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RESEARCH NOTE

Mark Mon-Williams · James R. Tresilian · Anna Plooy
John P. Wann · Jack Broerse

Looking at the task in hand: vergence eye movements and perceived size

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Abstract A retinal afterimage of the hand changes size when the same *unseen* hand is moved backwards and forwards in darkness. We demonstrate that arm movements per se are not sufficient to cause a size change and that vergence eye movements are a necessary and sufficient condition for the presence of the illusory size change. We review previous literature to illustrate that changing limb position in the dark alters vergence angle and we explain the illusion via this mechanism. A discussion is provided on why altering limb position causes a change in vergence and we speculate on the underlying mechanisms.

Key words Vergence · Depth perception · Illusion · Accommodation · Emmert's law

Introduction

Carey and Allan (1996) have described a compelling visual illusion, wherein an afterimage of the hand dramatically changes size when the same *unseen* hand is moved in darkness. The afterimage appears to increase in size when the arm is moved away and to decrease in size when the arm is moved closer. As Carey and Allan acknowledge, this illusion is a variation on an observation first made by Taylor (1941). Taylor described changes in the perceived size of a white card's afterimage when either the observer held the unseen card and moved it forward and backwards, or the card remained in a fixed position but the observer's head moved. The primary purpose of this paper is to demonstrate that vergence eye movements are necessary and sufficient to explain the illusion. The secondary, but related, purpose is to explain why limb position might be used to drive *either* the accommodation *or* the vergence system towards a proximal target.

Emmert (1881) demonstrated that the perceived size of an afterimage viewed against a surface depends upon the perceived distance to the surface. From this observation is derived Emmert's law: perceived size is a function of perceived distance. When an afterimage is viewed in darkness, it is seen at some distance from the observer. In visually reduced cue situations a major cue to the distance of a binocularly viewed target is the vergence angle of the eyes (Foley and Richards 1972; von Hofsten 1976; Foley 1980; Owens and Liebowitz 1980). According to Emmert's law it seems that the perceived size of an afterimage viewed in darkness should vary as a function of vergence angle. We therefore sought to establish whether a change in vergence is necessary and sufficient for the presence of the illusory size change reported by Carey and Allen (1996) and Taylor (1941). It should be noted that we are not the first to suggest that vergence might be responsible for producing the illusion. This suggestion was mooted by both Taylor (1941) and Carey and Allan (1996); the former author established that removing vergence eye movements attenuated the illusion but the latter authors stated that their informal observations suggested "no clear relationship" between the illusion and vergence and that the issue "warrants further investigation, perhaps by recording eye movements" (p. 485).

Materials and methods

Pilot observations

It is very easy to create the illusion by voluntarily crossing the eyes (as may be readily verified by the interested reader). Our initial studies sought to quantify the illusion using an afterimage of the hand (or a card held within the hand) viewed whilst participants exercised

M. Mon-Williams (✉) · J.R. Tresilian · A. Plooy
Department of Human Movement Studies,
University of Queensland, St. Lucia,
Queensland 4072, Australia
Tel.: +61(7) 3365 6817; Fax: +61(7) 3365 6877;
e-mail: markmw@hms.uq.edu.au

M. Mon-Williams · J.P. Wann
Department of Psychology, University of Reading,
3 Earley Gate, Reading RG6 6AL, UK

J. Broerse
Department of Psychology, University of Queensland,
St. Lucia, Queensland 4072, Australia

voluntary vergence. Unfortunately, this proved to be a difficult experimental manipulation for three reasons:

(1) Participants differed in their ability to change vergence voluntarily and the amount of vergence produced differed between participants.
(2) The vergence movements were commonly associated with conjugate eye movements. The conjugate movements were often large enough to cause the signals to fall outside the eye trackers' linear range.
(3) To avoid using verbal reports we adopted a technique that relied on grip aperture to measure the illusion (see Procedure). Quantifying the change in hand size proved to be difficult with this technique as the infrared markers used to record grip aperture were often "hidden" by the target hand.

We therefore decided to use disparity-driven vergence (produced using a point light), with a piece of white card as a target (8 cm × 7 cm), to explore the phenomenon. Prior to conducting the experiments we established that the point light used to drive vergence did not create an accommodative stimulus. This was verified on two separate participants (neither of whom was used within the actual experimental procedures). The participants were placed in the dark with the left eye covered and were asked to fixate the pinpoint light source. Accommodation was measured using a modified Canon Autoref R-1 infra-red objective optometer. No information was provided regarding the location of the light, which was randomly placed at 50 cm, 33 cm and 20 cm from the participants. The location of the target had no influence on the accommodative response and, in all positions, both observers showed accommodation equivalent to distant fixation. Post-hoc questioning revealed that both observers had assumed that the light was at the far end of the room in all three recording sessions.

