Vision Research 214 (2024) 108329

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Success rates, near-response patterns, and learning trends with free-fusion stereograms

Chandrika Ravisankar [a,b], Christopher W. Tyler [c], Clifton M. Schor [d], Shrikant R. Bharadwaj [a,b,*]

[a] Brien Holden Institute of Optometry and Vision Sciences, L V Prasad Eye Institute, Road no. 2, Banjara Hills, Hyderabad – 500034, Telangana, India
[b] Prof. Brien Holden Eye Research Centre, Hyderabad Eye Research Foundation, L V Prasad Eye Institute, Road no. 2, Banjara Hills, Hyderabad – 500034, Telangana, India
[c] Division of Optometry and Visual Sciences, School of Health and Psychological Sciences, City, University of London, Northampton Square, London – EC1V 0HB, United Kingdom
[d] Herbert Wertheim School of Optometry and Vision Science, University of California Berkeley, 360 Minor Hall, Berkeley – 94720, CA, USA

ARTICLE INFO

Keywords:
3D perception
Accommodation
Defocus
Cue-conflict
Retinal disparity
Stereoscopy
Vergence
Volition

ABSTRACT

Free-fusion stereograms are routinely used for demonstrating various stereoscopic effects. Yet, untrained observers find it challenging to perform this task. This study showed that only less than 1/3rd of sixty-one pre-presbyopic adults with normal binocular vision could successfully free-fuse random-dot image pairs and identify the stereoscopic shapes embedded in these patterns. Another one-third of participants performed the task with poor success rates, while the remaining could not perform the task. There was a clear dissociation of vergence and accommodative responses in participants who were successful with free-fusion, as recorded using a dynamic infrared eye tracker and photorefractor. Those in the unsuccessful cluster either showed strong vergence and accommodation or weak vergence and strong accommodation during the task. These response patterns, however, were specific to the free-fusion task because all these participants generated good convergence/accommodation to real-world targets and to conflicting vergence and accommodative demands stimulated with prisms or lenses. Task performance of the unsuccessful cluster also improved significantly following pharmacological paralysis of accommodation and reached the performance levels of the successful cluster. A minority of participants also appeared to progressively learn to dissociate one of the two directions of their vergence and accommodation crosslinks with repeated free-fusion trials. These results suggest that successful free-fusion might depend upon how well participants generate a combination of volitional and reflex vergence responses to large differences in disparity with conflicting static accommodative demands. Such responses would require that only one direction of the vergence-accommodation crosslinks be active at any given time. The sequence of near-responses could also be learnt through repeated trials to optimize task performance.

1. Introduction

Free-fusion stimuli of the type shown in Fig. 1 are ubiquitously used for demonstrating binocular vision phenomena such as stereopsis, binocular lustre, and binocular rivalry in scientific publications/presentations, classroom demonstrations and popular science forums. Their operational advantage over their optical counterparts is that they do not require anaglyphic filters, cross-polarizers, or stereoscopes to demonstrate the phenomena. The free-fusion task involves converging or diverging the two eyes using vergence eye movements to fuse the companion images while retaining focus at the plane of the stimulus display.

The ubiquitous use of free-fusion stimuli reflects the assumption that the task is easy and straightforward to perform. However, Cisarik et al. (2012) observed that more than 80 % of their cohort ($n = 142$) self-reported to be "poor" at free-fusing autostereograms. The majority of these participants took > 1 min to fuse the stimulus to experience 3D depth, even while many others failed to achieve this goal altogether (Cisarik et al., 2012). These results resonate well with the corresponding author's personal experience of undergraduate optometry students who have difficulty in performing this task in a classroom setting. Asthenopic symptoms of eyestrain were also reported by some students when they

---

[*] Corresponding author at: Brien Holden Institute of Optometry and Vision Sciences, L V Prasad Eye Institute, Road no. 2, Banjara Hills, Hyderabad – 500034, Telangana, India.

