

## The role of vergence in the perception of distance: a fair test of Bishop Berkeley's claim

ALEXANDER D. LOGVINENKO<sup>1,\*</sup>, JULIE EPELBOIM<sup>2,†</sup>  
and ROBERT M. STEINMAN<sup>3</sup>

<sup>1</sup> *School of Psychology, Queen's University, Belfast, BT9 5BP, UK*

<sup>2</sup> *Center for the Study of Language and Information, Stanford University, Stanford, CA,  
94305-4115, USA*

<sup>3</sup> *Department of Psychology, University of Maryland, College Park, MD 20742-4411, USA*

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**Abstract**—Binocular eye movements were measured while subjects perceived the wallpaper illusion in order to test the claim made by Bishop Berkeley in 1709 that we perceive the distance of nearby objects by evaluating the vergence angles of our eyes. Four subjects looked through a nearby fronto-parallel array of vertical rods (28–35 cm away) as they binocularly fixated a point about 1 meter away. The wallpaper illusion was perceived under these conditions, i.e. the rods appeared farther away than their physical location. We found that although binocular fixation at an appropriate distance was needed to begin perceiving the wallpaper illusion (at least for naive observers), once established, the illusion was quite robust in the sense that it was not affected by changing vergence. No connection between the apparent localization of the rods and vergence was observed. We conclude that it is unlikely that vergence, itself, is responsible for the perceived distance shift in the wallpaper illusion, making it unlikely that vergence contributes to the perception of distance as Bishop Berkeley suggested. We found this to be true even when vergence angles were relatively large (more than 2 deg), the region in which the control of vergence eye movements has been shown to be both fast and effective.

*Keywords:* Wallpaper illusion; vergence; distance perception; Panum's fusional area.

### INTRODUCTION

The role of vergence in distance perception has been debated for centuries (see e.g. (Boring, 1942, pp. 271–272) (Pastore, 1971) for reviews). The idea that a non-

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\*To whom all correspondence should be addressed. E-mail: a.logvinenko@qub.ac.uk; steinman@brissio.umd.edu

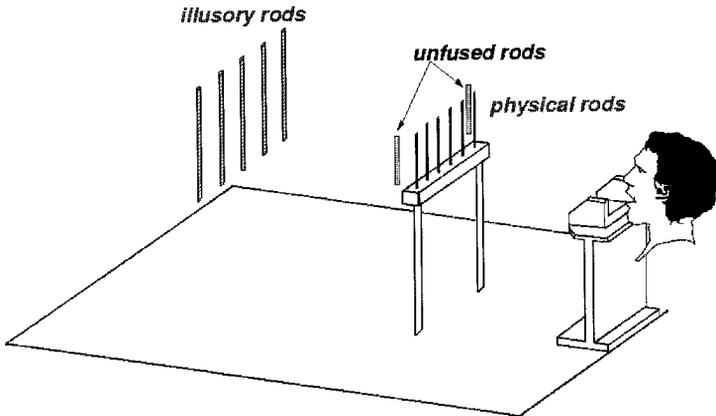
†Deceased, January 10, 2001. Her obituary can be seen in Herst, Epelboim and Steinman, Temporal coordination of the human head and eye during a natural sequential tapping task, *Vision Research* (in press).

visual signal related to the orientation of the two visual axes might serve as a cue for distance perception, was probably first put forward by Bishop Berkeley in the beginning of the 18th century. Specifically, Berkeley claimed that ‘... when an object is placed at so near a distance, as that the interval between the eyes bears any sensible proportion to it, it is the received opinion that the two optic axes (the fancy that we see only with one eye at once being exploded) concurring at the object, do there make an angle, by means of which, according as it is greater or lesser, the object is perceived to be nearer or further off’ (Berkeley, 1709, p. 15). In other words, Berkeley suggested that vergence, itself, is responsible for the perception of absolute distance (i.e. the distance between the observer and the binocularly fixated object), at least for nearby objects.

It took nearly one and a half centuries before Berkeley’s hypothesis, that the vergence angle required to fixate an object binocularly is used to estimate the distance from the observer to this object, was tested experimentally by Wundt (Wundt, 1862). Having found that distance discrimination improved under binocular viewing, Wundt claimed that vergence *might* have contributed to distance perception. Since then, Berkeley’s hypothesis has been both confirmed (Baird, 1903; Swenson, 1932; Grant, 1942; Gogel, 1962; Komoda and Ono, 1974; Foley, 1978; Mon-williams and Tresilian, 1999; Mon-williams *et al.*, 2000), and rejected (Hillerbrandt, 1894; Bourdon, 1902; Bappert, 1923; Heinemann *et al.*, 1959; Crannel and Peters, 1970). Despite its long history, Berkeley’s hypothesis remains controversial (see, Woodworth, 1938, pp. 475–480; Ogle, 1962; Collewijn and Erkelens, 1990; Howard and Rogers, 1995) for reviews). Considerably more effort has gone into discussing Berkeley’s hypothesis than has been devoted to designing and carrying out appropriate experiments.

A proper test of Berkeley’s hypothesis requires simultaneous measurement of both apparent distance and vergence angle. To date, almost all evidence, for, as well as against, vergence as a cue for distance has come from psychophysical experiments in which vergence eye movements were not recorded. Only a single, recent exception is known to the authors, namely, (Logvinenko and Belopolskii, 1994) who recorded the binocular eye movements of observers as they experienced the wallpaper illusion. Collewijn and Erkelens discussed logical reasons and circumstantial evidence against vergence as a cue for distance, but concluded that the contribution of vergence cannot be ruled out because it was not measured in any of the experiments that they reviewed (Collewijn and Erkelens, 1990). They advised that ‘in future studies of the relationship between disparity, vergence and perception it will be important to combine psychophysical techniques with high-quality eye movement recordings in order to avoid ambiguities in the interpretation of results’ (Collewijn and Erkelens, 1990, p. 257). This was the goal of our study.