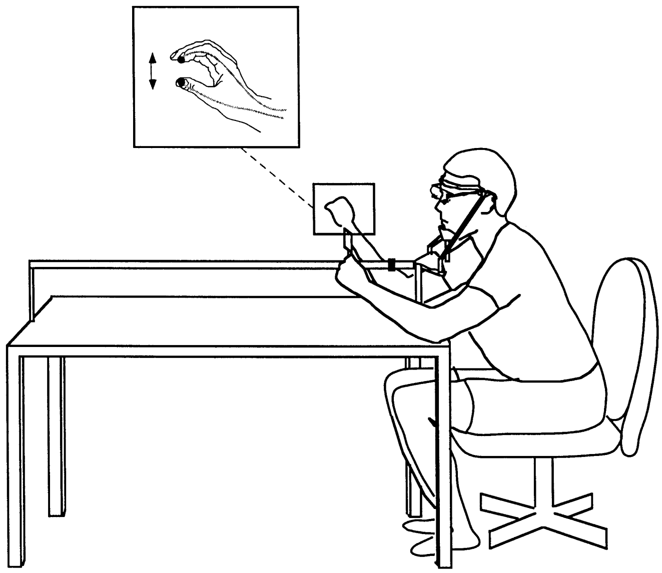

Fig. 1 A schematic of the experimental apparatus. An afterimage was formed of a white card whilst the observer viewed a red light-emitting diode (LED) in darkness. The LED then either stayed in a fixed location whilst the observer moved the card (condition 1) or was attached to the card which was moved by an experimenter (condition 2). The observer indicated the size of the afterimage by altering the aperture between the thumb and index finger of their right hand. An Optotrak infra-red (IR) system was used to measure the finger aperture in the dark and to ensure that the observer moved the card over the requisite range. Eye movements were simultaneously recorded using an IR Eye Tracker

Procedure

Eight observers originally participated in the experiments. All were right-handed and all had normal vision. The observers were naive as to the purpose of the experiments and none had previously participated in an eye movement recording experiment. There were two experimental conditions: condition 1 determined whether vergence is necessary whilst condition 2 determined whether vergence is sufficient for the presence of the illusion. Throughout both experimental manipulations the observers were asked to maintain fixation on a small red light-emitting diode (LED). The LED was too small to elicit an accommodative response but was able to drive disparity vergence. In condition 1, the LED was positioned in the centre of the card at the time the afterimage was created. In this condition, the LED stayed in exactly the same position whilst the card was moved backwards and forwards. In condition 2, the LED was placed in the middle of the white card and moved with the card. The fixation point and the centre of the card were on the same axis (i.e. the line of sight was coincident). In condition 1 the observer held the card with their left hand and moved it themselves, whilst in condition 2 the experimenter moved the card. The trials were evenly balanced between the target approaching (50 cm to 20 cm away) and receding (20 cm to 50 cm) from the observers. Metal stops were provided so that the observer and the experimenter could feel when the card had moved through the requisite distance. Initial target direction and conditions 1 and 2 were randomised between and across observers with five trials made for each target direction for each condition (i.e. a total of 20 judgements per observer).

The observer rested his or her head in a chin-and-head rest during the experiments. The room was made completely dark and the observer was asked to fixate the visible LED. A high-intensity flash of light (created by a standard camera "flashgun" held about 10 cm in front of the card) was then used to produce an afterimage of the card. Each observer judged the vertical size of the afterimage (the card's physical size was 7 cm). The observer made these judgements with their right hand by manipulating the gap between index finger and thumb to indicate perceived height (Fig. 1). The observer made an initial judgement on vertical size and then the card was moved (according to the condition), after which the observer made a final judgement.

Horizontal eye position was monitored for both eyes by comparing diffuse infra-red light from the nasal and temporal limbi (Eye Tracker Model 210, Applied Science Laboratories, Bedford, Mass.). The eye movement sensor's two output channels had bandwidths of 180 Hz. The channels were not low-pass filtered and eye movement data were digitised at 100 Hz and stored in computer memory. Noise in the system was equivalent to approximately 30 min of arc. The eye movement sensors were mounted in a trial frame adjusted so that the sensors were centred in the vertical and horizontal planes. Calibration routines were carried out before recording.