E-mail address: bharadwaj@lvpei.org (S.R. Bharadwaj).

https://doi.org/10.1016/j.visres.2023.108329
Received 4 May 2023; Received in revised form 19 October 2023; Accepted 21 October 2023

repeated the task. Other than Cisarik et al. (2012), we found no other study in literature that systematically addresses the participants' ability to free-fuse such stimuli. Therefore, the first purpose of the present study was to determine the percentage of individuals in a relatively homogenous cohort of visually healthy, emmetropic, pre-presbyopic adults who can free-fuse random-dot stereograms to successfully identify the 3D shape embedded within this stimulus.

The vergence and accommodative demands during the free-fusion task are different from those experienced during naturalistic viewing. For an emmetropic and orthophoric visual system, the demands on vergence and accommodation are consistent with each other under naturalistic viewing conditions (Eadie & Carlin, 1995, Fincham & Walton, 1957, Fry, 1937, Fry, 1939) However, these demands are in conflict during the free-fusion task. Participants experience a non-zero vergence demand to fuse the companion images while their accommodative demand remains unchanged at the stimulus plane (Fig. 2A). Resolving this vergence-accommodation conflict is non-trivial because it violates a strong neural coupling between the two systems (Schor, 2009). Once the companion images are successfully free-fused, the fusion response must also be successfully negated at the end of the trial to reinstate baseline viewing condition, a task that requires disengagement of the vergence-accommodation coupling in the opposite direction (i.e., between divergence and disaccommodation). An inability to resolve the conflict may result in a doubled and/or blurred binocular percept that adversely affects stereo perception in the free-fusion task (Fig. 2B – D). Additionally, the free-fusion task requires a volitional effort to converge, unlike the reflexive use of retinal disparity or blur (through the AC/A crosslink) to achieve clear and single vision in natural depth stimuli. The magnitude of this volitional response is defined by the horizontal separation between the companion images, and this

