Eye Movements Do Not Affect Perceived Size

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Visual Scale - Size Constancy - Vergence - Taylor Illusion – Multisensory Integration

Abstract

Since Kepler (1604) and Descartes (1637), it's been suggested that 'vergence' (the angular rotation of the eyes) plays a key role in size constancy (objects appearing to have a constant size despite changes in distance radically altering the size of the retinal image). However, this has never been tested divorced from confounding cues such as changes in the retinal image. In our experiment participants viewed a target which grew or shrank over 5 seconds. At the same time their vergence was increased from 50cm to 25cm. The question was whether this vergence increase biased the participants' judgements of whether the target grew or shrank? We found no evidence of any bias, and therefore no evidence that eye movements affect perceived size. This finding has three important implications: First, perceived size is much more reliant on cognitive influences than previously thought. This is consistent with the argument that visual scale is purely cognitive in nature (Linton, 2017; 2018). Second, vergence modulation of V1 should no longer be thought of as a candidate mechanism for size constancy. Third, the influence of multisensory integration on visual size appears to be reliant on subjective knowledge about changes in hand and gaze position.

Introduction

As objects move forwards or backwards in space, the image they cast on the retina varies drastically in size. And yet objects don't appear to change dramatically in size when they move closer or further away. This suggests that there is a neural mechanism ('size constancy') that compensates for the drastic changes in the retinal image caused by changes in distance (for a review see Sperandio & Chouinard, 2015). We can distinguish between two kinds of visual cues for size constancy: 1. Pictorial Cues, which are present in the static monocular retinal image (such as familiar size and perspective), and which account for the impression of size constancy in pictures. And 2. Triangulation Cues, which typically rely on introducing multiple viewpoints either simultaneously (vergence and binocular disparities) or consecutively (motion parallax).

1. Pictorial Cues: The neural correlates of size constancy are better understood for pictorial cues since 2D pictures are more easily presented to participants in fMRI scanners (e.g. Murray et al., 2006). However, pictorial cues are neither necessary nor sufficient for size constancy. First, pictorial cues are unnecessary because, as we shall discuss below, observers in the Taylor illusion appear to experience something close to full size constancy from vergence alone. Second, pictorial cues are insufficient because, as Sperandio et al. (2012) observe, size constancy in pictures is merely a fraction (10%-45%) of the full size constancy experienced in the real world (Emmert, 1881) (Murray et al., 2006; Leibowitz et al., 1969; Goodale, 2020 estimates 10%-30%; see also Millard et al., 2020 for a recent attempt to disambiguate static monocular and binocular size constancy, although recognising vergence may have influenced their monocular results).

2. Triangulation Cues: In terms of triangulation cues to size constancy (vergence, binocular disparity, motion parallax), the emphasis has been on vergence. There are two reasons for this. First, motion parallax is neither necessary for size constancy (full size constancy is observed by participants in an fMRI scanner in Sperandio et al., 2012), nor is there particularly strong evidence that motion parallax contributes to size constancy (Combe & Wexler, 2010 only marginally qualify

"the common notion that size constancy emerges as a result of retinal and vergence processing alone"). Second, binocular disparity is typically regarded as merely providing relative depth, and not absolute size and distance. Still, considering size constancy only requires relative changes in distance to be matched by relative changes in apparent size ($\text{distance}_1 \div \text{distance}_2 = \text{size}_1 \div \text{size}_2$), a merely relative depth cue could suffice. The problem is that binocular disparity doesn't even provide relative depth information until it has been scaled by absolute distance information, which is typically assumed to come from vergence. As Brenner & van Damme (1998) observe, a 1° change in retinal disparity could equally reflect a change in distance of 20cm to 21cm (5% increase in distance) or 2m to 4m (100% increase in distance).

There is also a deeper conceptual point. Although Linton (2017; 2018) explores the possibility that vision may be divorced from absolute size and distance, orthodox discussions of size constancy typically articulate it in terms of the visual system using absolute distance to determine perceived size. For instance, Emmert's Law (Emmert, 1881) is typically articulated as $S = c(R \times D)$, where S is perceived size, c is a constant, R is retinal image size, and D is perceived distance. But, as we already mentioned, binocular disparity is typically thought of as being a merely relative depth cue outside very limited circumstances (objects taking up at least 20° of the visual field; Rogers & Bradshaw, 1995). Instead, vergence is typically cited as being one of our most important absolute distance cues at near distances (Mon-Williams & Tresilian, 1999; Viguier et al., 2001; for a review and challenge to this consensus, see Linton, 2020).