An Optotrak three-dimensional optoelectronic movement recording system was used to measure the grasp aperture. This system measures the three-dimensional position of small infra-red light-emitting diodes (IREDs); it was factory pre-calibrated and had a static positional resolution of within 0.2 mm. An IRED was placed on the thumbnail and the fingernail of the observer's right hand. The data (recorded at 100 Hz) were stored for later analysis. Two participants had to be excluded from the results: the eye trackers failed to work with one participant whilst another participant consistently failed to hold the eyes steady in condition 1. Preplanned comparisons between the initial and final perceived afterimage size were carried out on the means of interest using Dunn's procedure (Keppel 1982, p. 146) for the six remaining observers. The experiments had ethical approval from the University and all participants gave informed consent.

Results

The results were clear: vergence is necessary and sufficient to cause the illusion. In condition 1, no change occurred in the perceived size of the afterimage. In contrast,

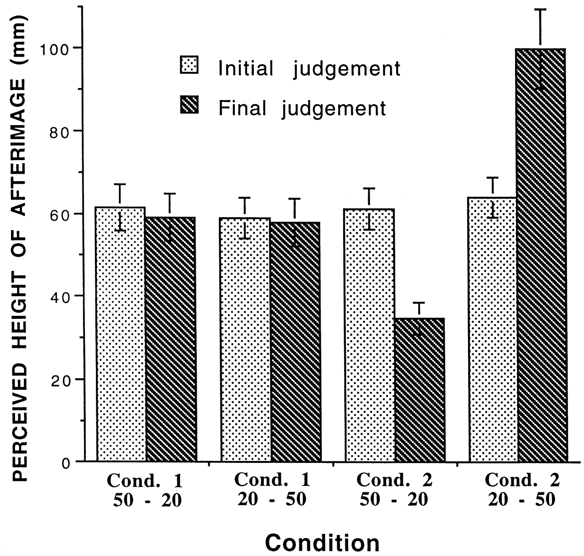

Fig. 2 Experimental results showing the initial and final judgements for condition 1 and condition 2, with the target either approaching (50–20 cm) or receding (20–50 cm) from the six observers. The perceived height of the afterimage is plotted along the *abscissa* and the condition along the *ordinate*. Standard error bars are shown

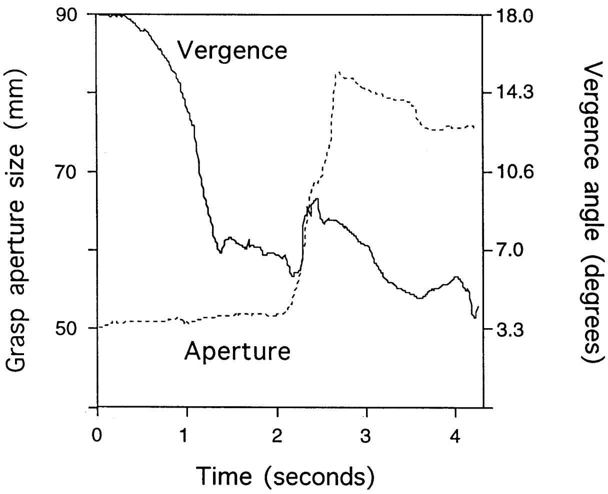

Fig. 3 Example of unfiltered eye movement and grasp aperture recordings (randomly selected from a single trial from observer 6). The observer followed the movement of the small red LED from a position 50 cm in front of the eyes to 20 cm in front. Associated changes in the perceived size of the afterimage are reflected by changes in the aperture size (distance between infra-red light-emitting diodes attached to the thumb and index finger)

the afterimage showed a marked size change in condition 2. It was ensured that vergence eye movements did not occur in condition 1 and that participants maintained fixation on the point light in condition 2. Four trials in condition 1 had to be excluded because of involuntary eye movements occurring with the self-generated arm movements. In condition 1, the Optotrak data were examined to ensure that the participants moved the white card over the 30-cm distance.