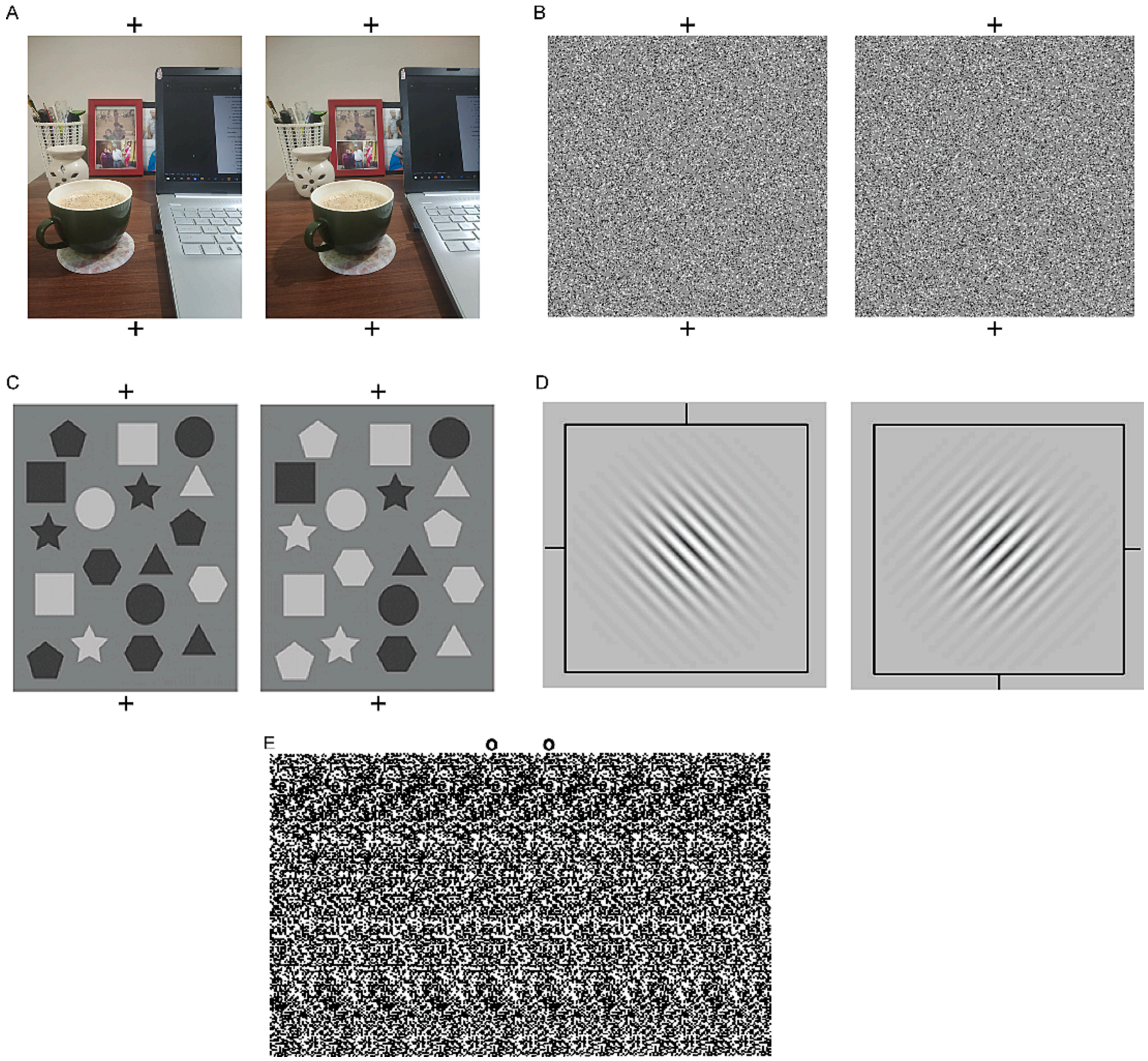

Fig. 1. Examples of free-fusion stimuli demonstrating various binocular vision phenomena. Panel A demonstrates 3D depth of a natural scene; panel B demonstrates a 3D shape (triangle) in crossed retinal disparity, embedded in a field of random-dots (random-dot stereogram); panels C and D demonstrate binocular lustre and binocular contrast rivalry [objects with opposite luminance polarity in the companion images will shimmer (Venkataramanan, Gawde, Hathibelagal & Bharadwaj, 2021)], respectively; and panel E demonstrates a 3D shape (heart symbol) in crossed retinal disparity in an autostereogram from Tyler and Clarke (1990). All images can be cross-fused to experience the said binocular vision phenomenon.

