence, motion parallax, and vertical disparities. However, the results in Glennerster et al. (2006) shouldn't be attributed to motion parallax or vertical disparities: First, motion parallax has proved a largely ineffective size and distance cue in virtual reality (Beall, Loomis, Philbeck, & Fikes, 1995; Luo, Kenyon, Kamper, Sandin, & DeFanti, 2007; Jones, Swan, Singh, Kolstad, & Ellis, 2008; Jones, Swan, Singh, & Ellis, 2011; Luo, Kenyon, Kamper, Sandin, & DeFanti, 2015), leading Renner, Velichkovsky, & Helmert (2013) to conclude that "there is no empirical evidence that providing motion parallax improves distance perception in virtual environments." Second, there is no suggestion that the vertical disparities in the scene in Glennerster et al. (2006) are anything close to the 20° of the

visual field required for them to be an effective absolute distance cue (Rogers & Bradshaw, 1995). Which, third, only leaves the gradual manipulation of vergence as the remaining absolute distance cue under Glennerster et al. (2006)'s account. Glennerster et al. (2006) therefore predicts that we should find that a gradual manipulation of vergence is an effective absolute distance cue. The fact that we don't is a significant finding that demands a new understanding of visual scale (see Linton, 2017; Linton, 2018 for this new account).

Conclusion

Vergence is considered to be one of our most important absolute distance cues. But vergence has never been tested as an absolute distance cue divorced from obvious confounding cues such as binocular disparity. In this article we control for these confounding cues for the first time by gradually manipulating vergence, and find that observers fail to accurately judge distance from vergence. We consider a number of different interpretations of these results, and argue that rather than adopt an ad-hoc reinterpretation of vergence as blind to gradual changes, or reliant on delta theta rather than theta, the most principled response to these results is to question the general effectiveness of vergence as an absolute distance cue. Given other absolute distance cues (such as motion parallax and vertical disparities) are limited in application, this poses a real challenge to our contemporary understanding of visual scale (Linton, 2017; Linton, 2018).

Acknowledgements

Open Practice Statement

All data and analysis scripts are accessible in an open access repository: https://osf.io/2xuwn/. Neither of the experiments were formally pre-registered, but the hypothesis that inspired these studies was stated and explored in Linton (2017).

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