Figure 2 illustrates the changes in perceived size indicated by the observers' hand aperture. No significant differences were found between the initial and final judgements in condition 1. In contrast, the perceived size of the afterimage altered in condition 2. The changes in perceived size were statistically reliable for condition 2 when the target was approaching ($t_{[5]} = 6.875$, $P < 0.001$) and receding from the observers ($t_{[5]} = 6.207$, $P < 0.0016$). Inspection of the individual trials showed that the change in perceived size occurred on every trial for every observer. It may be seen that the perceptual changes are consistent with the direction of the LED movement, viz. when the LED was moved away the afterimage appeared larger, and when the LED was moved nearer the afterimage appeared smaller (this was true in every condition 2 trial for every participant). No significant differences were found in the size change when the approaching target was compared with the receding one. Figure 3 provides some exemplary experimental plots.

Discussion

Our results show that changes in the perceived size of an afterimage are mediated through vergence eye movements. It was shown that when the arm is not moved but vergence alters, perceived size changes in accordance with predictions from Emmert's law. This finding implies that vergence movements are sufficient for changes in perceived size. It was further shown that when the hand is moved forwards or backwards, but vergence is held constant, no size changes are observed. This finding implies that vergence movements are necessary to perceive changes in afterimage size when the limb is moved. Furthermore, our results show that arm movements per se are not sufficient or necessary to cause afterimage size changes. Our simple observations therefore provide evidence that vergence eye movements are both necessary and sufficient for the perception of size changes in an afterimage. If this is true, Carey and Allan's (1996) observation that an afterimage of the hand changes size (when the hand is moved in darkness) is due to vergence movements occurring concurrently with movement of the hand. This could be due either to vergence responding to changes in the (kinaesthetically) perceived position of the hand, or to vergence movements made in anticipation of changes in hand position.

Erkelens et al. (1989) examined vergence responses to an imagined target whose "distance" was changed by participants moving their arm. It was reported that two of four participants produced vergence movements under these conditions and these were related, though rather imprecisely, to the arm movements. Koken and Erkelens (1993) later reported that moving a target with the hand leads to vergence that *predicts* the target movement. These results are further complemented by our own observations that some participants occasionally produced vergence movements when they moved their arms, despite an instruction to fixate a stationary point light source. When they did this they experienced changes in the size of the afterimage that were in line with the vergence changes (these trials were not included in the results). None of these observations demonstrate that movements of the arm in darkness lead to vergence eye movements which precisely track the limb – indeed the relationship would seem to be rather weak. The vergence explanation of Carey and Allan's observations does not, however, require that limb movements be closely tracked by vergence: it is only necessary that some vergence occurs in the right direction for the results to be explained. The presence of a fixation point allowed the illusion to be seen consistently across trials. It should be noted that the illusion is far more variable when a fixation point is not available. This discrepancy is consistent with our explanation, as the retinal disparity will produce accurate vergence whereas limb position is unlikely to produce precise vergence responses.

There are at least two reasons why vergence responses to hand movements in the dark are imprecise. First, it is what might be expected from a spatiotopic (as opposed to retinotopic, see below) stimulus to the vergence system. Second, the vergence responses may be produced via accommodative vergence and this will tend to result in a relatively low correlation between vergence response and limb position. We now elaborate on these points. Changing fixation from a distant target to a proximal one requires accommodation to provide a clear retinal image (remove blur), and a change in ocular vergence to ensure single vision (remove diplopia). The two systems rely on a feedback loop and are cross-linked so that a change in accommodation produces a change in vergence (accommodative vergence) and a change in vergence produces a change in accommodation (vergence accommodation). Although blur and disparity are extremely effective *retinotopic* feedback signals, they are only effective over small distances, so that larger changes are driven by *spatiotopic* stimuli (Schor et al. 1992). The spatiotopically driven changes get the accommodation and vergence systems into the right "ball-park" and then retinotopically driven responses act to achieve precisely located fixation.

