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Focusing on an illusion: Accommodating to perceived depth?

Trent Koessler, Harold Hill*

School of Psychology, University of Wollongong, NSW 2522, Australia

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ABSTRACT

Ocular accommodation potentially provides information about depth but there is little evidence that this information is used by the human visual system. We use the hollow-face illusion, an illusion of depth reversal, to investigate whether accommodation is linked to perceived depth. In Experiment 1 accommodation, like vergence, was in front of the physical surface of the mask when the mask was upright and people reported experiencing the illusion. Accommodation to the illusory face did not differ significantly from accommodation to the physically convex back surface of the same mask. Only accommodation to the inverted mask seen as hollow was significantly less and, like the physical surface, beyond the mid-plane of the mask. The effect on accommodation was the same for monocular as binocular viewing, showing that accommodation is not driven by binocular disparities through vergence, although voluntary vergence remains a possibility. In Experiment 2 a projected random dot pattern was used to flip perception between convex and concave in all presentation conditions. Accommodation was again in front of the physical surface when the illusion was experienced. Experiment 3 showed that projected dots are more effective in disambiguating the illusion as concave when they are sharp and provide a good accommodative stimulus than when they are objectively blurred. We interpret Experiments 1 and 2 as showing that accommodation is tied to perceived depth, directly or indirectly, even in a situation where multiple depth cues are available and feedback is not artificially open-looped. Experiment 3 is consistent with accommodation helping to disambiguate depth while not ruling out alternative explanations.

1. Introduction

The hollow-face illusion is the perception of a concave mask as a convex face (Brewster, 1826; Gregory, 1970). When we experience this illusion perceived depth diverges from physical depth. For example, the nose of an illusory face appears convex and thus closer than the illusory cheek although, physically, the cheek is closer. Here we measured whether people accommodate to the physical concave surface of the mask or to the illusory convex face when experiencing the illusion. If accommodation simply serves to minimize blur and maximize contrast through closed loop feedback we would expect accommodation to be to the physical surface. However, if accommodation is tied to depth perception it would be to the illusory depth.

It has been appreciated since at least Descartes and Berkeley that ocular accommodation, the focusing of the eye to bring objects into focus on the retina, has the potential to provide information about absolute egocentric distance, at least at close distances (Howard, 2012). More recently accommodation has been demonstrated to contribute to depth perception in a variety of animals including chameleons (Harkness, 1977; Ott, Schaeffel, & Kirmse, 1998), sandlances (Pettigrew, Collin, & Fritsches, 2000), toads (Collett, 1977), and barn owls (Wagner & Schaeffel, 1991). Evidence that accommodation contributes to human depth perception is much weaker. In a study where depth information was limited to accommodation, Fisher and Ciuffreda (1988) found that observers' mean accommodative state and finger-slide estimates of depth were linearly related to changes in the distance of high contrast patterns from 16 to 50 cm when accommodation was the only depth cue available. However, in a similar study, Mon-Williams and Tresilian (2000) replicated the finding but noted that, while the average reaching was related to accommodation at least in some observers, individual trials were not. While apparent absolute depth indication was highly variable, observers were generally accurate at indicating the direction of the change in distance, the ordinal depth difference, between one trial and the next. Mon-Williams and Tresilian concluded that accommodation can provide ordinal depth information when other information is not available but questioned its contribution to depth perception under full-cue conditions. Other evidence suggests that the detection of depth order does not require a change in accommodation but is specified in focus blur given long enough exposure and chromatic illumination (Nguyen, Howard, & Allison, 2005). Blur is both a pictorial depth cue (Mather, 1997; Pentland, 1987; Watt, Akeley, Ernst, & Banks, 2005) and the primary retinotopic stimulus for reflex

* Corresponding author.
E-mail addresses: trentk@uow.edu.au (T. Koessler), harry@uow.edu.au (H. Hill).

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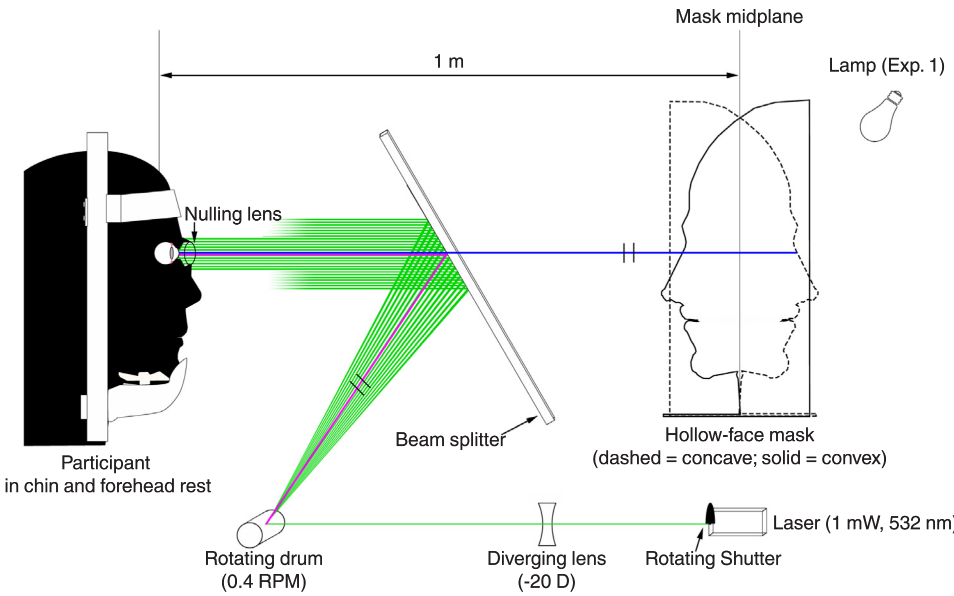

Fig. 1. Diagram of the experimental set up for measuring accommodation in Experiments 1 and 2. For participants a virtual image of the laser speckle pattern reflected off the beam splitter appeared superimposed on the bridge of the nose. The diagram depicts the location of the mask when both its upright concave and convex surfaces were presented (i.e. as 180° rotation around its vertical axis). In Experiment 2 the lamp was replaced with illumination from the projector. For Experiment 3 the set-up was the same as for Experiment 2 but accommodation was not measured. Please see text for details. Not to scale.

accommodation (Phillips & Stark, 1977; Schor, Alexander, Cormack, & Stevenson, 1992) even when below its threshold for perceptual detection (Kotulak & Schor, 1986). While monochromatic focus blur is ambiguous with regards the sign of depth relative to the focal plane, the accommodative system appears to be able to use chromatic and other aberrations (Kruger & Pola, 1987), the Stiles-Crawford effect (Fincham, 1951), and the dynamic blur produced by low level oscillation of the system (Charman & Heron, 1988; Yao, Lin, Huang, Chu, & Jiang, 2010) to adjust accommodation in the correct direction when changing depth of fixation. Under normal viewing conditions perceived layout of the scene may also be important in ensuring accommodation adjusts in the appropriate direction during saccades (Schor et al., 1992). There is some evidence for perceptually-appropriate proximal accommodation to pictorial depth but results are contradictory as to whether this occurs with binocular viewing and closed-loop feedback from optical blur (Takeda, Hashimoto, Hiruma, & Fukui, 1999; Takeda, Iida, & Fukui, 1990) or is restricted to conditions where accommodation and disparity vergence are open loop (Busby & Ciuffreda, 2005). There is also a report that accommodation does not change as a function of percept when viewing a three-dimensional Necker cube monocularly if accommodation is closed-loop (Ellis, Wong, & Stark, 1979).