There have been two different methodological approaches to evaluation of the contribution of vergence to perceived distance. Some researchers tried to isolate vergence and to study the observer’s ability to evaluate the absolute distance to real objects (usually, tiny light sources) in the absence of other potential cues. As a rule,



**Figure 1.** The wallpaper illusion setup. See text for full explanation.

their conclusion concerning the role of vergence in distance perception was negative. An affirmative conclusion has mainly come from stereoscopic experiments where it was shown that vergence was used very likely to scale the information from relative horizontal disparity; or from experiments on wallpaper illusion.

The perception of the wallpaper illusion is traditionally taken as strong evidence in favour of Berkeley's hypothesis (e.g. (von Helmholtz, 1909–1911/1924–1925, p. 316; Lie, 1965; Ono *et al.*, 1971); see also (Nelson, 1975, pp. 46–48; Logvinenko and Belopolski, 1994 for review). There are many different versions of this illusion. The experimental conditions used to establish and study the illusion by Logvinenko and Belopolskii (1994) and in the present report, are shown schematically in Fig. 1.

If an observer looks through a set of vertical rods (the rods near the observer in Fig. 1) while fixating a point beyond it, s/he usually sees the rods farther away than their physical location.<sup>1</sup> The rods appear thicker in size when they are perceived farther away. The rods are perceived to be at a definite and relatively fixed distance from the physical grid. The illusory perceived distance is reported to be very close to the distance predicted from the Keplerian projection of binocular space<sup>2</sup> as given by the following equation (Logvinenko and Sokolskaya, 1975; Logvinenko and Belopolskii, 1994):

$$I = \frac{b}{(b - a)} \cdot A, \quad (1)$$

where  $I$  is the predicted illusory distance, that is, the distance from the observer to the plane at which the illusory rods are perceived;  $A$  is the real (physical) distance from the observer to the grid;  $a$  is the horizontal distance between adjacent rods of the grid; and  $b$  is the observer's interpupillary distance.

The predicted distance  $I$  is the distance at which the eyes must converge to superimpose the right and left monocular images precisely so that adjacent rods (specifically, the left monocular image of the  $i$ th rod and the right monocular image of the  $(i + 1)$ th rod) fuse in binocular space. Note that the left eye's image of the

leftmost rod and right eye's image of the rightmost rod do not have counterparts from the other eye. There is no pair to fuse, and observers see both outside rods as located in or near to the physical plane in which the rods are located. The fact that the illusory rods are localized close to the predicted distance,  $I$ , has encouraged many visual scientists to believe that this illusion comes about because observers use the vergence angle as the basis for their perception of the distance of the illusory rods.

There is an alternative explanation of the wallpaper illusion. It suggests that disparity rather than vergence, provides the basis for the illusion (e.g. Ittelson, 1960, pp. 123–127). The disparity explanation treats the illusion as an apparent depth (relative distance) illusion induced by the relative disparity between the rods and the other objects in the visual scene, which is caused by moving the binocular fixation point beyond the physical plane.<sup>3</sup> Quantitatively, this relative disparity is the difference between the vergence angles at the distances  $A$  and  $I$  in equation (1). It is easy to see that it is the relative distance  $I - A$  that corresponds to this relative disparity. Therefore, without measuring eye movements, one cannot distinguish between the vergence and disparity explanations because the same illusory distance is predicted by both.

In this study, we have attempted to distinguish between the vergence and disparity explanations of the wallpaper illusion by measuring the vergence eye movements of a subject experiencing this illusion. Note that vergence and disparity explanations give distinctively different predictions concerning how the illusion will behave in the presence of vergence eye movements. If the localisation of the rods is based on the relative disparity, which is not affected by the binocular eye movements, no effect on the illusory localisation of the rods should be observed when vergence eye movements are made. On the contrary, by its nature, the vergence explanation predicts that the illusory localisation of the rods is determined by the actual state of vergence and, thus, it will change if the vergence changes.

An experimental test of these predictions was made by Logvinenko and Belopolskii who showed that, while the illusory rods are always seen close to the predicted distance  $I$ , the objective position of the intersection point for the visual axes could deviate considerably from the distance computed in equation (1) (Logvinenko and Belopolski, 1994). It could deviate in both directions, i.e. the lines of sight could intersect in front of and also beyond the plane of the illusion while the illusion was maintained at the distance predicted from equation (1). These results show that vergence does not contribute much, if anything, to the illusory distance characteristics of the wallpaper illusion. Logvinenko and Belopolskii (1994) concluded that they had resolved the vergence/disparity controversy in favour of disparity.

Note, however, that there is an important qualification in respect to this conclusion. As a matter of fact, Berkeley confined his consideration to near distances, forming 'obtuse angles', whereas Logvinenko and Belopolskii used vergence distances beyond 2 meters. At such distances, vergence angles were less than 2 degrees, at the edge of the range in which vergence eye movements become impor-

tant. Vergence eye movements become fast and accurate with objects that are much nearer, within arm's reach. Erkelens with collaborators showed that both saccadic and smooth vergence eye movements were much more effective in this range than had been reported in most prior studies of vergence in which targets were well beyond arm's reach and a far cry from the region in which Berkeley claimed that vergence would be effective (Erkelens *et al.*, 1989a, b).

In view of this evidence and after re-reading Bishop Berkeley's published essay, it seemed necessary to re-examine the role of vergence in the wallpaper illusion within the region of maximally effective oculomotor control. In other words, vergence may have failed to be effective in Logvinenko and Belopolskii's experiment simply because their stimuli fell beyond the range in which the vergence subsystem had evolved to operate efficiently.

This report describes the way in which both components of vergence, saccadic and smooth, operate in the presence of the wallpaper illusion when the illusion is established and changes of vergence angles are large. We found that vergence had no effect, whatsoever, on the illusion even when very large vergence changes were made.

## METHOD

### *Subjects*

Four subjects, RS, AL, YA and JE, 71, 52, 67 and 34 years old, respectively, participated. All were experienced eye movement subjects. All subjects had normal vision once allowance is made for their ages. They did not use spectacle correction during the experiment. Subjects RS, AL and JE are authors of this paper. Subject YA was unaware of the purpose of the experiment, and was paid for his participation.

### *Apparatus*

Details of the Maryland Revolving-Field Monitor (MRFM), used to record eye movements in this study, have been described in detail previously (Edwards *et al.*, 1994; Epelboim, 1995), so only a brief description will be given here.