Kepler (1604) and Descartes (1637) were the first to suggest that the visual system uses vergence (the angular rotation of the eyes) to estimate distance, and scale the size of the retinal image appropriately. For the last three hundred years, evidence for the role of vergence in size constancy has come from four specific contexts where it has been found that changing the vergence angle affects the perceived size of objects (so-called 'vergence micropsia'):

1. Wallpaper Illusion: Before the invention of the stereoscope by Wheatstone (1838), the earliest evidence of vergence micropsia was the 'wallpaper illusion', the observation that if you

cross your eyes whilst looking at a recurring wallpaper pattern, the wallpaper pattern appears smaller and closer (Smith, 1738; Priestley, 1772; Goethe, 1810; Meyer, 1842, 1852; Brewster, 1844; Locke, 1849; Lie, 1965; Ono et al., 1971; Kohly & Ono, 2002; see Howard, 2012 for review).

2. Stereoscopic Viewing: The invention of the stereoscope by Wheatstone (1838) (which presents separate images to each eye) enabled the eyes to be rotated independently of the retinal image. Wheatstone observed that if eye rotation was increased, the perceived image appeared to shrink, even though the images shown to each eye remained fixed (Wheatstone, 1852; Helmholtz, 1866, p.313; Judd, 1897; Frank, 1930; Hermans, 1937, 1954; Locke, 1938; Adams, 1955; Von Holst, 1955a, 1955b, 1957; Heinemann et al., 1959; Gogel, 1962; Biersdorf et al., 1963; Wallach & Zuckerman, 1963; McCready, 1965; Leibowitz & Moore, 1966; Leibowitz et al., 1972; Komoda & Ono, 1974; Regan et al., 1986; Enright, 1989).

3. Telestereoscopic Viewing: Building on Wheatstone (1838), Helmholtz (1857) invented the telestereoscope, and observed that if we use mirrors to artificially increase the distance between the two eyes, the world appears miniaturised. In his *Treatise on Physiological Optics* he observed that "it will seem as if the observer were not looking at the natural landscape itself, but a very exquisite and exact model of it, reduced in scale" (Helmholtz, 1866, p.312). This effect has been attributed to vergence by Helmholtz (1857; 1858; 1866, p.310) and Rogers (2009; 2011), since the eyes need to rotate more to fixate on the same physical distance (cf. Linton, 2018 for an alternative account), and has been extensively studied in the military research (where helicopter pilots often view the world through cameras with increased interpupillary separation, see Newman & Ostler, 2009; Stuart et al., 2009; and Priot et al., 2010; 2011; 2012; 2018).

4. Taylor Illusion: Vergence is also thought to be central to the multisensory integration of hand motion and the retinal image in the Taylor illusion. If you make an after-image of your hand with a bright flash, and then in complete darkness move your hand closer to your face, the after-image of your hand appears to shrink even though it is fixed on the retina (Taylor, 1941). The best current explanation for the Taylor illusion is that it is due (Taylor, 1941; Morrison & Whiteside,

1984; Mon-Williams et al., 1997) or almost entirely due (Sperandio et al., 2013) to the increase in vergence as the eyes track the physical hand in darkness (see also Gregory et al., 1959; Carey & Allan, 1996; Bross, 2000; Ramsay et al., 2007; Faivre et al., 2017a; and for vergence scaling of after-images see Urist, 1959; Suzuki, 1986; Lou, 2007; Zenkin & Petrov, 2015). Most notably, when Sperandio et al. (2013) moved the participant's hand and vergence in opposite directions, they found that (a) the after-image size changed in the direction of vergence, not the hand movement, and (b) the magnitude of the size change when vergence and the hand were in conflict was almost as large as when both the hand and vergence were moving in the same direction.

Surveying the literature on vergence micropsia, two things are striking: First, to our knowledge, there has never been a report of a failure of vergence micropsia within peripersonal space (near distances corresponding to arms reach). Even on the rare occasions when a change in vergence fails to provide an impression of motion-in-depth (for instance, when motion-in-depth is vetoed by a stimulus that takes up the whole visual field) as in Regan et al. (1986), the authors still report "apparent size changes as about threefold when convergence changed from about 0 deg to 25 deg". And this is to be expected. As Regan et al. (1986) note: "Changes in size and depth produced by ocular vergence changes are well known".