Accommodation is known to be synkinetically linked to binocular vergence (Fincham & Walton, 1957). The recovery of depth from accommodation may also be mediated by accommodative vergence even when viewing is monocular (Mon-Williams & Tresilian, 2000). The evidence that vergence contributes to human depth perception is stronger than that for accommodation (Tresilian, Mon-Williams, & Kelly, 1999). People are also known to verge in front of the physical surface when viewing both the hollow-face (Grosjean, Rinkenauer, & Jainta, 2012; Hoffmann & Sebald, 2007) and another example of three-dimensional depth reversal, a reverspective painting (Wagner, Ehrenstein, & Papathomas, 2009). This is despite the availability of the binocular disparities that would normally be expected to provide closed-loop feedback supporting accurate vergence to the physical surface (Wismeijer, Van Ee, & Erkelens, 2008).

The hollow-face illusion constitutes a valuable test stimulus for investigating depth perception, including the role of ocular cues, for a variety of reasons. Firstly, it is a compelling and cognitively impenetrable example of a depth reversal that works for a three-dimensional object viewed by a mobile binocular observer. It also does not involve artificial cue conflict as all available optical and ocular cues are directly determined by the structure of a physical object. Additionally, although a three-dimensional (3D) hollow-face mask is seen as hollow at close distances, photographs of the same mask are difficult if not impossible ever to see as hollow even when the photographs are presented stereoscopically (e.g. Matthews, Hill, & Palmisano, 2011) or as sequences of images in video or as simulated motion parallax (Rogers & Hill, 2013). This suggests that ocular depth information may be of particular importance in disambiguating the concave shape of 3D masks at close distances. A role for accommodation in disambiguating the mask is also consistent with previous findings that refractive error (Hill, Palmisano, & Matthews, 2012) and pinhole viewing (Koessler & Hill, 2015) both strengthen the illusion as both manipulations would be expected to disrupt accommodation despite their very different effects on blur. The effectiveness of the hollow-face illusion (e.g. Fig. 4a) may be in part because it constitutes a poor accommodative stimulus due to its lack of high spatial frequency content such as sharp contours (Charman & Tucker, 1977; Fisher & Ciuffreda, 1988).

We used laser speckle optometry to measure accommodation (Knoll, 1966; Leibowitz & Hennessy, 1975). This is an indirect subjective measure where observers report the apparent direction of motion (if any) of a speckle pattern produced by reflecting a laser off a rough rotating surface. If observers are focusing at the distance of the rotating surface producing the interference pattern the speckles appear to 'boil' without any coherent motion. If instead observers are focusing at a shorter or greater distance than that surface, parallax effects mean that they experience coherent motion in one of two opposite directions. Direction is determined by whether the speckle pattern is being focused in front of, or behind, their retina and thus indicates their state of accommodation relative to the reflecting surface. The set-up used here (Fig. 1) was such that the speckle pattern appeared superimposed on the mask and observers could make the judgement about speckle movement while viewing the mask. Distances and calibration were such that accommodation to the mid-plane of the mask would not result in any apparent motion while accommodation in front of or behind that plane, as would be expected for a convex or a concave surface respectively[1], would result in opposite directions of apparent motion. The task

[1] As pointed out by a reviewer, if the point of fixation was perceived at its actual distance with the rest of the illusory face perceived as behind this, there would be no fixation disparity. Previously authors have assumed that the illusory face is in front of the physical face (e.g. Fig. 1 in Hoffmann & Sebald, 2007) and this is consistent with the finding that observers verge in front of the physical surface when experiencing the illusion. Here we seek to measure where people verge and accommodate with respect to the physical surface without making assumptions about, or trying to determine, where they perceive the

for the observers is simply to judge whether the speckles appear to be moving upwards, downwards or not at all. After observers initially reported any apparent motion of the speckle pattern, positive or negative lenses were used to null the speckle motion with the strength of the lens required providing an estimate of the magnitude as well as direction of accommodation relative to the mid-plane (Ingelstam & Ragnarsson, 1972). In Experiments 1 and 2 we measure accommodation to the hollow mask both when seeing the mask as hollow and when experiencing the illusion of a convex face. As a control we also measured accommodation to the convex side of the same hollow mask.

2. Experiment 1

2.1. Introduction

The aim of Experiment 1 was to measure accommodation both while participants reported seeing a hollow face mask incorrectly as convex and when they saw the mask correctly as concave. The mask was presented upright or inverted and viewed monocularly or binocularly as these are manipulations known to affect the strength of the illusion and thus have the potential to result in different percepts at the viewing distance used here, one metre. The convex back surface of the same mask was also presented under the same viewing conditions to provide a comparison condition where there is no change in percept. Vergence was measured both to replicate previous reports that vergence is towards the illusory surface (Grosjean et al., 2012; Hoffmann & Sebald, 2007) and to monitor the extent to which vergence and accommodation covaried.

2.2. Methods

2.2.1. Participants

All research was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) under the University of Wollongong Human Research Ethics Committee application HE14/078. All participants provided informed written consent before participating.

Ten observers (three females) with a mean age of 22 years (range 15–39) took part in Experiment 1. Inclusion criteria were that participants did not normally wear glasses, exhibited stereo-acuity equal to or better than 60 arc-seconds, and visual acuity equal to or better than a logMAR ratio of 0.0 for both eyes together and for each eye separately. Measured acuities are provided in the raw data for this experiment, supplementary materials file E1data.xlsx. For Experiment 1 technical issues with image quality prohibited the eye-tracking data for three participants from being analysed. Replacement eye-tracking data but not lens nulling data were collected for two replacement participants from the same demographic.

It is possible that some of participants in the experiments reported were mildly hyperopic or presbyopic. As all comparisons were within subjects neither of these possibilities would be expected to lead to differences between conditions.

2.2.2. Materials

2.2.2.1. Face mask. A 35.0 cm wide × 44.5 cm high × 10.5 cm deep hollow-face mask in a 35.0 cm × 44.0 cm surround was used for all experiments reported (Fig. 4a). The mask was positioned 1 m from the seated observer's chin rest, at head height and perpendicular to their line-of-sight projecting a visual angle of approximately 20° by 25°. In Experiment 1 the mask was lit from one side and slightly above and behind using a halogen lamp (12 V 50 W; 700/900 LM, 3050 K colour temperature).

2.2.2.2. Calibration object. A three-plane transparent rhomboid with a high contrast printed focus target placed on each plane was used as an accommodative calibration target at the start of testing. Focus targets were equidistant and 5 cm from each other and from the virtual image of the speckle pattern in the frontal plane. The distance between the outer vertical planes of the rhomboid (i.e. front- and back-faces of the object relative to the viewer) was approximately equal to the depth of the hollow-face stimulus, 10.5 cm.

Both visual stimuli were viewed through a matte black bordered 20.0 cm × 32.5 cm aperture 50 cm from the viewer and mid-plane of the mask (visual angle 23° × 36°) that served to occlude other parts of the apparatus.

2.2.2.3. Laser speckle optometer. A laser speckle optometer was custom built for the experiments (Leibowitz & Hennessy, 1975) (Fig. 1). A 1 mW, 532 nm bench mounted laser was used with its beam diverged through a -20 D lens and reflected off a 28 mm radius rotating drum to generate the speckle pattern. A semi-reflective polycarbonate sheet situated at approximately 45° to the mask base was used as a beam-splitter allowing the speckle pattern to appear superimposed on the centre of the bridge of the nose of the mask (visual angle approx. 1.5°) for both upright and inverted orientations. No laser light was reflected from the actual mask. The reflecting drum rotated at 0.4 rpm controlled using micro-controlled (Arduino Uno) and driver-regulated (Pololu DRV8825) stepper motors.