The MRFM consists of two major parts: (1) a machine that produces three, mutually perpendicular, magnetic fields that revolve at different frequencies (976, 1952 and 3904 Hz) inside the MRFM chamber, and (2) sensor-coils that, when placed inside the chamber, carry an induced current that is dependent on the spatial orientation of the sensor-coils. Each revolving field is produced by two sets of 5-element, a.c. current-carrying coils in a cube-surface coil arrangement (Rubens, 1945). The magnetic field is spatially homogeneous throughout a large fraction (>1 cubic meter) of the volume inside its cubical frame. When a sensor coil is placed inside the MRFM chamber, a.c. current is induced in the coil by the revolving

magnetic fields. The total a.c. current induced in each sensor-coil immersed in this field is a superposition of three sinusoids, each having a different frequency and amplitude. Precision of angle measurement is better than 1' with linearity better than 0.01%. Data were stored at 488 Hz (effective bandwidth = 244 Hz). Sensor coils embedded in a silicone annuli (SKALAR-DELFT), held on each eye by suction, measured horizontal and vertical eye rotations. Head movements were minimized using dental-impression bite-boards. The MRFM uses phase-detection on both horizontal and vertical meridians. This unique quality makes it insensitive to fluctuations in the strength of the magnetic field, and, therefore, capable of absolute calibration. However, the placement of sensor-coils on the eyes varies somewhat from session to session, and had to be measured to determine the orientation of the line-of-sight in terms of the space-fixed MRFM coordinate system. The offsets of the sensor-coils were determined at the start of each experimental session by recording horizontal and vertical eye angles while the subject fixated the image of his pupil in a mirror placed in a known location straight ahead. Five 3-sec 'mirror trials' were recorded for each eye, with the non-viewing eye patched. The means of the angles recorded during these trials were used as horizontal and vertical offsets and subtracted from all eye angles recorded during that session before calculating vergence. Horizontal and vertical vergence angles were computed by subtracting the horizontal or vertical angle for the right eye from the corresponding angle for the left eye.

### *Stimulus*

The stimulus consisted of a horizontal wooden holder (25 cm wide) with holes for placing thin (1.5 mm in diameter) aluminium rods (23 cm long), painted black. The distance between rods, and the placement of the grid were calculated individually for each subject, in order to produce the illusion just in front of the far wall of the chamber. Table 1 shows the stimulus parameters for each subject. A white sheet was placed on the far wall to increase the visibility of the illusion.

The apparent distance to the illusory grid was measured for each subject and each placement of the physical grid in a separate session during which eye movements were not recorded. This was done as follows: after the subject established the illusion, the experimenter moved a marker until the subject told the experimenter that the marker appeared at the same distance as the illusory grid. The measurement was repeated six times and the mean is reported in column 6 of Table 1. The standard error was less than 3% for all four observers.

### *Procedure*

The experiments took place in a well-lit room, with clear views of the walls and the MRFM frame. The subject was seated comfortably, with the head supported on a dental-impression bite-board. The subject started each trial, when ready, by pressing a button.

**Table 1.**

Parameters for the 4 subjects. The variables are the same as in equation (1):  $a$  is the distance between adjacent rods of the grate;  $b$  is the interpupillary distance;  $A$  is the distance from the observer to the grate;  $I$  is the theoretical distance of the illusory grate and 'Illusory distance' is measured apparent distance of the illusory grate. There are 2 entries for subject JE, because 2 different grate distances were used on different days.  $\gamma_A$  shows vergence at the plane of the physical grate;  $\gamma_I$  shows expected vergence at the plane of the illusory grate, derived from equation (1)

Subject	$a$ (mm)	$b$ (mm)	$A$ (mm)	$I$ (mm)	Illusory distance (mm)	$\gamma_A$	$\gamma_I$
RS	45	68.0	273	807	825	14.20°	4.82°
YA	35	56.3	270	714	670	11.90°	4.52°
AL	40	64.0	281	749	758	13.00°	4.89°
JE (1)	35	54.8	280	775	774	11.18°	4.05°
JE (2)	35	54.8	325	900	843	9.64°	3.49°

At the start of each session, the subject performed ten 3-sec trials during which he fixated his pupil in the mirror, in order to determine the offsets of the sensor-coils for this session (see above). Next, the subject performed several tasks. Some tasks were controls used to establish that the subject was capable of performing different types of eye movement and of perceiving the wallpaper illusion. The tasks were as follows:

1. *Smooth vergence tracking*: The subject used smooth vergence movements to track a fixation target that he was moving back and forth along the midline.
2. *Counting physical rods*: The subject made saccades from one to another of the rods making up the physical grid.
3. *Counting illusory rods*: The subject first established the wallpaper illusion, then started the trial, and finally made saccades from one to another of the rods making up the illusory grid.
4. *Changing vergence*: The subject started each trial after establishing the illusion and fixated the leftmost rod in the illusory plane. The subject was instructed to make saccadic jumps between this illusory rod and the leftmost unfused monocular rod, localised near the physical plane. The subject was asked to continue fixating the unfused rod for a few seconds without losing the illusion, before saccading back to the fused rod. At the end of each trial the subject reported if the illusion was lost, if diplopia occurred or if the illusory rods appeared to change location at any time during the trial. The same procedure was repeated for the rightmost fused and unfused rods on alternate trials.

The rationale behind this task was to see how far the subjects could change vergence without losing the illusion. If the subjects could not fixate the monocular rods without losing the illusion, they were instructed to bring the binocular fixation point as close as they could to the physical plane, while maintaining the illusion without diplopia.

## RESULTS

### *The two lines-of-sight did not intersect in a single point*

The very definition of vergence assumes that the lines-of-sight cross in a single point — the point of binocular fixation. However, it was found that the lines-of-sight rarely intersect. In fact, there was always a vertical disparity of monocular images even when observers tried to binocularly fixate the rods as accurately as they could. Such a fixational vertical disparity was also registered in our other experiments, both with the head stabilised on the bite-board, and with the head free to move naturally. We have measured the fixational vertical disparity as an angular length of a line segment that is perpendicular to both lines-of-sight. It can be shown that this line segment is (a) unique and (b) is the shortest distance between the two lines-of-sight. We found that the fixation vertical disparity ranged from 0.2 to 2.5°, depending on the subject. Similar vertical disparities have been observed before (Epelboim *et al.*, 1995).