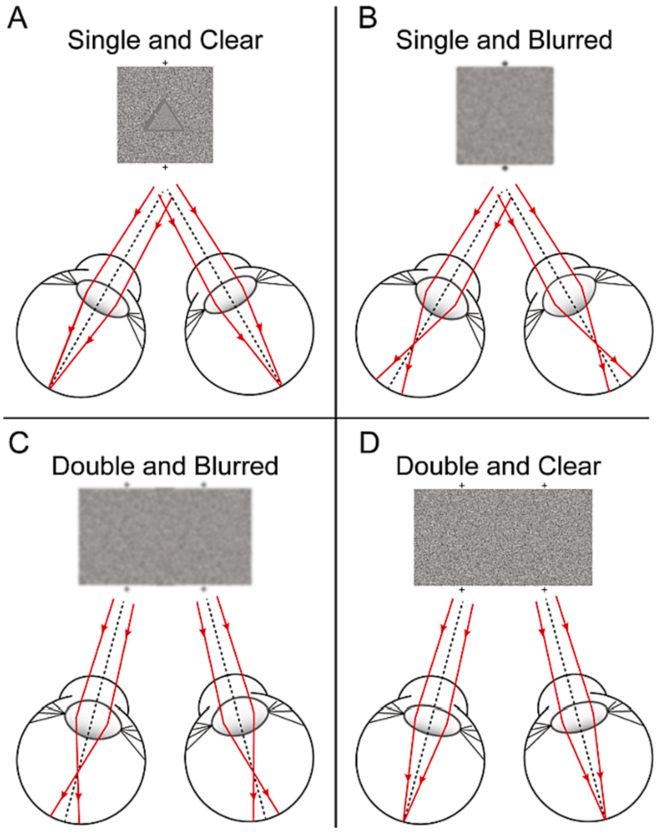

Fig. 2. Schematic of the different perceptual patterns that may be experienced during the free-fusion task used in this study, depending on the status of the vergence and accommodative responses. Single and clear vision of the stereogram may be experienced when the image pair is successfully fused using vergence eye movements while maintaining accommodation at the plane of the computer monitor (panel A). Single and blurred vision of the stereogram may be experienced when the image pair is successfully fused using vergence eye movements but with excessive accommodation resulting in myopic defocus (panel B). Double and blurred vision of the stereogram may be experienced when the image pair is not successfully fused, coupled with excessive accommodation, resulting in myopic defocus (panel C). Finally, the image pair may remain double and clear with poor task compliance (panel D).

may require internal calibration for accurate fusion (Read, Kaspiris-Rousellis, Wood, Wu, Vlaskamp & Schor, 2022). In this context, two additional aims were investigated in the present study. The second aim investigated the pattern of vergence, and accommodation responses generated during this task that facilitates/inhibits the achievement of a single and clear cyclopean percept. Due to its atypical nature, the free-fusion task may require a period of learning for the participants to successfully resolve the motor cue conflict. The third aim investigated the evidence for such perceptual and motor learning, their temporal characteristics and the underlying pattern of vergence and accommodation with repeated attempts at free fusion. To address these aims, a total of six experiments – one main experiment and five supplementary experiments – were conducted. Table 1 lists the purpose, hypothesis, and the sample size for each experiment.

2. Methods

2.1. Subjects

The study was conducted at the L V Prasad Eye Institute (LVPEI), Hyderabad, India. The protocol adhered to the tenets of the Declaration of Helsinki and the study protocol was initiated after the participant signed a written informed consent form that was approved by the Institutional review board of LVPEI. Sixty-four pre-presbyopic individuals (18 – 36 years of age; 45 female) from the student and staff pool of the institute were recruited after undergoing a comprehensive eye examination that ruled out any oculomotor pathology. All these individuals were administered the Computer Vision Symptom Survey (CVSS) questionnaire (https://cvss17.com/english) to identify symptoms of binocular vision dysfunction (Gonzalez-Perez, Susi, Antona, Barrio & Gonzalez, 2014) and two participants were excluded following this questionnaire. A third participant who was originally inducted into the study had to be subsequently excluded excessive ocular fatigue. Data from a total of 61 participants is therefore reported here. All these participants had spherical equivalent refractive error of $<\pm0.50$D in both eyes, high contrast visual acuity equal to or better than 20/20, stereoacuity equal to or better than 40 arc seconds, and CVSS scores between 1 and 3, indicating no dysfunctional binocular vision (Gonzalez-Perez et al., 2014).