Despite the importance of the spatiotopic response, it remains unclear what information provides the necessary stimuli. Limb position is one potentially salient source of spatiotopic information available to the oculomotor system. Many naturalistic tasks require a sudden change of fixation from a distant object to an object held in, or located close to, the hand. The accommodation and vergence systems are known to require "training " during infancy and the correspondence between holding and looking at an object would appear to be a useful relationship for the system to exploit. Somewhat surprisingly, this spatiotopic cue has received little attention. One possible reason for this lack of attention is that an early study (Fincham 1962) stated that ″the brain is unable to use the information from proprioceptor nerves of the hand and the arm to direct the eyes and control accommodation in darkness″ (p. 425). This conclusion was based on nine measurements with eight observers who looked at their finger positioned 33 cm away (requiring accommodation of 3 dioptres and vergence of 3 metre angles).[1] Fincham's conclusion relied on the finding that for only one observer was the accommodation response directly equivalent to the finger position. As stated above, however, the spatiotopic ("feedforward") mechanism might only drive the responses towards the correct distance before the retinotopic system takes over. Accommodative vergence is normally expressed as a ratio to accommodation (the AV/A ratio) and, likewise, vergence accommodation is expressed as its ratio to vergence (VA/V ratio). Fincham's data show that the mean primary response (either accommodation or vergence) to the finger was 1.57 (D or MA), which suggests that finger position was actually providing a reasonable spatiotopic input. Further inspection of Fincham's data reveals that one system always responded to a greater extent than the other. If one calculates the respective response magnitudes then it appears that the smaller response is being driven by cross-link interaction. The normal AV/A ratio measured under clinical conditions is approximately 0.6 ± 0.2 MA/D and the VA/V ratio around 0.5 ± 0.2 D/MA (McLin and Schor 1988). In four of Fincham's observers, limb proprioception directly influenced accommodation with secondary vergence occurring through the accommodative vergence cross-link, whereas in three observers limb proprioception directly affected vergence with secondary accommodation occurring through the vergence accommodation pathway. This observation is made on the basis that the calculated ratios were in the normal ranges (Table 1). Notably, all the responses reported by Fincham were undershoots of the target. It would make sense for the system to undershoot rather than having to reverse response direction on the basis of retinotopic information. It may also be the case that limb position initially provided a stronger signal to Fincham's observers, but that the response decayed in the absence of a retinotopic stimulus. This would act to decrease the response measured after sustained fixation of the finger.

It is also possible to elicit voluntary responses from the accommodation and vergence system (i.e. to cross one's eyes). McLin and Schor (1988) have shown that such voluntary control is initiated by the accommodation system in the majority of individuals, with a secondary vergence response generated by accommodative vergence. One of the most compelling aspects of both Fincham's (1962) and McLin and Schor's (1988) data is that only the vergence *or* the accommodation system is driven by a feedforward spatiotopic signal. Neurological advantages may exist in using the spatiotopic signal to drive only one system directly whilst the other responds via the normal cross-link pathway, as the spatiotopic input only needs to be coded in one set of motor coordinates.

[0] It is easiest to describe the accommodation and vergence responses in terms of dioptres (D) and metre angles (MA) respectively: these are the reciprocal of distance in metres (the MA is the angle through which each eye has rotated from the primary position in order to fixate an object located 1 m away), so that 1 D or MA corresponds to 100 cm, 2 D or MA corresponds to 50 cm, etc.

Table 1 Re-analysis of Fincham's (1962) second table of data (this table supplied the accommodation and convergence responses of eight participants looking at the position of their finger held at 33 cm in darkness). The *first column* indicates the observer, the *second column* identifies the largest response (which we have presumed to be the primary response) and *third column* provides the secondary cross-link response calculated from Fincham's data. The normal VA/V ratio is approximately 0.5 ± 0.2 D/MA and the AV/A ratio around 0.6 ± 0.2 MA/D (McLin and Schor 1988): it may be seen that the calculated cross-link responses are within the normal range. Two participants are of particular note: P.A. exercised convergence without accommodation whilst B.S. showed the converse response (marked by an *asterisk*). B.S. was examined twice but only once accommodated without convergence. B.S. is remarkably similar to an individual (R.P.) observed by McLin and Schor (1988) who, dependent upon task instruction, could exercise voluntary accommodation with or without vergence when changing fixation in an open-loop situation (see text for details)

Observer	Primary response	Cross-link response
R.H.	Convergence = 1.5 MA	VA/V = 0.39
C.S.	Convergence = 1.0 MA	VA/V = 0.56
C.R.Q.	Convergence = 2.5 MA	VA/V = 0.7
P.A.	Convergence = 1.2 MA	Negligible
C.J.	Accommodation = 2.2 D	AV/A = 0.77
P.A.C.	Accommodation = 1.0 D	AV/A = 0.8
L.W.	Accommodation = 0.5 D	AV/A = 0.8
B.S.	Accommodation = 3.0 D	AV/A = 0.42
B.S.*	Accommodation = 1.2 D	Negligible