Such sizeable fixational vertical disparity means that in our experiment there was no point which was really binocularly fixated. Thus, a vergence angle, strictly speaking, did not exist because the lines-of-sight did not intersect. So, we had to redefine the very concept of vergence angle to proceed with our investigation.

In an attempt to redefine vergence, we have chosen to restrict ourselves to only a horizontal plane (horizontal vergence). However, even in this case such a redefinition could be done in different ways. One possible operational definition of horizontal vergence was given in the Method section (as the left-eye-horizontal angle minus the right-eye-horizontal angle).

Another possible operational definition of horizontal vergence in the presence of a vertical fixational disparity uses the ‘point of nearest approach’ between the two lines-of-sight. This point is taken as the virtual binocular fixation point. Horizontal vergence can then be defined as the angle that the two gaze vectors (calculated using measured eye angles and locations of the sighting centres of the eyes) make with this point. The point of the nearest approach is defined as the midpoint of a line segment that is simultaneously perpendicular to both lines-of-sight (the same line segment used to measure fixational vertical disparity).

We found that the difference between the two ways of calculating horizontal vergence rarely exceeded 10 minarc. Because vergence changes reported in this study were large, this difference had no particular significance, so all vergence angles to be reported below were calculated using the simpler calculation, i.e. the difference between the horizontal angles of the two eyes. (For details on measuring sighting centres and calculating this approximate binocular fixation point, also called the ‘cyclopean gaze point’, see Epelboim *et al.*, 1995.)

### *Subjects perceived the illusory grid as a real object in a stable location*

All subjects were able to perceive the illusion. They reported that the illusory rods looked like solid, real objects localized at a definite position in space. Although

there is a small difference between the actual and predicted illusory distance for each subject (see Table 1), this difference is not as large as differences reported by other researchers (e.g. Ono *et al.*, 1971). Probably, this difference could be accounted for by unavoidable errors in measuring observers' interocular distance.

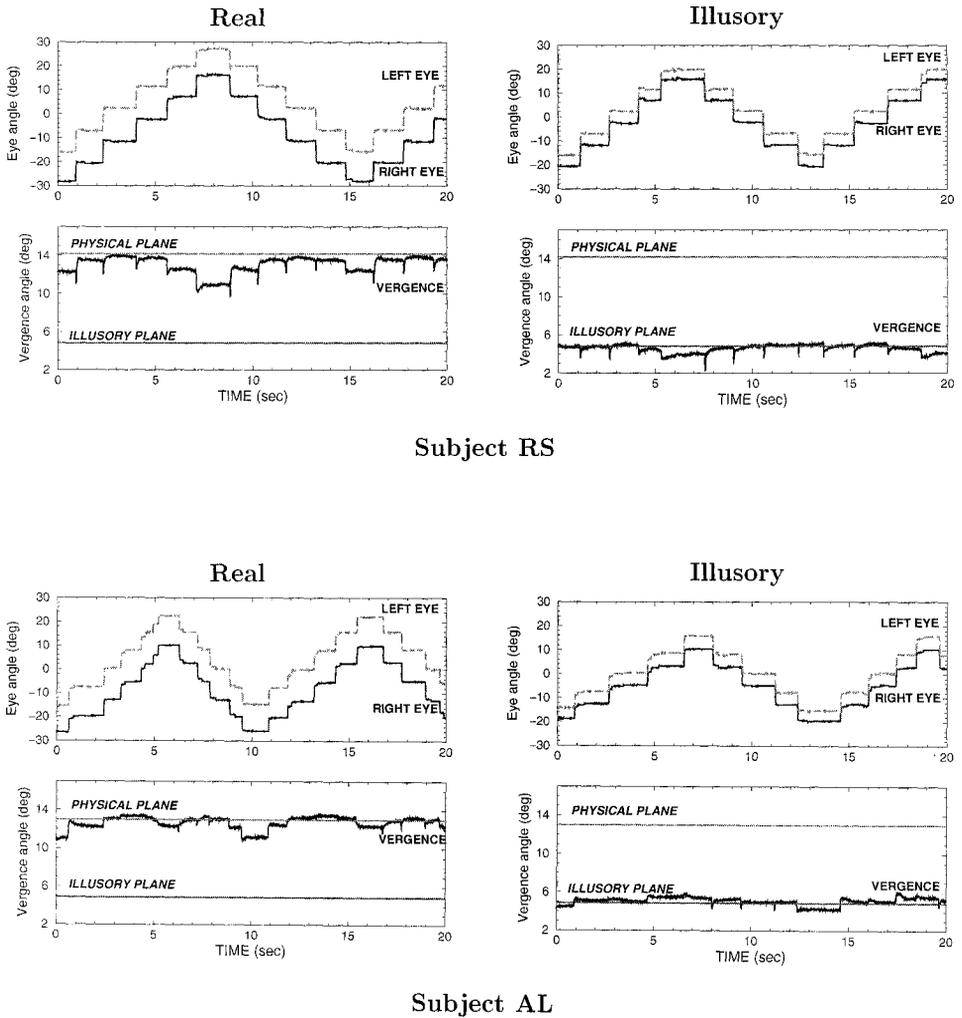
Subjects also reported that they could shift their gaze freely within an extended volume of space without losing the illusion, or experiencing diplopia.<sup>4</sup> The size of this volume varied among our subjects. Subjects could count the illusory rods by saccading from one rod to the next as easily as they could count the physical rods. Eye movements of subjects RS and AL during this task are shown in Fig. 2. Surprisingly, when counting the illusory rods, the subjects kept the vergence angle at the level that corresponded to the illusory plane better than they kept the vergence angle at the physical plane when they counted the physical rods. The size of the saccades they used to count was the same in the two tasks. This was to be expected because the angular distance between the illusory rods was the same as the angular distance between the physical rods.