Second, the after-image literature appears to suggest that vergence provides something close to perfect size constancy for distances between 25-50cm. This can be seen for two reasons: First, because size constancy appears close to perfect for 25-50cm when vergence is the only distance cue. Apparent size doubled for the representative subject in Sperandio et al. (2013) (incongruent condition) from 3.3cm at 25cm (suggested by the $y = -0.61x + 3.3$ line of best fit) to 6.3cm at 50cm (average of size estimates after a >3° vergence eye movement) (my analysis of their Fig.5 using WebPlotDigitizer 4.2; Marin et al., 2017). Second, the same conclusion is arrived at by a combination of the fact that (a) the Taylor illusion provides near perfect size constancy in this distance range (Bross, 2000; Ramsay et al., 2007; Sperandio et al., 2013), coupled with the fact that (b) the Taylor illusion can be attributed almost entirely to vergence (Sperandio et al., 2013).

Vergence size constancy is therefore regarded as a fundamental aspect of visual perception. However, we believe that vergence size constancy should be re-evaluated for two reasons:

First, our recent work suggests that vergence is an ineffective absolute distance cue once confounding cues have been controlled for. Participants are unable to use vergence to judge absolute distance (Linton, 2020), and we are reluctant to embrace the possibility (raised by Ono & Comerford, 1977 and Bishop, 1989) that vergence might still be an effective size constancy cue even if it proves to be ineffective for absolute distance judgements.

Second, one surprising fact is that to the best of our knowledge vergence size constancy has never been tested divorced from confounding cues (such as changes in the retinal image or changes in hand position) which inform the observer about changes in distance. The reason for this is easy to appreciate. Vergence can only be driven in one of two ways. Either participants track the retinal slip of a visual object moving in depth (such as an LED: Mon-Williams et al., 1997; Sperandio et al., 2013), in which case participants are informed about the change in distance by binocular disparity (the apparent retinal slip of the stimulus as it moves in depth). Or participants track their own hand moving in depth (as in the Taylor illusion), but this gives them proprioceptive information about the changing distance instead. The purpose of our experiment was therefore to test vergence size constancy in a context where it is known to be effective (vergence changes over 5 seconds from 25cm to 50cm: Sperandio et al., 2013), but in a way that controls for subjective knowledge about the changing distance.

Materials and Methods

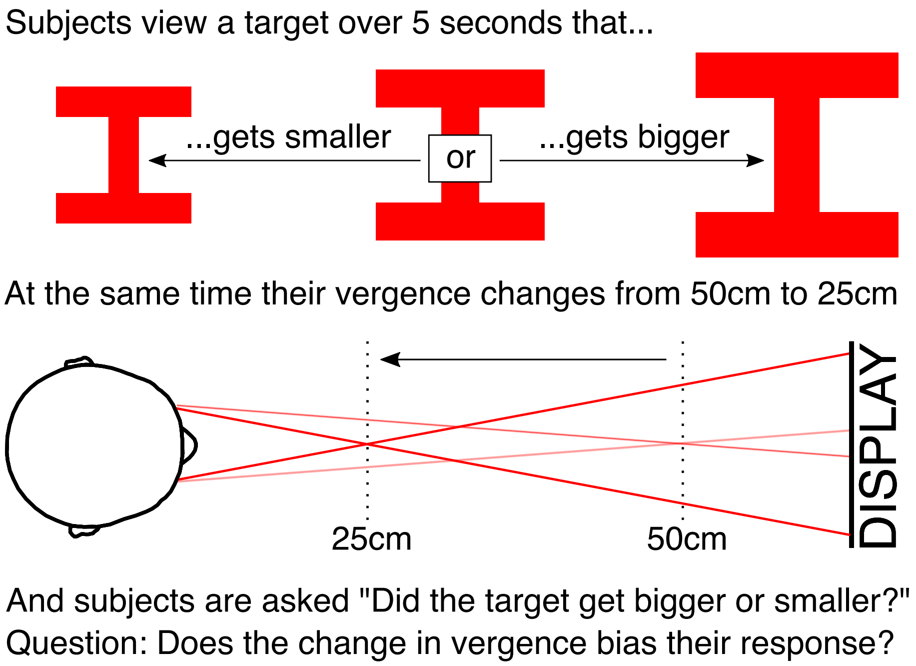

Figure 1. Experimental Paradigm. Subjects viewed a target getting bigger or smaller over 5 seconds whilst their vergence changed from 50cm to 25cm, and were asked to judge whether the target got bigger or smaller? The question was whether vergence biased their response?

This posed a complex technical challenge which we resolved in five ways:

1. First, in order to drive vergence without providing subjective distance information, we used a visual stimulus that (unlike an LED) provided 'sub-threshold' binocular disparities: binocular disparities that are visible to the participant's visual system (in order to drive vergence), but subjectively invisible to the participant themselves. This we achieved with a 3° target moving in depth from 50cm to 25cm over 5 seconds. The target consisted of two targets on a display: a left-hand target that only the right eye could see, and a right-hand target than only the left eye could see. And by increasing the separation between the targets, we could increase the participant's vergence angle (Fig.1). Rotating metal plates (Fig.3) ensured that each eye only saw the appropriate

target, and participants were asked to confirm that they saw a single fused target when they first entered the apparatus, and to report if the target ever went double.