Subjective measures of accommodation such as the laser speckle optometer can differ from their objective counterparts. Post, Johnson, and Owens (1985) showed that effort to see or mental tasks changes accommodative measures in some subjects. As this experiment involved a calibration stage, was within-subjects, and the order of trials within subjects was randomised, we believe any effect of, for example, differences in effort to see or distraction are minimised. Another concern recognised by Hennessy and Leibowitz (1972) was that the pattern itself may be an accommodative stimulus when presented for periods of 500 ms or longer. To ensure that exposure time to the speckle pattern was less than 500 ms a semicircle of cardboard was attached to the front of the laser and rotated at 70 rpm. This gave observers 429 ms exposures to the speckle pattern separated by equal length pauses.

2.2.2.4. Lenses. Lenses used were from a 266-piece 36.5 mm aperture metal rim trial lens set (CT4301) and were used with the CT2202 trial frame (Canton Shanghai Optics Equipment Co., Ltd). The lowest power lenses available were ± 0.12D making this the limit of precision for measurements.

2.2.2.5. Eye tracking hardware. A binocular pupil tracking system was purpose-built for use in the Experiment 1 in order to allow vergence to be measured at the same time as accommodation. Eye and scene cameras were mounted on a rigid headset. Both scene cameras were unmodified "Logitech C525" web-cameras running at 30 fps (1280 × 720 px). Both eye cameras were "Sony Playstation 3 Eye" cameras that were modified for manual near-focusing and infrared capture, running at 60 fps (640 × 480 px). Scene cameras were positioned along the sagittal plane. Eye cameras were positioned below and slightly lateral with respect to each eye. Eye images were recorded from cameras beneath the trial lens frame worn by the participants to avoid possible lens and frame artefacts. The headset was suspended from ceiling-mounted hooks above the chinrest and fitted to each observer with the aid of an adjustable strap, such that camera movement was rigid with respect to any head movement. Eye-camera lenses were adjusted in focus and zoom to frame each eye. Gaze calibration was performed within the chinrest using a monitor positioned on what would be the mid-plane of the mask. Gaze data based on the scene cameras are not reported but provided visual verification of the non-overlapping lines-of-sight associated with vergence in front of, or behind, the mid-plane of the mask.

(*footnote continued*)
illusory face.

Tracking utilised the dark pupil method with infrared LED illuminators and high-pass 850 nm light wavelength filters. The infrared LEDs were safely diffuse (Jaeger & Siedersbeck, 2018) and adjusted manually until pupil detection confidence was judged by the experimenter to be consistently near maximum. Captured images were analysed offline using an adapted version of the open-source Pupil project (Kassner & Patera, 2012). All data with a low level of confidence (< 65%, e.g. blinks) as determined by the pupil-detection algorithm were automatically discarded in pre-processing. Spatial resolution was theoretically 0.08°. Post-processing involved manually generating timestamps for stimulus onset/offset and corresponding eye activity and matching timestamps across separate eye recordings. Timestamps were derived from the monotonic Linux system clock function which was synchronised across camera-pair computers at the beginning of each experiment. Pupil co-ordinates were normalized so that the bottom left of each sensor image corresponded to a coordinate of [0,0] and the top right of each sensor returned a coordinate of [1,1]. Horizontal disparity between the centres of each respective pupil was taken as the metric for vergence: $Dx = (X2 - X1) - Bk$ where Dx denotes horizontal pupil disparity; X2 denotes the right pupil x-coordinate; X1 denotes the left pupil x-coordinate, and Bk denotes a constant: the mean difference during a period k that was recorded while observers verged to the mid-plane of the accommodation calibration target (Daugherty, Duchowski, House, & Ramasamy, 2010; Grosjean et al., 2012). Thus, a value of zero represents vergence to one metre, while positive values reflect divergence and negative values convergence. We did not attempt to calibrate this measure in terms of magnitude of vergence angle and report, analyse and interpret only the raw normalised value. In order to minimise the effects of novelty, non-adherence to instructions, saccades, and miscellaneous occlusion of the pupil, the first 5-second epoch available at the end of the first suitable eyes-open period for each experimental trial was manually selected when determining vergence. This was also chosen to ensure steady state vergence, as well as accommodation, rather than the initial response on eye opening.

2.2.3. Design

Experiment 1 used a 2 Orientation (Upright, Inverted) × 2 Curvature (Concave, Convex) × 2 Eye Number (One, Two) fully factorial repeated-measures design. Orientation refers to the vertical orientation of the mask, curvature to which surface of the mask was visible, and eye number to whether viewing was monocular or binocular. The primary dependent variable was the lens power needed to null speckle motion. Normalized horizontal pupil separation was also recorded and analysed as a measure of vergence.

2.2.4. Procedure

After informed consent was obtained, the participant's visual and stereo acuity was measured using a computerised Sloan letter LogMAR chart (http://hilmi.eu/hilmi-chart/) and the Stereo Butterfly stereoacuity kit (SO-005 Stereo Optical Co., Inc) respectively. Visual acuity was first assessed for each eye individually and then for both together. Both Snellen and LogMAR values were recorded simultaneously at a distance of 2 m from the monitor screen. Letters were randomised for each viewing. Stereoacuity assessment was performed as a 4 alternative forced choice and the highest score immediately following two correctly answered lower acuity items was recorded.

The experiment took place in a 1.85 m × 3.40 m matte-black painted and darkened room. Participants sat on a high-lift computer chair and were asked to lean forward onto a reinforced prop and padded chinrest. Calibration then took place with the calibration object described in 2.2.2.2 viewed binocularly. This established the lens strength needed, if any, to give a globally stable stationary speckle pattern when viewing the central focus target and opposite directions of motion when viewing near and far targets. All nulling lens values reported are relative to this calibration value calculated for each individual participant. Values for the lenses needed to null the speckle pattern for the calibration objects are included in supplementary data file E2data.xlsx. For both calibration and the subsequent stages, observers were instructed not look directly at the speckle pattern itself but to judge its direction of movement using their near peripheral vision.

Gaze tracking was then calibrated using a 9-point high contrast concentric circle pattern presented on a monitor that replaced the calibration object. Re-calibration was performed when fewer than 200 points were sampled or when the proportion of used data points was less than 0.85 within that calibration sequence.

For the main experiment, the monitor was replaced with the hollow-face mask stimulus and participants instructed to look at the nose. Order of the eight conditions was fully randomized for each participant with the first condition repeated at the end, making a total of nine trials. Convex/concave and upright/inverted trials involved the experimenter rotating the mask around its midpoint. For monocular conditions a matte black occluding lens was inserted in-front of the observer's non-dominant eye. Observers kept their occluded eye open allowing continued tracking of vergence.

The lens required to null speckle motion was determined using a staircase procedure. Lens power was adjusted in the direction determined by the direction of motion reported with 0.12D the smallest increment available. This was repeated until the observer reported perceiving no global directional motion of the speckle at which point the power of the lens was recorded. If the two closest available consecutive lenses produced opposite directions of speckle motion and neither was associated with a globally stationary percept, their average power was recorded. Nulling lens value was typically determined after four to six lens changes.