Fincham's data reveal that one observer was able to drive accommodation independently of vergence, with another observer showing the opposite response. The observer who drove accommodation independently of vergence was retested on another occasion whereupon the accommodation response drove vergence via the normal cross-link. This observation is remarkably similar to that made by McLin and Schor (1988), who studied an individual who could exercise accommodation with or without vergence when voluntarily changing fixation to near in an open-loop situation. McLin and Schor discovered that the different responses were dependent upon task instruction (accommodation worked independently when the observer was asked to "look through" a fixation target). Why task instruction should determine which pathway responds to the spatiotopic signal remains a mystery. Fincham's discovery of an observer who could exercise vergence independently of accommodation agrees with previous reports of proximal vergence independent of accommodation (Hofsetter 1942; Morgan 1944; Ogle and Martens 1957). In summary, limb position does act as a spatiotopic stimulus and, in common with voluntary generation, the stimulus will directly drive only one or the other of the cross-linked systems. Which system directly responds (and the precise nature of the response) appears to be determined by complex factors including task instruction. It is hoped that future research will clarify exactly how the systems respond to spatiotopic input.

The use of limb position as a signal to vergence explains why the illusion occurs in complete darkness: the change in limb position provides an input to the feedforward (spatiotopic) component of the vergence system and can therefore drive vergence in the absence of a visual stimulus. An afterimage is of fixed size so that the nervous system registers a change in distance (via the change in vergence) and the perceived size of the retinal image alters according to Emmert's law. Carey and Allan (1996) made an additional interesting observation: the illusion is not observed if an afterimage is made of one hand and then the *other hand* is moved. This finding is consistent with our explanation if it is supposed that it is the flash-illuminated limb which is providing an input to the vergence system: presumably this input is provided by the limb which is the current focus of attention.

It is also worth noting that the vergence angle account of afterimage size change can explain Taylor's (1941) observation that if an afterimage is viewed whilst the head is moved backwards or forwards, the afterimage will appear to change size. This is expected on the basis of the vergence explanation, as Erkelens et al. (1989) have shown that vergence is altered prospectively on the basis of self-generated head movement. Taylor's observations were later repeated by Gregory et al. (1959), who seemed unaware of Taylor's original report. Gregory et al. also observed that if the afterimage was superimposed upon a moving hand then it would either (i) appear to move with the hand and accordingly change size or (ii) appear to remain fixed in space and not alter its size. It will be seen that observation (i) is an analogue of Carey and Allan's (1996) illusion whilst (ii) corresponds to our no-vergence condition. Gregory et al. also noted that no change was observed when the head and hand were moved together, such that the distance between the two remained constant. This result is predictable if one assumes that the vergence system takes account of the head-hand relationship (Erkelens et al. 1989; Koken and Erkelens 1993).

It might be argued that vergence explains the data we collected using a white card but that the "hand illusion" represents a different case (i.e. afterimages of body parts lead to the use of mechanisms of perceived size quite different from those of other types of object). We note that this argument lacks parsimony and conflicts with the data from our pilot experiments. Indeed, we can see neither theoretical nor empirical justification for proposing such a dichotomous mechanism and prefer not to discuss it further.

We will finally consider some of the applied implications of our proposal. Grossberg and Kuperstein (1989) have developed a biologically plausible computational theory of sensori-motor mapping, in which multimodal maps are developed through early experience. The use of limb position as a source of distance information for the oculomotor system would appear to be consistent with this "empirical" view of human development. It is known that newborn human infants have a fixed vergence angle and demonstrate inaccurate, inconsistent convergence until they reach the age of 3–4 months (Aslin and Jackson 1977). Aslin and Jackson reported that although accurate and persistent vergence tracking may be obtained from a 3-month-old infant, retinal disparity cues do not trigger a vergence response in infants before the age of 6 months.

On the basis of these observations, Aslin and Jackson have proposed that "proximity" cues are primarily responsible for driving vergence in neonates. It seems reasonable to suggest the possibility that limb position plays an essential early role in the development of vergence. The illusion also has relevance to Virtual Reality (VR) systems. VR systems present separate images to the right and left eyes. These images are subsequently fused and located at a distance specified by the resulting vergence angle (Wann et al. 1995). If the VR system presents an image of the user's hand but does not update the position of the image on the basis of hand movements in three-dimensional space, then illusory size changes may occur. The implications of a hand changing size might be of great concern in applications such as remote surgery.

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