2. Second, in order to present a constant retinal image with eye rotation, we rendered the targets to maintain a constant radius from, and orientation to, the eye. This was achieved in OpenGL by 'projecting' the target onto the display, so that the correct retinal image was achieved when the participants viewed the target (Fig.2) (camera set in OpenGL to nodal point of the eye, and an asymmetric frustum was used so that the far clipping plane matched the distance and dimensions of the display). A bite bar was used to ensure that the nodal point of the eye remained fixed during the experiment (Fig.3), and the 6mm difference between the nodal point and the centre of rotation of the eye was intentionally ignored (cf. Linton, 2019; Konrad et al., 2019).

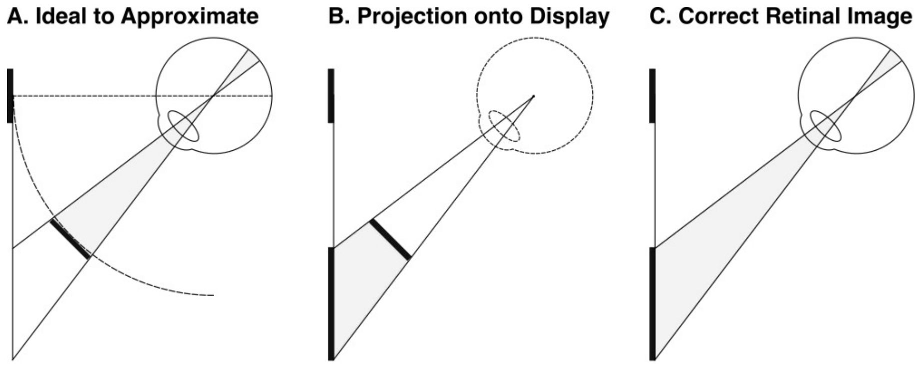

Figure 2. OpenGL rendering of target achieves the correct retinal image for a target with a constant radius and orientation to the eye, whilst presenting the target on a fronto-parallel display.

3. Third, another challenge of this display is that it requires the eyes to focus (or 'accommodate') at the distance of the display (160cm), whilst vergence (the angular rotation of the eyes) is at 25-50cm. This decoupling of vergence and accommodation doesn't happen in normal viewing conditions, and too much vergence-accommodation conflict can lead to the target going blurry or double. To solve this problem we had an optometrist fit each participant with contact lenses (based on the participant's valid UK prescription) so that the optical distance of the display

was 33cm even though its physical distance was 160cm. This ensured a maximum of +/– 1 dioptres of vergence-accommodation conflict, well within the zone of 'clear single binocular vision' (Hoffman et al., 2008). Indeed, some of the most dramatic reports of vergence micropsia have been in the presence of large vergence-accommodation conflicts (e.g. 6.5 dioptres in Regan et al., 1986), so the presence of +/– 1 dioptre should not be objectionable.

4. Fourth, we wanted the target to be presented in darkness to exclude any residual visual cues. An interesting finding from piloting was that the usual technique (having participants view a CRTs through neutral density filters) wasn't effective in eradicating residual luminance from the display (it degraded the target before residual luminance was completely eradicated). Instead, we achieved this in four ways: First, we used an OLED display (LG OLED55C7V) which unlike normal displays does not produce residual luminance for black pixels. Second, subjects wore a mask to block out any residual light, which had red eye filters through which the red stimuli were viewed (blocking out 100% green and ~90% blue light). Third, subjects viewed the stimuli through a narrow (17°) viewing window of 48cm x 18cm at a distance of 60cm. Fourth, the whole apparatus was covered by blackout fabric, and before the experiment began subjects pulled a hood of blackout fabric over their heads and the external lights were turned off.