Observers sometimes reported that the mask appeared globally concave but that the nose still appeared convex. In these cases, observers were asked to gaze at a point on the mask that was clearly concave while judging speckle motion. As all other points on the mask are physically closer than the concave nose this procedure would bias against reduced accommodation for concave trials. To validate the procedure accommodation was also measured across multiple gaze points (e.g. hair vs. nose) for a pilot observer. When viewing two different points that were both illusorily convex the mean difference was 0.06 D whereas the difference between viewing the same point when seeing it as illusorily convex or veridically concave was 0.53 D. This suggests that exact fixation did not substantially affect the measured accommodation.

2.3. Results

An alpha level of 5% was used throughout. Inspection of the data suggested departures from normality for measures of accommodation and vergence in a number of conditions. Equivalent permutation-based analyses were performed as a check, but parametric results are reported here due to their greater familiarity. Any inconsistencies in the pattern of significant differences are noted and the non-parametric analyses included as supplementary materials file PermutationAnalysis.docx. Inspection of *F*-max indicated that homogeneity of variance was satisfied throughout. Raw data are included in supplementary material E1data.xlsx.

2.3.1. Accommodation

A 2 Orientation (Upright/Inverted) × 2 Curvature (Convex/Concave) × 2 Eyes (Monocular/Binocular) repeated measures Analysis of Variance on nulling lens diopter values showed main effects of Orientation, $F(1, 9) = 11.38$, $p = .008$, $\eta_p^2 = .56$, and Curvature, $F(1, 9) = 17.53$, $p = .002$, $\eta_p^2 = .66$, qualified by a significant Orientation × Curvature interaction, $F(1, 9) = 34.10$, $p < .001$, $\eta_p^2 = .79$. This interaction is illustrated in Fig. 2 with means collapsed across monocular and binocular viewing.

The only condition that produced an accommodative response to a point beyond the mid-plane (indicated by the need for a positive,

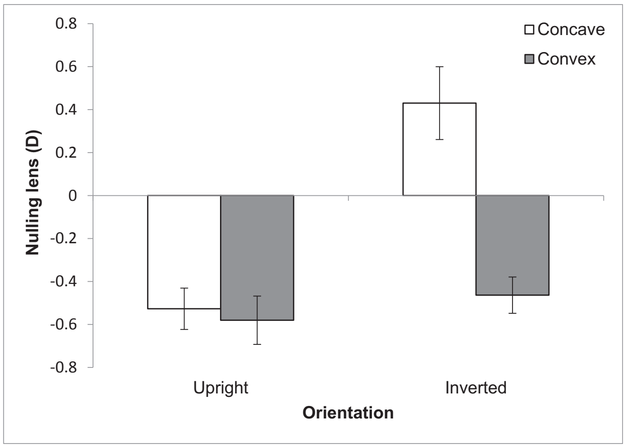

Fig. 2. The interaction between orientation and curvature on accommodation found in Experiment 1. Observers (N = 10) reported seeing a convex face, real or illusory, under all conditions except when viewing the inverted concave mask. The expected difference in accommodation between the nose and the surround of the mask would be 0.1 D (± 0.5 D relative to the mid-plane) and reasons why the measured value exceeds this are discussed in the text. Results are shown collapsed across monocular and binocular viewing as this factor had no significant effect on accommodation. Error bars indicate ± 1 standard error of mean after adjusting for between subject variation.

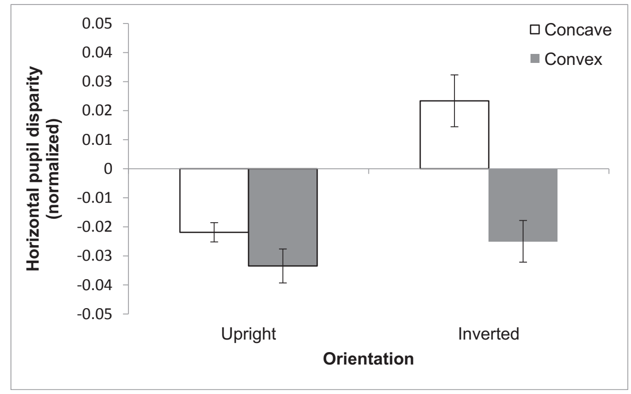

Fig. 3. The interacting effects of orientation and curvature on vergence found in Experiment 1. Horizontal disparities are normalized pixel values (please section 2.2.2.5) and vergence to the mid-plane would correspond to a disparity of zero. Negative values indicate convergence and positive values divergence relative to the mid-plane. Observers reported seeing a convex face, real or illusory, under all conditions except when viewing the inverted concave mask. Results are shown collapsed across monocular and binocular viewing as this interaction was independent of this factor. Error bars indicate ± 1 standard error of mean after removing between subject variation.

converging lens to null the speckle motion) was the inverted concave mask. Paired *t*-tests showed a significant difference between accommodation to convex and concave surfaces when the mask was inverted, $t(9) = 5.30$, $p < .001$, *Cohen's d* = 2.60, but not when the mask was upright, $t(9) = 0.61$, $p = .55$, *Cohen's d* = 0.13.[2]

No other main effects or interactions approached significance (all *p*'s > 0.1) except for a marginal interaction between the number of eyes and curvature, $F(1, 9) = 3.72$, $p = .086$, $\eta_p^2 = .29$. This reflected a trend for a reduced difference in accommodation to convex and concave surfaces for monocular (mean difference = 0.35D, SE = 0.14) as compared to binocular viewing (mean difference = 0.60D, SE = 0.13).

The mean difference in lens power between the first trial and its repeat was −0.04 D (*SD* 0.56), 95% *CI* [−0.47, 0.38]. This difference was not significant, $t(8) = 0.23$, $p = .821$, *Cohen's d* = 0.08, consistent with test-retest reliability. Equivalent non-parametric analyses gave an identical pattern of main effects and interactions and significant differences as described above.

2.3.2. Vergence

A 2 Orientation (Upright/Inverted) × 2 Curvature (Convex/Concave) × 2 Eyes (Monocular/Binocular) repeated measures Analysis of Variance on normalized inter pupillary distance gave significant main effects of Orientation, $F(1,8) = 22.72$, $p = .001$, $\eta_p^2 = .74$, and Curvature, $F(1,8) = 17.94$, $p = .003$, $\eta_p^2 = .69$, qualified by significant Orientation × Curvature, $F(1, 8) = 6.73$, $p = .032$, $\eta_p^2 = .46$, and Curvature × Eyes, $F(1, 8) = 18.77$, $p = .003$, $\eta_p^2 = .70$, interactions. The Orientation × Curvature interaction is plotted in Fig. 3 and shows a similar pattern to that found for accommodation. Vergence to convex and concave surfaces was significantly different when the mask was inverted and the reported percept differed, $t(8) = 3.77$, $p = .001$, *Cohen's d* = 1.79. For vergence there was also a marginal difference between convex and concave in the upright condition, $t(8) = 1.93$, $p = .089$, *Cohen's d* = 0.51, reflecting somewhat less convergence to the illusory as compared to the physically convex face.

The Curvature × Eyes interaction reflected a significant difference in vergence to physically convex and concave surfaces for binocular, $t(8) = 4.98$, $p = .001$, *Cohen's d* = 2.12, mean difference = 0.048 (*SE* = 0.010), but not monocular, $t(8) = 1.79$, $p = .111$, *Cohen's d* = 0.52, mean difference = 0.012 (*SE* = 0.006), viewing. Means (and SEs) were −0.007 (0.007) for monocular concave, −0.019 (0.008) for monocular convex, 0.008 (0.004) for binocular concave and −0.040 (0.010) for binocular convex.