2.2. The experiments

2.2.1. Stimulus

Participants free-fused random-dot stereograms generated with custom-written software in Matlab® (R2016a; The MathWorks Inc, Natick, MA, USA) on a luminance calibrated CRT monitor from 150 cm viewing distance (Fig. 1B). Each image in the stereogram pair subtended a visual angle of 2.86° at the eye's nodal point, with a dot density of 94 dots/deg^2. Each stereogram contained one of eight geometric shapes (triangle, trapezium, square, rectangle, circle, semicircle, oval and star) embedded into them with a crossed retinal disparity of 250 arc sec that was within the disparity range for stereo-depth perception (Fig. 1B). The 3D geometric shape subtended a visual angle of 1.71° at the eye's nodal point. The stereo pairs were separated on the display screen by 14 cm, resulting in a convergence demand of 2.2 Meter Angles (MA; Meter Angle is the reciprocal of the viewing distance in meters; corresponding to the unit of diopters for accommodation) for 6 cm interpupillary distance (or 7.63°) at the viewing distance of 150 cm to achieve cross-fusion. Free fusion of the stereo pairs using divergence eye movements results in a demand of 0.89 MA for the same viewing distance and interpupillary distance. Further, the vergence demands change by no more than 0.1 MA with up to 5 mm change in interpupillary distance. Since all stimuli were displayed on the computer monitor at a fixed viewing distance, the accommodative demand remained constant at 0.67 D throughout the experiment. Each participant attempted to free-fuse 32 such stereograms, with each trial containing a stereogram with randomly assigned geometric shape. In addition, eight uniform random-dot stereograms with no geometric shape were also included as catch trials in random order in the presentation sequence. In total, each participant had 40 free-fusion stereogram presentations divided into 4 blocks of 10 presentations each (8 trials with stereo pattern and 2 catch trials). Each stereogram presentation lasted 20 sec, with an inter-trial interval of 10 sec. Breaks were provided between each block to avoid fatigue and boredom.

2.2.2. Psychophysical assessment of task performance

Before the start of the session, participants were oriented to the luminance profiles of the various geometric shapes embedded in the random stereograms that could "pop-out" in 3D during the stimulus presentation. The beginning and end of each trial was primed by the words "Start" and "Relax" displayed on the computer monitor, respectively. They were then instructed to "cross their eyes" to fuse the stereogram and identify the geometric shape that appeared to "pop-out of the screen" upon successful fusion. Participants were asked to guess the 3D geometric shape if it was not apparent during the trial. They were also explicitly instructed to attend to the fused central percept and ignore the peripheral monocular percepts. Before the start of the experiment, subjects were asked to free-fuse a set of fixation crosses in

Table 1
Details of the six experiments that were conducted in this study to understand various aspects of free-fusion behavior in pre-presbyopic adults with normal binocular vision. The main experiment was conducted on all study participants while the supplementary experiments (S1 to S5) were conducted on subsets of those who participated in the main experiment.

Expt	Specific aims	Hypothesis	n
Main	1. Determine the success rate of study participants in a free-fusion task. 2. Determine the patterns of vergence and accommodation during the free-fusion task. 3. Determine if initially-unsuccessful study participants show a learning curve with repeated attempts at free-fusion.	1. Based on Cisarik et al. (2012), only a minority of study cohort will be successful at identifying 3D shapes in a stereogram using free-fusion. 2. Successful participants will show dissociated vergence and accommodative responses that enable single and clear perception of the stereogram. 3. Study participants will not demonstrate any learning curve across the 40 repeated trials of free-fusion used in this study.	64
S1	Determine if the unsuccessful participants generate robust vergence and accommodation to naturalistic changes in near-vision demand.	Unsuccessful participants will generate robust vergence and accommodation when retinal disparity and defocus cues change consistently to naturalistic near-vision demands.	5
S2	Determine if there were any differences in the vergence and accommodation parameters typically evaluated during a binocular vision exam between participants who were successful and unsuccessful in the free-fusion task.	Relative vergence and accommodation measurements that evaluate the vergence-accommodation conflict management ability will be poorer in unsuccessful participants, vis-à-vis, those successful at the task.	29
S3	Determine if the mitigation of the vergence-accommodation conflict through cycloplegia will improve free-fusion task performance.	Free-fusion task performance will improve following cycloplegia, vis-à-vis, pre-cycloplegia levels.	5
S4	Determine if free-fusion task performance improves with a reduction in the magnitude of vergence-accommodation conflict.	Reduction in the magnitude of vergence-accommodation conflict results in any improvement of free-fusion task performance.	14
S5	Determine if the accommodative transient observed in successful participants is a measurement artifact of photorefraction.	Accommodative transients are not a measurement artifact. They reflect the interactive dynamics of vergence-accommodation conflict management during free-fusion.	5