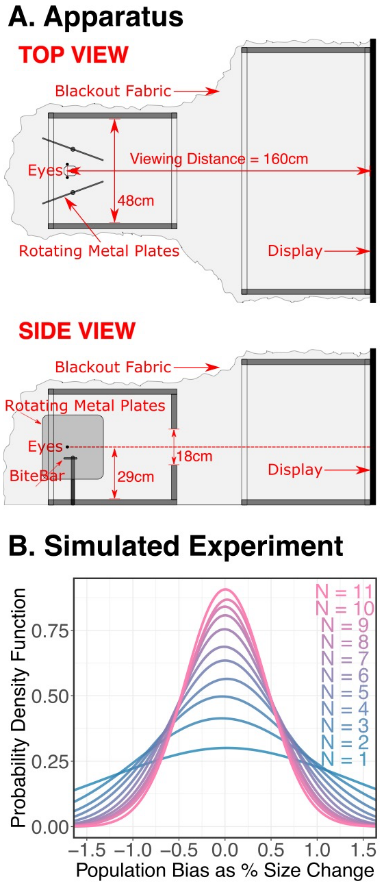

Figure 3. Methods. A. Experimental Apparatus. B. Simulated Experiment. We simulated the experiment 10,000 times in Quest+ (bias = 0, detection threshold = 5%, lapse rate = 2%) to model how increasing the number of participants would improve the accuracy of our hierarchical Bayesian estimate of the true bias (true bias = 0). We determined that we needed n ≥ 5 to rule out an effect greater than our smallest effect size of interest (vergence size constancy > 1.5%).

5. Fifth, rather than ask participants to match their visual experience to (1) a visible chart (Bross, 2000; Lou, 2007; Sperandio et al., 2013) or (2) a memorised chart (Ramsay et al., 2007), or ask for conscious judgements of (3) the physical size of the after-image (Mon-Williams et al., 1997), or (4) the after-image's % size change (Carey & Allan, 1996), we (5) built size change estimation into the stimulus itself (something which cannot be done with an after-image). We increased or decreased the physical size of the target on each trial by between –20% and +20%, and asked the participants to make a forced choice ("did the target get bigger or smaller?"). And we tested

whether the change in vergence biased their response? If there was no vergence size constancy, then participants would be at chance in determining whether there was a size change when the target's physical size didn't change. By contrast, if participants experienced vergence micropsia, then we would have to increase the physical size of the target in order to cancel out this vergence micropsia for them to be at chance. And the degree of the bias (i.e. the amount that we have to increase physical size before participants are at chance) will indicate just how large the vergence micropsia effect size is.

We used a four-parameter maximum likelihood model (Quest+: Watson, 2017; Brainard, 2017) to estimate when participants were at chance. Participants completed 200 trials (10 sets of 20 trials), and on each trial Quest+ tested the size change that would be most informative. In piloting, we found that the author (an experienced psychophysical observer) could not detect size changes over 5 seconds that were smaller than 1.5%. So, if vergence changes the perceived size of the target by less than 1.5%, vergence size constancy can be dismissed as smaller than the smallest effect size of interest under an inferiority test (Lakens et al., 2018; in our actual experiment this was revised down to 1.43%, the detection threshold of our most sensitive observer).

Assuming vergence doesn't bias size judgements, how would the number of participants affect our ability to determine this fact? We can simulate the experiment 10,000 times (bias = 0, detection threshold = 5%, lapse rate = 2%), and fit a hierarchical Bayesian model (discussed below) to the data (Fig.3B). We found that with 5 or more observers we should be able to rule out any size constancy effects greater than 1.5%.

11 observers (8 female, 3 male; age ranges 20-34, average age 24.5) participated in the experiment: the author and 10 participants recruited using an online advertisement (13 were originally recruited, but 1 was excluded because they could not fuse the target, and 2 were excluded because their vision was blurry with the contact lenses). All participants were screened to ensure their accommodation was within normal bounds for their age (tested with a RAF near-point rule), vergence within normal bounds (18D or above on a Clement Clarke prism bar), and stereoacuity

within normal bounds (60 arc secs or less on a TNO stereo test). The author's participation was required to (a) confirm Quest+ mirrored the pilot data, and (b) provide a criterion for the minimum effect size. All other subjects were naïve as to the purpose of the experiment, and were paid £15/hr for 3 hours. The study was approved by the School of Health Sciences Research Ethics Committee at City, University of London in accordance with the Declaration of Helsinki.

The code for running the experiment is openly available: https://osf.io/5nwaz/ , running on Matlab 2019a (MathWorks) with PsychToolBox 3.0.15 (Kleiner et al., 2007).

Results

Let us consider what we would expect to find according to (a) the null hypothesis (vergence has no effect on perceived size) and (b) the alternative hypothesis (vergence has an effect on perceived size). As we have already discussed, if vergence has no effect on perceived size, then it is obvious that participants should be at chance at determining whether there is a size change just when we don't introduce a size change (bias = 0). By contrast, if participants experience something close to full size constancy, then we would have to increase the size of the target by 100% in order to cancel out the reduction in perceived size caused by vergence micropsia (which in normal viewing conditions would be a reduction in size of 50% because halving the distance leads to a doubling of the retinal image size, assuming the small angle approximation).

These two hypotheses, and various intermediate degrees of size constancy between these two extremes, are plotted in Fig.4A. What the hierarchical Bayesian model of our results in Fig.4A show is that the bias we found was ≈ 0, consistent with there being no vergence size constancy.