No other main effects or interactions approached significance (all *p*'s > .1). Equivalent permutation-based analyses gave the identical pattern of significant differences with the exception that the difference between convex and concave in the upright condition was not significant, $p = .129$.

2.4. Discussion

When the concave mask was presented upright participants reported seeing an illusory convex face and both vergence and accommodation were in front of the mid-plane of the mask. Accommodation to the illusion was of the same magnitude as to the physically convex surface. Vergence to the illusory face was also in front of the mid-plane but of marginally reduced magnitude relative to the physically convex mask. Only when the mask was inverted and seen as hollow were accommodation and vergence beyond the mid-plane. This pattern of results suggests accommodation, like vergence, is not to the physically concave surface even when any available feedback is closed-loop. The difference in accommodation to the mask when perceiving the illusion as opposed to when seeing it as veridically hollow, was found for monocular as well as binocular viewing. This shows that that accommodation was not driven by binocular disparities through vergence although voluntary vergence remains a possibility.

The magnitudes of accommodation reported are greater than those that would be expected on the basis of the depth differences involved. This is true for the convex face used as a control as well as for the illusory face. Focussing on the nose of the convex physical surface should require 0.05D more accommodation than focussing on the mid-plane of the mask, much less than the 0.58D increase shown for the upright convex condition in Fig. 2. The reason for this is not known but may include limitations of the measurement technique used here as well as an effect of depth of focus, estimated as ± 0.3D for a 3 mm dimeter pupil under optimal conditions (Campbell, 1957). Similar magnitudes have been reported for accommodation to pictorial depth

[2] The "*Cohen's d*" values reported here and throughout use pooled standard deviation as the denominator with the SD from the collapsed data for each condition (i.e. treating comparisons as pairwise as using the pooled variance estimate as the basis for the denominator).

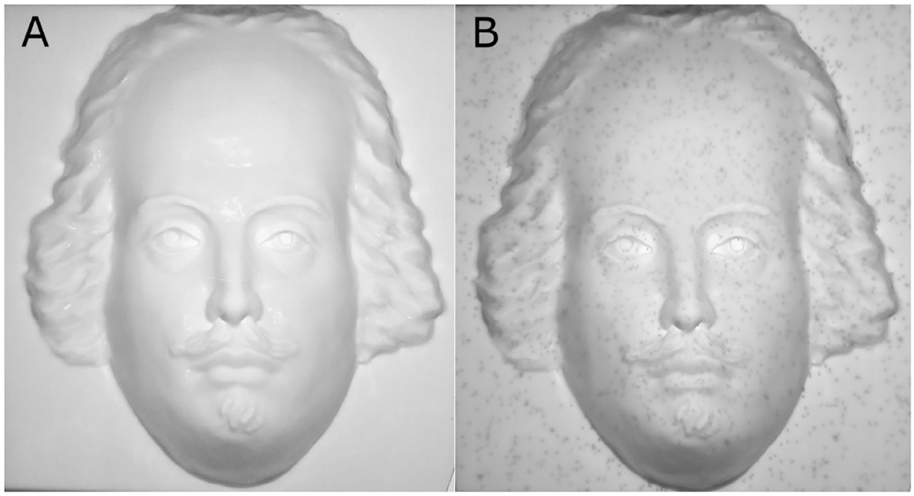

Fig. 4. Images of the hollow-face mask used in all experiments as it was presented in Experiment 2. A) 0% dot contrast B) 100% dot contrast.

(Busby & Ciuffreda, 2005; Takeda et al., 1999, 1990) relative to the physically flat surface although that would not account for the equally exaggerated accommodation when viewing the physically convex surface here. Our central claim is that accommodation was in front the physically concave surface when participants were reporting seeing the upright mask as a convex face. The measured sign and magnitude of that response was similar to the response to a physically convex face but opposite in sign from the response to a physically concave surface seen as concave. The simplest explanation of why viewers converge and accommodate in front of the mid-plane of the mask is that this is where they experience the illusory face as being located.

Accommodation to perceived rather than physical depth was not previously found with an ambiguous three-dimensional cube (Ellis et al., 1979). The stimulus used here was different in many respects to that tested previously, despite both involving depth reversal of a three-dimensional object: the hollow-face was perceptually stable and comparison was between different trials as opposed to reports while a percept continuously alternated; the mask was a continuous smooth surface without distinct contours to support accurate accommodation; the hollow-face did not self-occlude in the way that a ‘wire-frame’ model can, and the mask was larger (though not much deeper, 10.5 compared to 9 cm) and viewed from a greater distance with object depth corresponding to a 0.1 D difference around 1D as compared to 0.65D around 2.9D. Any of these stimulus differences, or the differing method of measuring accommodation, may account for the different pattern of results with regards the influence of perceived depth. Both studies showed differences in accommodation to physical points at different depths seen veridically (in this case the front and back surfaces of the inverted mask).

The pattern for vergence found here replicates previous reports of vergence to the illusory surface (Grosjean et al., 2012; Hoffmann & Sebald, 2007). It also extends those findings to monocular viewing. As can be seen from Fig. 3, vergence was always to a point in front of the mid-plane of the mask in the upright condition and the marginal effect is consistent with a flattened convex surfaces as has also been reported previously (Hartung, Schrater, Bulthoff, Kersten, & Franz, 2005; Kroliczak, Heard, Goodale, & Gregory, 2006; Matthews et al., 2011). No similar evidence of apparent flattening was found for accommodation, again suggesting that accommodation was not a function of vergence. The interaction between vergence and accommodation would anyway be expected to affect the phasic portion of the response rather than the steady state response measured here (Schor et al., 1992; Schor & Kotulak, 1986). Binocular disparities are not controlling either vergence or accommodation in the monocular conditions, but we cannot exclude the possibility of voluntary vergence is driving both. We did not attempt to calibrate the relationship been normalised pupil disparity and vergence angle and so cannot make strong claims about the magnitude of vergence in different conditions. However, it is clear that observers only diverged relative to the mid-plane when they were seeing the inverted mask as hollow. When they perceived the upright mask as convex they converged, as they did when viewing the physically convex surface either upright or inverted.

In this experiment a change in percept was associated with different presentation conditions, particularly whether the mask was upright or inverted. There was no effect of inversion when viewing the convex surface of the mask suggesting that the effect of inversion on accommodation when viewing the hollow mask was due to the change in percept not physical factors. In Experiment 2 we sought to further rule out explanations in terms of presentation conditions.

3. Experiment 2

3.1. Introduction

A hollow mask with a random pattern of dots projected onto it is seen as hollow at least when viewed binocularly (Georgeson, 1979). One potential reason is that the projected dots provide disparity information that specifies the true shape of the mask in the binocular condition. In Experiment 2 we used a random dot pattern to ‘flip’ perception between convex and concave for all observers under all viewing conditions for the concave mask. By increasing or decreasing contrast in 5% steps we could elicit a change in percept from convex to concave or vice versa, respectively. The “flipping contrast”, the contrast at which perception flips, also provides a measure of the strength of the illusion with a higher contrast indicating a stronger illusion (Rogers, 2010). The convex surface of the mask was used as a control for any effect of the contrast of the dots themselves on perception independent of a change in percept.