#### *Vergence changes did not have an effect on the localisation of the illusory grid*

The size of vergence changes under which the illusion could be maintained varied among the subjects. All subjects could change vergence by at least  $1^\circ$  while maintaining the illusion and avoiding diplopia. Figures 3–6 show individual eye movement records for the four subjects, as they made saccadic vergence movements from the illusory plane in the direction of the physical plane (see Method, task 4). All trials shown in Figs 3–6 are trials during which subjects never lost the illusion, never experienced diplopia (except for brief periods of diplopia for JE in Fig. 6b) and never observed any changes in the location of the illusory rods. The details of each subject's behaviour will be described next.

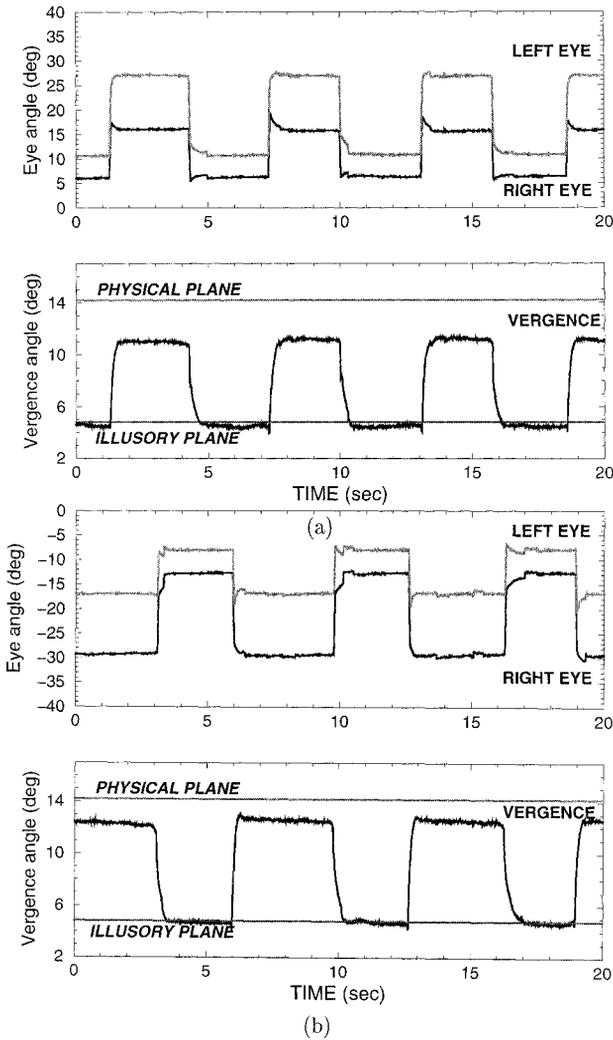
*Subject RS.* RS was the most experienced eye movement subject of the four. His first eye movement records were published 36 years ago (Steinman, 1965). He was able to make the largest deviations from the illusory plane, moving his gaze almost all the way to the physical plane, and holding his binocular gaze at that vergence level for a long time. For example, in Fig. 3, RS makes vergence changes of  $>7^\circ$  from the illusory plane, maintaining vergence at  $12^\circ$  for 3–4 sec. Note, that for RS the level of vergence angles for the illusory and physical planes were  $4.82^\circ$ , and  $14.2^\circ$ , respectively (see Table 1). Fixating near the physical plane, while maintaining the illusion, did not require any special effort on his part. RS could keep his binocular gaze at the vergence level of  $12^\circ$  indefinitely without losing the illusion or experiencing diplopia. Furthermore, the illusion did not appear to change location even after the largest saccadic vergence changes.

*Subject YA.* YA had been an eye movement subject on and off for about a year and a half, but his participation in this experiment was his first contact with the



**Figure 2.** Subjects counting real and illusory rods. Horizontal eye angles are plotted as a function of time. Positive numbers represent angular direction to the right of straight ahead. Negative numbers represent angular direction to the left of straight ahead. The graph on the bottom of each plate shows vergence, calculated as left eye angle minus right eye angle. Larger numbers (i.e. vergence angles) indicate that the eyes converged more. The lines labeled ‘physical plane’ and ‘illusory plane’ correspond to theoretical values of vergence angles when binocularly fixating the center of the physical and illusory planes, respectively. Since only central rods lie on the horopter, the vergence for the peripheral rods is actually somewhat smaller than for the central rod.

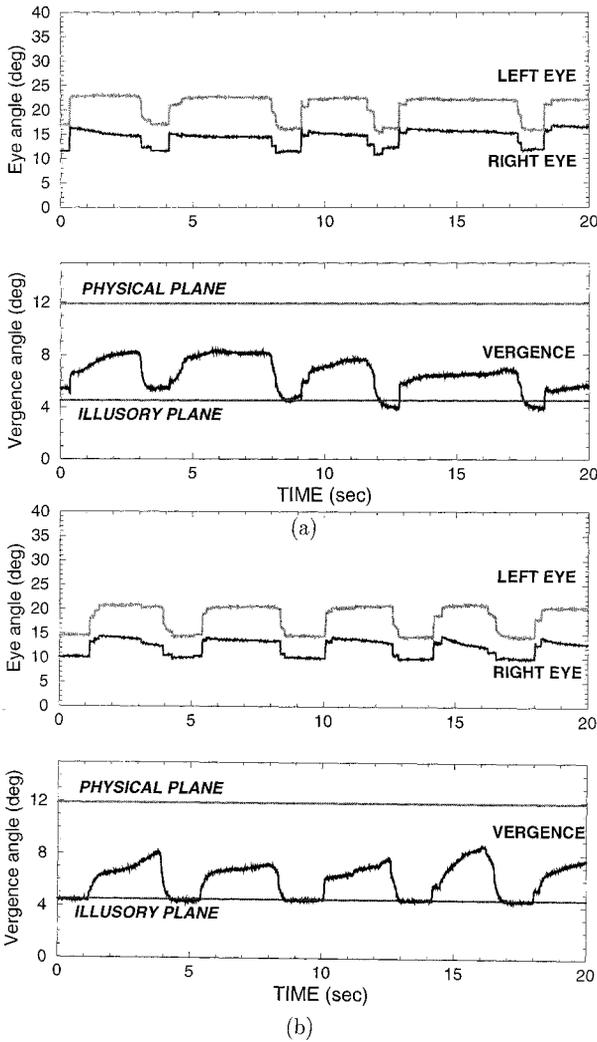
wallpaper illusion. YA was naive as to the purpose of the experiment. He also had no prior practice with making saccadic vergence changes on a bite-board in a laboratory setting. Nevertheless, he did not have any problems either establishing or maintaining the illusion. His illusion was very strong, and he never experienced diplopia after the illusion had been established. Figure 4 shows that YA was able



**Figure 3.** Horizontal and vergence eye movements for subject RS as he made vergence changes while perceiving the wallpaper illusion. Two trials are shown. See Fig. 2 for explanation of the axes.

to make vergence changes of over  $4^\circ$  (a) while maintaining the illusion. His typical vergence changes were  $2\text{--}3^\circ$  (b). YA, like RS, was able to maintain the illusion indefinitely at its original location, while holding binocular gaze away from the illusory plane by at least  $2\text{--}3^\circ$ .