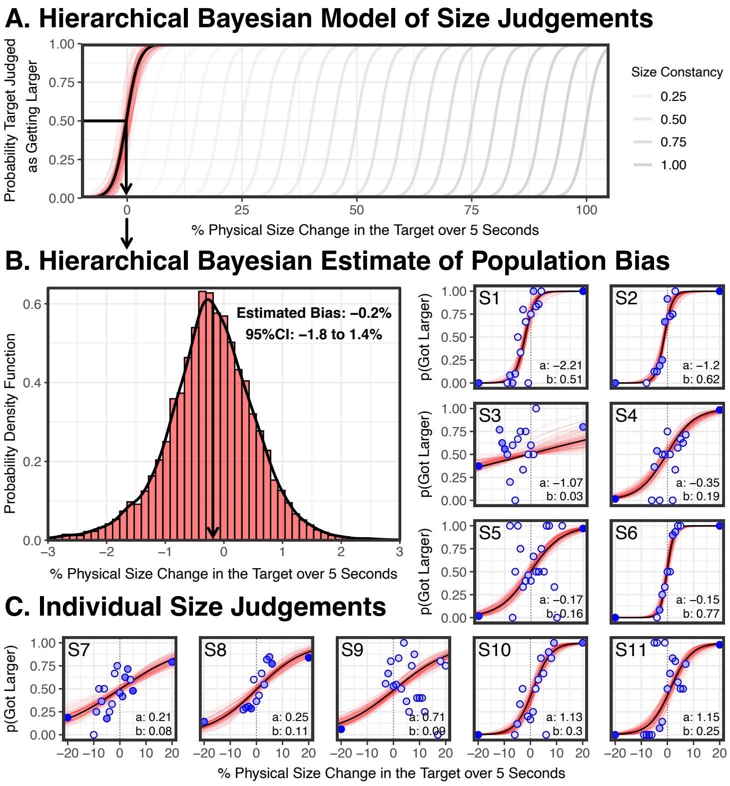

Figure 4. Results. A. Hierarchical Bayesian model of the population psychometric function in black (based on 15,000 posterior estimates, 100 representative posterior estimates in red), plotted against predictions for various degrees of vergence size constancy effect sizes (in grey). B. Probability density function of 15,000 posterior estimates of the population bias, with a non-significant bias of –0.2%. C. Individual subject results fitted with Bayesian psychometric functions in black (based on 15,000 posterior estimates, 100 representative posterior estimates in red). Blue dots indicating the physical size changes tested by Quest+ (with darkness of the dot indicating the number of times it was tested). Individual biases cluster around zero (from –2.2% to 1.2%). For each participant, alpha (a) is the bias of the logistic function, and beta (b) is the slope.

To explain our conclusion, the individual results are plotted in Fig.4C. Each blue dot represents a physical size change that was tested by the Quest+ maximum likelihood model, and the darkness of the dot indicates the number of times it was tested. We then fit each of the individual sets of data with a four-parameter logistic Bayesian psychometric function (indicated with a black line), using the Palamedes Toolbox 1.10.1 (Prins & Kingdom, 2018) with CmdStan 2.22.0, using the toolbox's standard priors (bias and slope: normal (0,100), upper and lower lapse rates: beta (1,10)), and based on 15,000 posterior estimates (100 posterior estimates illustrated in red). Fig.4C shows individual biases range from –2.2% to +1.2%, but cluster around 0.

To estimate the population level psychometric function illustrated in Fig.4A, we used the Palamedes Toolbox 1.10.1 (Prins & Kingdom, 2018) with CmdStan 2.22.0 to fit a four-parameter logistic hierarchical Bayesian psychometric function, which fits the data with a multilevel model that takes into account the variability of each subject. We used the toolbox's standard multilevel priors which are documented by Prins & Kingdom (2019) and, based on 15,000 posterior estimates (100 posterior estimates illustrated in red), found a population level bias of –0.219% (95% CI: –1.82% to 1.39%) and a population level slope of –0.732 (95% CI: –1.07 to 0.378).

The estimate that particularly interests us is the population bias, so in Fig.4B we provide a probability density function of the 15,000 posterior estimates of the bias. We find no statistically significant bias, and therefore no statistically significant effect of vergence on perceived size. Indeed, the non-significant bias of –0.2% is in the wrong direction for size constancy.

To go beyond the negative claim that we found no statistically significant effect (null hypothesis not rejected) to the positive claim that there is no effect of vergence on perceived size (null hypothesis accepted), we can make two further arguments.