Descending measures are taken when participants first report that the mask percept has changed from concave to convex. Therefore, if accommodation is to the illusory surface then for the descending measures it should be in front of the mid-plane of the mask. Accommodation should only be beyond the mid-plane of the mask for ascending measures as those will correspond to a hollow percept. For the convex surface accommodation should be in front of the mid-plane for both ascending (100% contrast) and descending (0% contrast) measures, consistent with the perceived and physical surface unless contrast alone is affecting accommodation. We also expected flipping contrast to be higher for the mask upright than inverted, and viewed with one eye rather than two as these conditions would be expected to

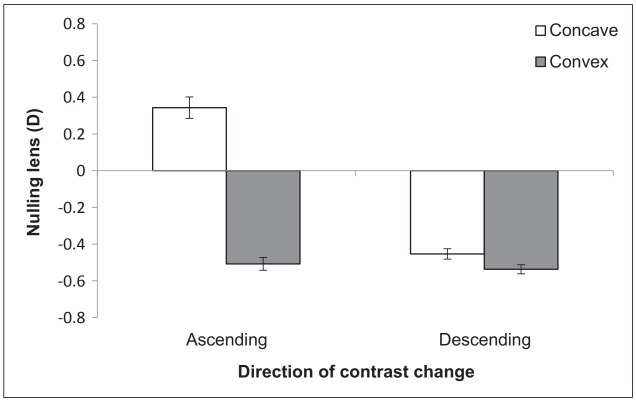

Fig. 5. The effect of curvature and direction of contrast change on accommodation in Experiment 2. Ascending measures correspond to a concave percept and descending to convex. When the convex surface of the mask was presented there was no change in percept and accommodation was measured at 100% contrast for ascending measures and 0% for descending measures. As noted and discussed in Experiment 1, measured differences in accommodation are again greater than the 0.1 D (± 0.5 D relative to the mid-plane) that would be expected on the basis of distance and depth differences. Results are shown collapsed across orientation and monocular/binocular viewing as neither of these factors had a significant effect on accommodation. Error bars indicate standard error of mean after removing between-subjects variance.

generate a stronger illusion if flipping contrast is consistent with flipping distance (Hill & Bruce, 1993). Similarly flipping contrast would also be higher for ascending measures if there is perceptual hysteresis reflecting a tendency for the initial percept to be maintained.

3.2. Methods

3.2.1. Participants

Seventeen (fourteen females) participants with a mean age of 25 years (range 18 to 50) took part in Experiment 2. Inclusion criteria and consent procedures were as for Experiment 1. Two volunteers were excluded before taking part due to poor acuity.

3.2.2. Materials

The set up for measuring accommodation was the same as for Experiment 1 except that vergence was not measured and the mask was lit by the projector. Twenty-one random dot images were generated in MATLAB (MATLAB 2015b, The MathWorks, Natick). Dots were 2 × 2 pixels in extent and constituted 5% of the 768 × 1366 image. The mean luminance was set to 242 for all contrast levels. 5% was chosen to minimize the disruption of facial features while still ensuring that the mask was seen as hollow at high contrasts. Contrast was controlled by varying the luminance difference between the dots and the background luminance while keeping a mean luminance constant. Michelson contrast values defined in terms of grey level intensity values were varied from 0% to 100% in 5% steps. The 0% and 100% contrast conditions are shown in Fig. 4. The random dot stimuli were projected onto the mask from a distance of 1 m using a Mitsubishi XD300U. The projector was the only lighting. At 100% the luminance ratio of white:black was 20:1 with white areas having a luminance of 79 cd/m2.

3.2.3. Design

Experiment 2 used a 2 Direction (Ascending, Descending) × 2 Orientation (Upright, Inverted) × 2 Curvature (Concave, Convex) × 2 Eye Number (One, Two) repeated measures fully factorial design. Direction refers to whether contrast was increased from 0% (ascending) or decreased from 100% (descending) on a particular trial. Direction determined which percept was being experienced when the concave surface was being viewed with ascending measures corresponding to an ultimately concave percept and descending to an ultimately convex percept. Nulling lens power was the primary dependent variable but flipping contrast, the contrast at which participants reported that their percept changed between convex and concave, was also recorded and analysed as a measure of the strength of the illusion.

3.2.4. Procedure

Experiment 2 followed the same procedure as Experiment 1 except that vergence was not tracked. Only a basic level of stereoacuity was tested using the Bernell Quoits Vectogram as the Stereo Butterfly Test was not available. The order of orientation, eyes and surface shown was again randomized. Accommodation was always measured one contrast level after participants first reported a change in percept and 'flipping contrast' recorded. In each condition both ascending and descending measures were made with the initial direction tested also randomised. For trials where the convex surface of the mask was presented and there was no change in percept, accommodation was measured at 0% for descending trials and 100% for ascending.

3.3. Results

Raw data is provided in supplementary materials file E2data.xlsx. Inspection of the data again suggested departures from normality for measures of accommodation in some conditions. Robustness was assumed but equivalent permutation analyses performed as a check with any differences noted. Due to the likely loss of accommodative power with age, the two participants aged over 40, both female, were dropped from this analysis.

3.3.1. Accommodation

A 2 Direction (Ascending/Descending) × 2 Curvature (Convex/Concave) × 2 Orientation (Upright/Inverted) × 2 Eyes (Monocular/Binocular) repeated measures ANOVA on nulling lens strength gave significant main effects of Direction, F(1,14) = 152.14, $p < .001$, $\eta_p^2 = .92$, and Curvature, $F(1,14) = 122.55$, $p < .001$, $\eta_p^2 = .90$, qualified by a significant Direction × Curvature interaction, $F(1, 14) = 89.76$, $p < .001$, $\eta_p^2 = .87$. The Direction × Curvature interaction is shown in Fig. 5. There were no other significant effects or interactions (all *p*'s > .1).

Simple effects analysis of the Curvature × Direction interaction showed a significant difference in accommodation between ascending and descending measures for the concave surface, $t(14) = 12.03$, $p < .001$, *Cohen's* $d = 5.07$, mean difference = 0.833 ($SE = 0.036$), but not for the convex surface, $t(14) = 0.58$, $p = .583$, *Cohen's* $d = 0.11$, mean difference = 0.021 ($SE = 0.036$). There was also a significant difference in accommodation between convex and concave surfaces for descending measures, $t(14) = 2.16$, $p = .048$, *Cohen's* $d = 0.46$, mean difference = 0.080 (SE = 0.037) consistent with the illusory convex surface appearing flatter than the veridical convex surface. The difference for ascending measures, where concave and convex surfaces were both perceived veridically, was also significant, $t(16) = 11.37$, $p < .001$, *Cohen's* $d = 4.93$, mean difference = 0.893 (SE = 0.079).

The difference between first and repeat trials was not significant for either ascending, $t(14) = 0.61$, $p = .551$, *Cohen's* $d = 0.13$, or descending, $t(14) = 1.69$, $p = .114$, *Cohen's* $d = 0.46$, measures.

Non-parametric analysis gave the same pattern of results with the exception that a Wilcoxon signed rank test for the difference in accommodation between convex and concave surfaces was not significant, $T = 15$, $p = .061$.

3.3.2. Flipping contrast

Conditions where the convex mask was presented were excluded from this analysis as there was no change in percept associated with this factor. Assumptions of normality and homogeneity of variance were satisfied in all except one condition.