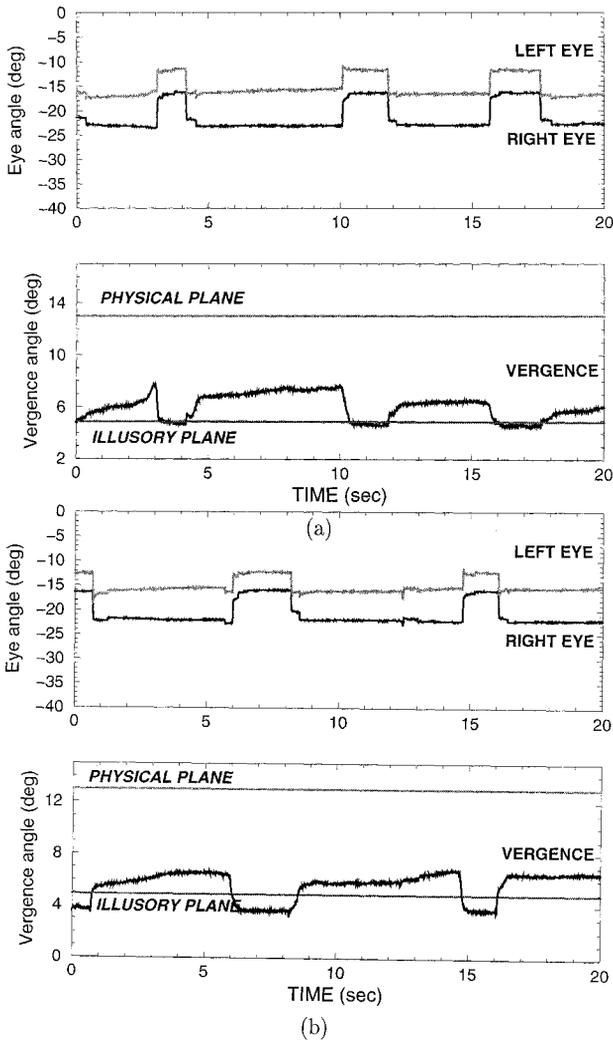
*Subject AL.* AL has been studying the wallpaper illusion over 25 years (Logvinenko and Sokolskaya, 1975). He has had, however, only limited experience as an eye movement subject. AL had more difficulty making saccadic vergence changes in this experiment than either RS or YA. However, in his best case, shown in Fig. 5a, AL was able to maintain a stable illusion while holding gaze 2 degrees off the il-



**Figure 4.** Horizontal and vergence eye movements for subject YA as he made vergence changes while perceiving the wallpaper illusion. Two trials are shown. See Fig. 2 for explanation of the axes.

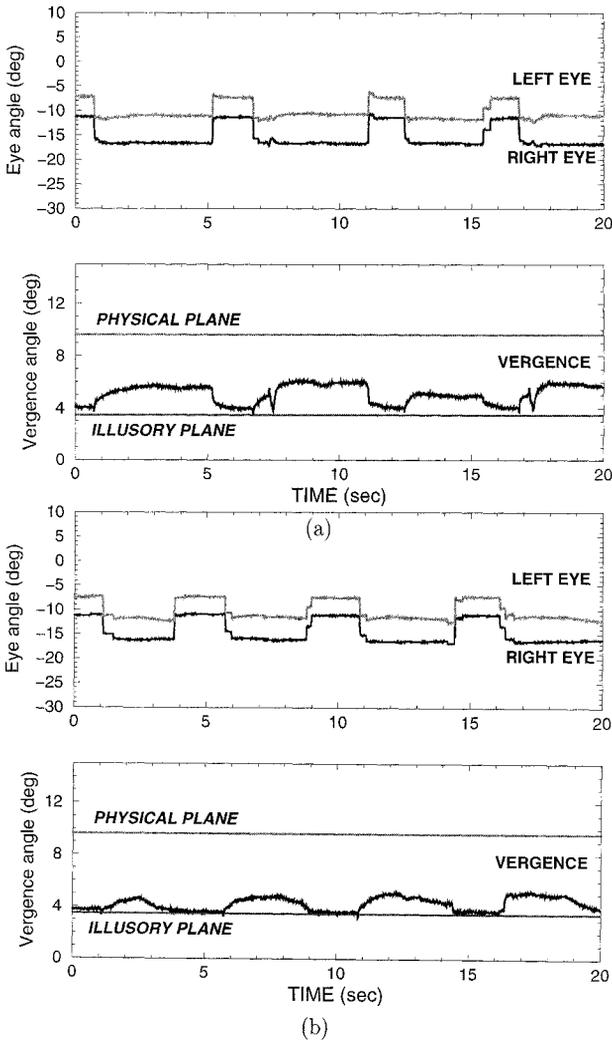
lusory plane. AL, like RS and YA, could hold his gaze at this location indefinitely without losing the illusion, experiencing changes in localisation of the illusion, or experiencing diplopia. In the more typical trial, shown in Fig. 5b, AL moved his gaze beyond the illusion and in front of the illusion by about  $1^\circ$  and held it there for about 5 sec., while keeping the illusory rods at their original location and without experiencing diplopia.