First, from a Bayesian perspective, we can perform a JZS Bayes factor (Rouder et al., 2009). The estimated Bayes factor that we found was 3.99 (±0.03%), which suggests that the data are four times more likely under the null hypothesis (bias = 0) than under the alternative (bias ≠ 0).

Second, from a frequentist perspective, we can perform an inferiority test that tests whether, if there is a vergence size constancy effect, it is at least as large as the smallest effect size of interest (Lakens et al., 2018). You'll remember, we defined our smallest effect size of interest as the detection threshold for our most sensitive observer (which is 1.43%). Put simply, any vergence size constancy effect that's smaller than a 1.43% size change won't be detected by any of our observers. Since we have a directional hypothesis (vergence micropsia should reduce, rather than increase, the apparent size of the target), we specifically tested whether there is a bias > 1.43%. We therefore performed an inferiority test by taking the 90% confidence interval of the population bias in Fig.4B in the predicted direction, which is 0.96%. Since this is smaller than 1.43% (our smallest effect size of interest), from a frequentist perspective we can conclude that any vergence size constancy effect is effectively equivalent to zero (Lakens et al., 2018).

Discussion

According to the literature, "it is well known that vergence is a reliable source of depth information for size constancy" (Sperandio et al., 2013). But we find no evidence that vergence makes any contribution to perceived size. To our knowledge, ours is the first study to report a failure of vergence size constancy at near distances. But ours is also the first study that controls for confounding perceptual cues (changes in the retinal image) whilst also controlling for confounding cognitive cues (keeping subjects naïve about changes in absolute distance). Beyond vergence size constancy, our results have three further important implications:

1. Visual Scale: First, these results substantiate a broader concern about visual scale. Visual scale is thought to be provided by a number of well-established distance cues, such as vergence, accommodation, motion parallax, familiar size, and the ground-plane. However, first, accommodation (Mon-Williams & Tresilian, 2000) and motion parallax (Renner et al., 2013) have been found to be largely ineffective as absolute distance cues, second, the ground-plane only applies to limited viewing conditions (Creem-Regehr et al., 2015), and third, familiar size is merely thought to affect our cognition, rather than our perception, of visual scale (Gogel, 1969; Predebon, 1992). Given these shortcomings, vergence was meant to provide a solid anchor for our size and distance judgements in near space. But our results challenge this conclusion. Instead, our results demonstrate that visual scale is much more reliant on cognitive influences than previously thought.

Our results are consistent with our argument in Linton (2017; 2018) that visual scale is based solely on higher level cognitive processes, where we extend Gogel (1969)'s and Predebon (1992)'s observations about familiar size to argue that visual scale itself is a purely cognitive process.

2. Neural Mechanisms: Ever since Trotter et al. (1992) found that the large majority of neurons in the monkey primary visual context (V1) were modulated by vergence, it has been suggested that processing of the vergence signal in V1 plays an important role in size constancy. Further evidence for the vergence modulation of V1 is found by Trotter et al. (1993); Trotter et al. (1996); Masson et al. (1997); Dobbins et al. (1998); Trotter & Celebrini (1999); Cumming & Parker (1999); Trotter et al. (2004); Cottereau et al. (2014); see also Richards (1968) on LGN; Gnadt & Mays (1991; 1995); Quinlan & Culham (2007); Culham et al. (2008) on the parietal cortex; and Lehky et al. (1990) and Pouget & Sejnowski (1994) for an early neural network model that Trotter et al. (1992) complements.

More recently Chen et al. (2019) have looked at the time course of size constancy, and found that vergence and the retinal image are not integrated during (a) initial processing in V1 (~50ms), but instead during (b) recurrent processing within V1, and/or (c) re-entrant projections from higher-order visual areas (e.g. Gnadt & Mays, 1991; 1995), both of which are consistent with the ~150ms timeframe. And this is consistent with Trotter et al. (1992)'s suggestion that whilst vergence responsive neurons encode vergence distance, further computations are required to scale the retinal image, so vergence responsive neurons "constitute an intermediate step in the computation of true depth, as suggested by neural network models [Lehky et al., 1990]."

However this whole line of research, from Trotter et al. (1992) to the present, is prefaced on the fact that "psychophysical data suggest an important role for vergence" (Trotter et al., 1992). But this is exactly what our results in this experiment, and in Linton (2020), question. We therefore conclude that there is no link between the vergence modulation of neurons in V1 (or indeed anywhere else) and size perception. According to our alternative account, visual scale is entirely dependent upon top-down cognitive processing. Indeed, without the vergence signal we appear to lose any early visual processing of absolute distance (one exception might be vertical disparities, but Trotter et al., 1992 proceed on the basis that they are ineffective, and the subsequent evidence in favour is equivocal at best: see Cumming et al., 1991; Sobel & Collett, 1991; Rogers & Bradshaw, 1995). So what are we to make of the results in Trotter et al. (1992)? One possibility is that they reflect the participant's own purely cognitive knowledge about their changing gaze position, even though this has no effect on their visual experience. This is consistent with increasing evidence that V1 is implicated in purely cognitive (non-visual) processing, e.g. the location of rewards amongst visually identical targets (Saleem et al., 2018).