Flipping contrast for concave mask conditions was analysed using a 2 Direction (Ascending/Descending) × 2 Orientation (Upright/Inverted) × 2 Eyes (Monocular/Binocular) repeated measures ANOVA. There were significant main effects of Eye Number, $F(1, 14) = 19.44$, $p = .001$, $\eta_p^2 = .58$, with higher contrast needed to flip the illusion viewed monocularly, 59% (3%) than binocularly 41% (3%); and of Orientation, $F(1, 14) = 5.41$, $p = .035$, $\eta_p^2 = .28$, with higher contrast need to flip the upright mask 55% (3%) than the inverted mask 45% (4%). The three-way Direction × Orientation × Eyes interaction was marginal, $F(1,14) = 3.95$, $p = .067$, $\eta_p^2 = .22$.

The pattern of differences was the same for the non-parametric analysis.

3.4. Discussion

The results of Experiment 2 were again consistent with accommodation in front of the physical, concave, surface when experiencing the illusion. This was independent of the orientation of the mask and of whether viewing was with one or both eyes. This experiment ruled out the possibility that there was something about the inverted orientation that caused people to accommodate beyond the mid-plane: in this experiment when people saw the inverted mask as convex they accommodated in front of the mid-plane. Both percepts were achieved for all presentation conditions by varying dot contrast but there was no effect on accommodation of a maximal change in dot contrast when the convex surface was presented and there was no change in percept. In this experiment there was evidence of reduced accommodation to an illusory convex surface compared to the veridically convex surface. Accommodation was in front of the mid-plane in both cases. This difference in accommodation is consistent with the apparent flattening associated with the illusion reported previously (Hartung et al., 2005; Kroliczak et al., 2006; Matthews et al., 2011) and found for vergence but not accommodation in Experiment 1. Although vergence was not measured in this experiment, the "flattening" effect for accommodation found here suggests that vergence and accommodation do not necessarily dissociate in this respect.

Flipping contrast was higher for monocular viewing and the upright mask as expected. There was no overall difference between increasing or decreasing contrast but the effect of monocular/binocular viewing marginally depended on direction with larger effect for ascending measures. The effects of orientation and number of eyes were independent of each other as has been reported before (Hill & Bruce, 1993; Papathomas & Bono, 2004) and as would be expected if orientation primarily effects top-down object specific knowledge about faces while monocular viewing disrupts binocular stereopsis and/or vergence.

Experiments 1 and 2 show that accommodation is in front of the physically concave surface when experiencing the hollow-face illusion. The results show that accommodation is not simply driven by feedback from low-level image properties. One possibility is that the illusory face is perceived as in front of the physical surface and that this affects accommodation. In the final experiment reported we tested whether accommodation helps determine perceived depth as well as being affected by it.

4. Experiment 3

4.1. Introduction

This experiment tested whether blur driven accommodation can help disambiguate perceived depth. We compared flipping contrast using the same random dot pattern with or without convolution with a Gaussian filter. The object blur resulting from Gaussian filtering approximates the appearance of focus blur (Pentland, 1987) and is open loop in that it cannot be made sharper by accommodation (Phillips & Stark, 1977). The accuracy of accommodation depends on both the spatial frequency composition and contrast of the target (Fisher & Ciuffreda, 1988). The intermediate and higher spatial frequencies lost by blurring, together with the smoothing of luminance gradients, would be expected to adversely affect accommodation (Ciuffreda, 1991; Ward, 1987a, 1987b; Watson & Ahumada, 2011). Ward (1987a) shows there is a frequency dependent contrast below which accommodative error occurs which could help determine flipping contrast if accommodation is critical.

If accommodation helps disambiguate the illusion, we would expect blurred dots to require a higher flipping contrast as they provide a poorer accommodative stimulus. As with experiment 2 we also expected upright orientation and monocular viewing to be associated with higher flipping contrast and these effects to be independent. Lastly any perceptual hysteresis would result in higher contrast for ascending measures.

4.2. Methods

4.2.1. Participants

Sixteen (six males) participants with a mean age of 21 years (range 18–43) took part in Experiment 3.

4.2.2. Materials

For Experiment 3, 768 × 1366 random dot images with 50% 16-pixel square dots were used. Fig. 6 shows these images as projected onto the mask. Dots of this size would approximate a 1.2 cycles/degree square wave as projected. Dots were blurred by convolving the image with a 10-pixel standard deviation Gaussian using a 30 × 30-pixel

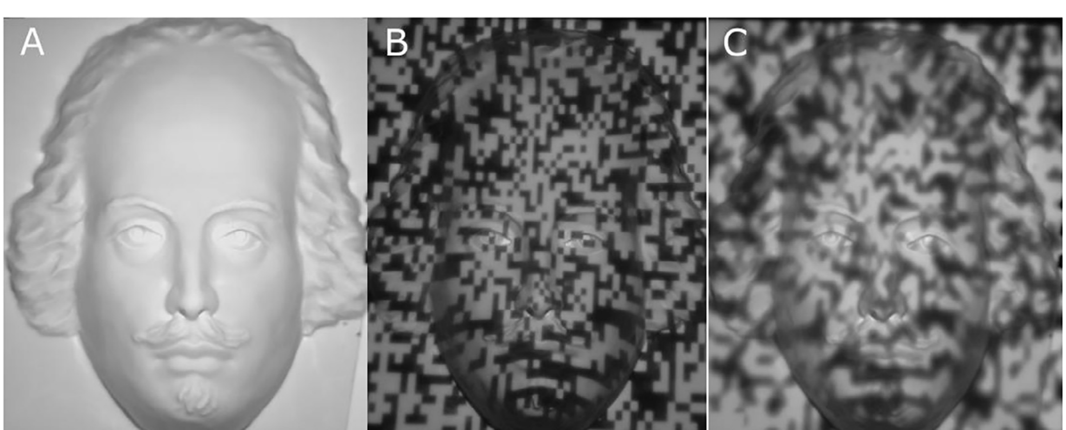

Fig. 6. Images of the hollow-face as seen in Experiment 3. A) 0% dot contrast; B) 100% dot contrast, sharp; C) 100% dot contrast, blurred.

window. Mean luminance was 127.5 and Michelson contrast again varied in 5% steps from 0 to 100%. The increased proportion of dots was used to allow control of luminance and contrast for both sharp and blurred images.

4.2.3. Design

Experiment 3 used a 2 Target Blur (Sharp, Blurred) × 2 Direction (Ascending, Descending) × 2 Orientation (Upright, Inverted) × 2 Eye Number (One, Two) repeated measures fully factorial design. Target blur refers to whether the dots projected onto the face were sharp or had been blurred as described in 4.2.2. Flipping contrast, defined in terms of Michelson contrast, was the only dependent variable and only the concave surface of the mask was shown.

4.2.4. Procedure

Experiment 3 followed the same procedure as Experiment 2 except that only the concave surface of the mask was ever shown and only flipping contrast was measured.

4.3. Results

Raw data is available in supplementary materials file E3data.xlsx. One 43-year-old female participant is not included in the analysis due to the possibility of age related changes in accommodation.

4.3.1. Flipping contrast

Data showed some departures from normality and homogeneity of variance, but robustness was assumed. Non-parametric analyses carried out as check with any difference noted and the full analyses included as supplementary material (PermutationAnalysis.docx).