*Subject JE.* JE has participated in eye movement experiments for almost 10 years, but she had never experienced the wallpaper illusion prior to the present study. She was able to experience a stable illusion and maintain it without effort



**Figure 5.** Horizontal and vergence eye movements for subject AL as he made vergence changes while perceiving the wallpaper illusion. Two trials are shown. See Fig. 2 for explanation of the axes.

while fixating near the illusory plane. However, she had difficulty making saccadic vergence changes away from the illusory plane without experiencing some diplopia. Typically, she experienced brief periods of diplopia after each saccade. The typical amount of diplopia was about 10% of the horizontal distance between adjacent rods. JE's diplopia usually lasted for a fraction of a second, after which the rods fused. One of JE's best trials is shown in Figure 6a. During this trial, she was able to hold gaze  $1-1.5^\circ$  away from the illusory plane, while maintaining the illusion in its original location and without any diplopia. Figure 6b shows a more typical trial where JE made smooth vergence changes about  $1^\circ$  away from the illusory plane while maintaining the illusion, and with only brief periods of diplopia.



**Figure 6.** Horizontal and vergence eye movements for subject JE as he made vergence changes while perceiving the wallpaper illusion. Two trials are shown. See Fig. 2 for explanation of the axes.

## DISCUSSION

We found, in a ‘fair’ test, that Berkeley’s classical explanation of the wallpaper illusion, which is based on vergence, itself, does not explain the illusion even when vergence angles are quite large, the kind of angles Berkeley thought provided information about depth. The failure of vergence to explain the wallpaper illusion had been reported previously for small ( $<2^\circ$ ) vergence angles by Logvinenko and Belopolskii (1994). This fact is particularly striking when large vergence angles are considered. Consider, for example, the eye movement record of RS in Fig. 3 when he fixated the single monocular image of one of the outer rods while maintaining

the illusion (there was no counterpart for this rod in his opposite eye). The record shows that RS binocularly fixated the point that was quite close to the physical plane, where the monocular images of the outer rods were localized, and at the same time, experienced the illusory rods as if they were positioned nearly 1 meter away. In other words, RS's vergence informed his visual system that the rods were near the actual physical plane, whereas RS perceived the rods at the illusory plane. Furthermore, this paradoxical localization could last for tens of seconds, which shows that it cannot be accounted for by any sort of hypothetical visual inertia or persistence since it would be unlikely that such a mechanism would operate for such a long time.

The present experiment, as well as the prior, similar experiment (Logvinenko and Belopolskii, 1994) clearly show that while binocular fixation at the proper distance [defined by equation (1)] is needed to start experiencing the wallpaper illusion, especially for naive observers, once established, the illusion is quite robust despite vergence changes made when the illusion is perceived. Changing the actual positions of the visual axes had no effect on either the stability of the illusion or on its apparent distance. Our objective measurements confirm our subjective experience when the illusion is observed, namely, one can move the eyes freely without losing the illusion. Such eye movements have no effect on the illusory localization of the apparent rods. It follows that there was no connection between the apparent localization of the rods and the vergence setting in our experiment. Our subjects did not use information from vergence eye movements even when they fixated within distances ( $>2^\circ$ ) where vergence is most effective and accurate. Once we take into account similar results reported for vergence angles less than  $2^\circ$  (Logvinenko and Belopolskii, 1994), we think it exceedingly unlikely that vergence is a direct determinant of the illusory distance shift observed in the wallpaper phenomenon.

It seems natural, therefore, to consider an alternative, disparity explanation which asserts that the apparent distance shift in the wallpaper illusion is due to binocular disparity rather than to vergence. In other words, it suggests that the wallpaper illusion is an apparent depth phenomenon rather than an illusory shift in absolute distance.

Of the many types of binocular disparity relevant to depth perception, (see, Howard and Rogers, 1995, chap. 7, for review), the most obvious candidates for the determinant of the wallpaper illusion seem to be absolute and relative horizontal disparities (see Ogle, 1962; Logvinenko, 1981, pp. 100–108; Collewijn and Erkelens, 1990 for discussions of two kinds of horizontal disparity, absolute and relative, and their role in binocular depth perception). Indeed, after the illusion is established, vergent eye movements produce an absolute disparity of the rods which could, in principle, be used to localise the rods relatively to the point of intersection of the visual axes. However, our ability to evaluate absolute disparity is known to be quite poor (see Collewijn and Erkelens, 1990 for review), so the absolute horizontal disparity is not likely to be responsible for the wallpaper illusion.

We believe, like most if not all other researchers, that it is relative disparity that is responsible for the wallpaper illusion. However, it is not obvious which elements of the stimulus provide the relative disparity in this case. It should be kept in mind that after the left and right arrays of the monocular images of the rods are laterally shifted over each other by divergent eye movements causing them to fuse at the first farther level of the Keplerian projection, an incorrect binocular match of the rods results. Specifically, at the first level of the Keplerian projection, each  $(i + 1)$ th left monocular image comes into correspondence with (has the same visual direction as) the  $i$ th right monocular image. However, the other objects in the visual scene, including the holder to which the rods are attached, are matched correctly. Therefore, a relative disparity emerges between the holder (and other correctly matched objects) and the mismatched rods. For example, when the point of binocular fixation is at the distance  $I$  as defined in equation (1), the absolute disparity for the mismatched rods (the  $(i + 1)$ th left with  $i$ th right monocular image) is zero (no diplopia) whereas it is non-zero for the holder. Certainly, when the eyes move (without breaking the established incorrect binocular matching), the absolute disparity values for the mismatched rods and the holder will change, but the difference between them, the relative disparity, will remain same. In other words, the relative disparity between the holder and mismatched rods remains constant despite vergence eye movements unless the binocular matching is changed. When the binocular matching changes, the illusion is broken. We believe that this relative disparity between the holder (and other correctly matched objects) and the mismatched rods is likely to be responsible for the illusory perception of distance in the wallpaper illusion.