3. Multisensory Integration: Subjective knowledge of gaze position also appears to play an important role in multisensory integration. The Taylor illusion (where an after-image of the hand appears to shrink or grow with physical hand movements) is an important paradigm for recent discussions of multisensory integration (Faivre et al., 2017a; Grove et al., 2019). The best current explanation for the Taylor illusion is that it is due (Taylor, 1941; Morrison & Whiteside, 1984; Mon-Williams et al., 1997) or almost entirely due (Sperandio et al., 2013) to the change in vergence as the eyes track the hand moving in darkness. However, in light of our results this explanation no longer seems sustainable, since vergence had no effect on the perceived size of the target once subjective knowledge about the fixation distance had been controlled for. Nor does this imply that the Taylor illusion is primarily due to proprioceptive information from hand motion directly influencing visual perception (Carey & Allan, 1996; Ramsay et al., 2007), since Sperandio et al. (2013) demonstrate that when vergence and hand motion are in conflict, the Taylor illusion follows vergence, and the effect is only marginally reduced in size.

Instead, what both accounts are missing is the participant's subjective knowledge about their own changing hand and gaze positions. This explains why Sperandio et al. (2013) found that vergence affects perceived size when their participants knew about their changing gaze position (from their hand or from the motion in depth of an LED), but why we didn't when our participants were ignorant of this fact. There are two ways in which conscious knowledge about our changing hand or gaze position could influence size constancy. First, our subjective knowledge could influence our visual experience (so-called 'cognitive penetration' of perception by cognition). But we are skeptical of invoking 'cognitive penetration' to explain an effect that could also be explained as a purely cognitive bias (for further skeptical discussions of 'cognitive penetration' see Fodor, 1983; Pylyshyn, 1999; Firestone & Scholl, 2016). Second, under our alternative cognitive bias account, the integration of the retinal image and our changing gaze position could be purely cognitive, rather than perceptual. Our visual experience of the after-image's angular size remains constant, but our hand movements cognitively bias our interpretation of our constant visual experience: because we know that our hand is moving towards our face, we interpret the constant angular size of the after-image as a reduction in physical size.

This purely cognitive interpretation of the Taylor illusion has wide reaching implications for multisensory integration, specifically the integration of vision and hand movements. The Taylor illusion is taken as evidence of multisensory integration at the level of perception. Specifically, that vision "relies on multimodal signals" (Sperandio et al., 2013; Chen et al., 2018) and that "visual consciousness is shaped by the body" (Faivre et al., 2015; Faivre et al., 2017a; Faivre et al., 2017b). But if the integration of proprioception and the retinal image could be purely cognitive in the context of vergence (the major driver of the Taylor illusion, Sperandio et al., 2013), there's no reason why the integration of proprioception and the retinal image in the context of integrating vision and hand movements (the minor driver of the Taylor illusion, Sperandio et al., 2013) couldn't equally be accounted for in purely cognitive terms. This cognitive approach also suggests a non-perceptual explanation for variants of the Taylor illusion that appear to demonstrate the integration of vision with the rubber-hand illusion (Faivre et al., 2017a) and tool use (Grove et al., 2019). And cognitive interpretations of the integration of vision and proprioception are also advanced in the contexts of vision and touch in slant estimation (Hillis et al., 2002; Gepshtein et al., 2005) by Linton (2017), pp.37-38 and pp.65-66, and vision and vestibular cues in self-motion (Fischer & Kornmüller, 1930; Ash et al., 2011) by Linton (2018).

Conclusions

Vergence is thought to provide an essential signal for size constancy. We tested vergence size constancy for the first time without confounding cues, and found no evidence that eye movements make any contribution to perceived size. This suggests that (1) our impression of visual scale is much more reliant on cognitive processing than previously thought, with the further implications that (2) vergence modulation of neurons in V1 cannot be responsible for our impression of visual scale, and (3) the integration of the retinal image with proprioceptive cues from the hand appears to be reliant upon observers having subjective knowledge about their hand and gaze position.

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Open Practice Statement

Code for running the experiment, and all the data and analysis scripts, are accessible in an open access repository: https://osf.io/5nwaz/

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