Flipping contrast was analysed using a 2 Target Blur (Blurred/Sharp) × 2 Direction (Ascending/Descending) × 2 Orientation (Upright/Inverted) × 2 Eyes (Monocular/Binocular) repeated measures ANOVA. There were main effects of Target Blur, $F(1,14) = 26.92$, $p < .001$, $\eta_p^2 = .66$, *Cohen's* $d = 1.33$, with higher flipping contrast for blurred dots ($M = 56\%$, $SD = 11\%$) than sharp dots ($M = 40\%$, $SD = 13\%$); Eyes, $F(1,14) = 23.23$, $p < .001$, $\eta_p^2 = .62$, *Cohen's* $d = 1.70$, with higher flipping contrast for monocular ($M = 60\%$, $SD = 15\%$) than binocular ($M = 36\%$, $SD = 13\%$) viewing; and Orientation, $F(1,15) = 8.11$, $p = .012$, $\eta_p^2 = .31$, *Cohen's* $d = 0.93$, with higher flipping contrast for upright ($M = 53\%$, $SD = 9\%$) than inverted ($M = 42\%$, $SD = 17\%$). There was also a marginal Target Blur × Direction × Orientation, $F(1,14) = 4.29$, $p = .057$, $\eta_p^2 = .24$, interaction and main effect of direction, $F(1,14) = 4.04$, $p = .064$, $\eta_p^2 = .22$, *Cohen's* $d = 0.73$, with higher flipping contrast for Ascending ($M = 53\%$, $SD = 15\%$) than descending ($M = 43\%$, $SD = 14\%$) measures.

4.4. Discussion

The main finding of Experiment 3 was that sharp dots were more effective in disambiguating the illusion than blurred dots. This is consistent with blur driven accommodation helping to disambiguate the illusion. As expected, the upright mask and monocular viewing were associated with higher flipping contrast and these effects were independent. In this experiment descending measures were associated with lower flipping contrast than ascending measures, consistent with the initial percept tending to be maintained.

A problem with interpreting the effect of blurring on flipping contrast is that blurring inevitably reduces contrast on some measures, for example root mean square contrast (O'Shea, Govan, & Sekuler, 1997). Our stimuli were equated for Michelson contrast[3] and, calculated that way, flipping contrast was 56.5 for blurred and 38.7 for sharp, indicating that blurred dots producing a stronger illusion. However, expressed as RMS contrast[4] blurred and sharp would be 23.0 and 49.4 respectively. This would mean that blurred dots resulted in a lower flipping contrast, indicating a weaker illusion. Contrast, like distance, affects many if not all depth cues in a variety of ways making it difficult if not impossible to know how flipping contrast should be defined. This would be further complicated by taking into account any non-linearities in contrast associated with projection. As outlined in 4.1, blurring would be expected to disrupt accommodation. One way to test whether the effect of blurring on flipping contrast is due to accommodation would be by replicating the experiment using stereoscopic and monocular viewing of photographs where accommodation would beof no help disambiguating depth. Whatever measure of flipping contrast is used, blurring would be expected to have less effect when viewing photographs if accommodation is involved when viewing the 3D mask. Alternative explanations of the effect of blurring include worse binocular stereopsis or greater masking of the face by sharp dots, but interactions with monocular/binocular viewing or orientation respectively would have been expected in these cases. Another limitation of the current study is that because the dots were back projected, dot size would have provided a possible cue to depth. Dots on the parts of the mask nearest the projector and furthest from the observer, the facial features, would have been smaller as a result of both projection and viewing distance. When front projected these effects cancel out (Georgeson, 1979). This effect can be seen in Fig. 6 where the reader can judge the extent to which it disambiguates depth. When the depth of the face is misperceived as being closer than it is this might be expected to exaggerate the effect further through size being scaled by an inappropriate distance. While this size cue should help disambiguate actual depth it is present in all conditions and therefore does not explain the differences found.

In summary blurred dots were less effective in disambiguating the illusion. Blurring would affect accommodation and the results are consistent with accommodation playing a role in disrupting the illusion. However, blur would be expected to affect many aspects of visual processing, any of which may contribute to this difference.

5. General discussion

Experiments 1 and 2 both showed that accommodation was in front of the physical surface when a hollow mask was perceived as a convex face. The sign and magnitude of accommodation as measured when perceiving the illusion were the same as when viewing the equivalent convex surface.

In Experiment 1 we replicated previous findings that we verge to perceived depth (Grosjean et al., 2012; Hoffmann & Sebald, 2007), at least to the extent that we verge in front of the mid-plane of the mask when experiencing the illusion even though the physical surface is behind that plane. The simplest explanationfor this is that the illusory face is perceived as in front of the physical mask and that both accommodation and vergence are biased by perceived depth. Experiment 2 replicated and extended Experiment 1 by showing that accommodation was to illusory depth under all conditions of presentation. Perceived depth flipped when the contrast of projected dots was sufficient and accommodation changed at the same point. Changing dot contrast did not affect accommodation to the convex surface when there was no change in perceived shape. Experiment 3 showed that blurred dots were less effective in disambiguating depth. While alternative explanations cannot be ruled out, this is consistent with accommodation affecting, as well as being affected by, perceived depth.

[3] (Lmax-Lmin)/(Lmax + Lmin) where Lmax and Lmin are maximum and minimum grey values.

[4] $\frac{\sqrt{\sum_{x=1}^{1366}\sum_{y=1}^{768}(I_{xy}-\bar{I})^2}}{1366*768}$ where x and y define the location of individual pixels, I_{xy} is the grey level of that pixel and $\bar{I}$ is the mean grey level.

Accommodation to the illusory rather than the physical surface is not what would be expected from a system that simply minimizing blur and maximising contrast. Instead, accommodation was towards perceived depth despite any available feedback from blur, contrast and, in binocular viewing conditions, binocular disparities being closed-loop. In this respect accommodation to this illusion behaves like vergence, as reported previously and replicated here. Just as potentially disambiguating optical depth cues including binocular disparities and self-generated motion parallax are not vetoed but perceived in a manner consistent with the illusory percept (Matthews et al., 2011; Papathomas, 2007; Rogers & Gyani, 2010; Yellott & Kaiwi, 1979), the ocular systems adopt a steady state consistent with perceived illusory depth. One possibility is that this is a voluntary choice by observers just as it is possible to voluntarily cross your eyes and deliberately misfocus. However, it is not generally possible to choose which percept to experience when viewing the hollow face illusion as it is "cognitively impenetrable" (Bruce, Hill, & Langton, 1999). Proximal and voluntary accommodation and vergence were equated historically (Heath, 1956) and the result reported here is, at the least, an example of proximal accommodation occurring with a three-dimensional object under relatively natural viewing conditions with multiple depth cues and closed-loop feedback available.

Experiment 3 provided evidence that accommodation may help determine perceived depth as well as being affected by it. Objectively blurred dots that were intended to open-loop accommodation were less effective than equivalent sharp dots in disambiguating depth. This is consistent with previous evidence suggesting that disrupting accommodation strengthens the illusion (Hill et al., 2012; Koessler & Hill, 2015) although blur affects many aspects of visual processing and alternative explanations cannot be ruled out. In this sense accommodation behaves like other depth cues that help disambiguate the illusion at close distances such as the binocular disparities lost by monocular viewing. The strengthening of the illusion associated with monocular viewing and upright presentation previously shown using both flipping distance and percept predominance (Hill & Bruce, 1993; Papathomas & Bono, 2004) were replicated here using flipping contrast.

In summary, these experiments suggest that accommodation is linked to human depth perception, both affecting and being affected by perceived depth even in a situation where multiple depth cues are available.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.visres.2018.11.001.

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