It should be noted, however, that having accepted the binocular disparity explanation, we encounter a new and different problem. It is known that to experience depth and single stereoscopic vision, disparity should not exceed a threshold value and be within the range called Panum's fusional area (e.g. Ogle, 1950). Experimental measurements of Panum's fusional area made by different researchers differ. They depend a great deal on the particular experimental conditions. For example, Panum's area gets broader when tested outside of the centre of the visual field (Ogle, 1952; Blakemore, 1970), or when tested with stimuli of low spatial and temporal frequency (Schor and Tyler, 1981; Schor *et al.*, 1984). Measured Panum's areas are usually only minutes of arc for parafoveal vision (e.g. Ogle, 1950; Mitchell, 1966; Woo, 1974; Tyler, 1991; Howard and Rogers, 1995). It is obvious in the individual records shown in Figs 3–6 that our observers could see the illusory rods without diplopia despite of disparities of several degrees.

For example, for observer RS (Fig. 3), the difference between the vergence angles corresponding to the two fronto-parallel planes between which he could easily jump back and forth without experiencing diplopia, was more than  $7^\circ$ . It means that the binocular image of the rods remained fused when disparity was more than  $7^\circ$ . Observers JE and AL were able to sustain a single fused vision for rather narrower

disparity range — about  $1-3^\circ$ , but even these values exceed the textbook values of Panum's fusional area for parafoveal vision.

It is known that single binocular vision can result either from fusion itself, or from binocular suppression of one of the two monocular images (Ogle, 1962). It was easy to show that there was no binocular suppression in our experiments. One can easily find out whether a single binocular image is a result of fusing two different monocular images of adjacent rods, or just a single diplopic image from one rod with the other diplopic image of the rod being suppressed. One simply needs to make each rod distinctive. We did this and found that when we made small marks of different colours on two adjacent rods both marks could be seen in the fused binocular image of the rod. This observation proves that it is fusion rather than binocular suppression that took place in our experiments.

There is clear phenomenological evidence for the fact that, during the wallpaper illusion, relative disparities very far beyond the Panum's fusional area can be experienced without diplopia. This had been shown previously by Logvinenko and Sokolskaya (1975) who reported that one can perceive the wallpaper illusion from a compound grid when two illusory arrays of rods at two different apparent distances are experienced as single and fused at the same time (see also Nakamizo *et al.*, 1999). The relative disparity corresponding to a depth shift between these two arrays of single fused rods was even larger (up to  $10^\circ$ ) than in the present experiment. So both the present study, as well as the study of the wallpaper illusion induced by a compound grid, shows that single binocular vision is possible despite disparities that exceed the established limits of Panum's fusional area.

Fender and Julesz (1967) reported disparities considerably greater than Panum's fusional area in experiments with random-dot stereograms. These findings were replicated by a number of other investigators (Steinman *et al.*, 1985; Piantanida, 1986; Erkelens, 1988). There is a similarity between how fused random-dot stereograms resist breaking down when disparity increases far beyond Panum's fusional area and how the wallpaper illusion resisted breaking down in our study. It should be noted, however, that neither Fender and Julesz nor the subsequent authors reported single binocular vision when disparity was in excess of two degrees.

So, if one accepts the disparity, or stereoscopic, explanation of the wallpaper illusion, one must now explain why the disparity limits for single stereoscopic vision become so large and flexible in the case of the wallpaper illusion. Or, to put it the other way round, why are the reported disparity limits so low and rigid in the case of standard stereoscopic vision?

Regardless of the ultimate answer to this question, it is clear that simultaneous observations of vergence eye movements and apparent distances made while subjects saw the wallpaper illusion allow us to conclude that this illusion is not based on vergence angle. Therefore, the wallpaper phenomenon cannot serve as the evidence that vergence is a cue for distance perception as Bishop Berkeley proposed so long ago. Does it mean that Bishop Berkeley's speculation can finally be laid to rest, just a decade short of its 300th anniversary? We think it does unless one

believes that a fair test of Bishop Berkeley's hypothesis can be done only in the absence of all other potential cues.

Although the latter view is accepted by visual scientists, there is no reason to believe that all cues except vergence must be eliminated to test Bishop Berkeley's hypothesis. This approach has its own shortcomings. First of all, it is virtually impossible to be sure that all the cues except vergence have been eliminated. Moreover, in those experiments in which vergence was presumably isolated, strong evidence for a role of vergence in distance perception has not been obtained (e.g. Crannel and Peters, 1970). It is generally accepted that the strength of a cue depends on which other cues are also available. That is, cue *A* may be weaker than cue *B* but in the presence of another cue *C*, it may be stronger. So, it is possible that vergence which is ineffective when isolated, may be effective in the presence of other cues. Therefore, if one wishes to understand the role of vergence in normal perception (i.e. perception in the natural world) one should evaluate its role under natural conditions. The wallpaper illusion provides an opportunity to do this. We found that a systematic variation of vergence did not affect illusory localisation in the wallpaper illusion and we conclude that, first, the wallpaper illusion cannot be used as evidence for vergence as a cue for distance perception; and second, it is unlikely that vergence, itself, can provide a reliable cue for the perception of absolute distance.

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### **NOTES**

1. Perceiving this illusion requires some effort and it sometimes is necessary to provide a real fixation target before the illusion can be perceived by someone who has never seen it before. There is no need to provide a real fixation target, however, after the illusion has been seen a few times. Once it has been seen, the illusion is perceived effortlessly without a real fixation target. The illusion comes out vividly when only an imaginary target is provided. For this reason when we say 'fixation target' we always mean an 'imaginary' fixation target unless we say otherwise.
2. See e.g. Tyler, 1991; Howard and Rogers, 1995 for more about the Keplerian projection of binocular space.
3. The disparity explanation has gained support from the discovery that the wallpaper illusion can be produced by using a single random-dot pattern which is viewed by both eyes. This pattern is called an 'autostereogram' because its

design is similar to the classical random-dot stereogram (Tyler, 1983, p. 40). The autostereogram challenges any vergence-based explanation since it provides no visual cues for vergence eye movements.

4. It should be stressed that the spatial location of the illusory grid remained unchanged when the subjects made such shifts. It was easy for the subject to be sure, and report, that the spatial location had not changed because the experiment was conducted in an illuminated room that contained many visible objects. This meant that the position of every illusory rod was easily ascertained simply by noticing its position relative to the objects on the desktop holding the physical grid responsible for the illusion. If the illusion changed, or was lost, during any trial, the subject said so, and this trial was excluded from further analyses. Fortunately, very few trials were dropped for this reason.

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