order for them to understand the task. No other specific instruction or feedback on performance was provided to the participant during the session. Task performance was quantified as the percentage of the total trials in which the 3D geometric shape was correctly identified by the participant. Given that all participants had a stereoacuity of at least 40 arc sec, the suprathreshold retinal disparity of the geometric shapes used in these stereograms (250 arc sec) should have enabled their easy identification upon fusion of the companion images. An inability to discern the geometric shape should thus reflect the participant's inability to achieve a clear and single vision of the stereogram, either from inaccurate vergence or accommodation or both.

2.2.3. Measurement of vergence and accommodation

Binocular vergence (in degrees), accommodation (in diopters, relative to the photorefractor distance; D) and pupil diameter (in millimeters; mm) were recorded in synchrony with the stimulus presentation using a dynamic (50frames per second), eccentric, infrared photorefractor (PowerRef3®, PlusOptix GMBH, Nuremberg, Germany). The photorefractor was placed directly in front of the participant at 1 m viewing distance, slightly inferior to the stimulus presentation monitor so as to not occlude the visual stimulus. All data were collected using the standard settings of the photorefractor as recommended by the device manufacturer. Detailed evaluation of the PowerRef 3 as a tool to measure the near-triad responses is already available in the literature (Bharadwaj, Roy & Satgunam, 2020, Candy, 2019). The photorefractor measures the refractive power of the eye by converting the luminance slope of the reflected IR light formed across the pupil into diopters using an in-built defocus calibration factor (Roorda, Campbell & Bobier, 1995, Wu, Thibos & Candy, 2018). This defocus calibration factor is known to be different for Indian eyes, compared to the Caucasian population on whom the in-built defocus calibration of the device is based (Bharadwaj, Sravani, Little, Narasaiah, Wong, Woodburn & Candy, 2013, Sravani, Nilagiri & Bharadwaj, 2015). To avoid errors in the measurement of accommodation arising from the calibration factor, the raw data were scaled using the average calibration factor for the Indian ethnicity available in the laboratory from an earlier study (Sravani et al., 2015).

The individual eye's gaze position is recorded by the photorefractor by tracking the relative separation between the first Purkinje image and the entrance pupil center and applying an in-built Hirschberg ratio (11.8°/mm) to convert this separation into angular units of degrees (Ntodie, Bharadwaj, Balaji, Saunders & Little, 2019). Binocular vergence was then derived by taking the difference between the two eyes' gaze positions at each frame (Bharadwaj & Candy, 2008). To be able to effectively compare the vergence and accommodative responses obtained in this study, the former was converted into units of meter angles (MA) using Eq (1). Blinks and other outliers were removed from the raw data, following which the gaze position, vergence and accommodative responses were smoothed using a 100 msec running average filter.

$$\text{Vergence demand (in MA)} = \{100 \text{ x } \tan(\text{angular rotation of eye balls [in deg]})\} / \text{Inter} - \text{pupillary distance (in cm)} \quad (1)$$

The operating range of the photorefractor is restricted to pupil diameters between 3- and 8-mm. Significant pupil miosis that precluded noise-free recording of gaze position and accommodation was observed in pilot experiments with the free-fusion task. Hence, the pupils of all participants were dilated by instilling 10 % Phenylephrine Hydrochloride in both eyes before the start of the experiment. Previous literature has shown that usage of this drug for pupil dilation has limited impact on the accommodative responses (Esteve-Taboada, Del Aguila-Carrasco, Bernal-Molina, Ferrer-Blasco, Lopez-Gil & Montes-Mico, 2016). The experiment commenced ~ 60 min after instillation of the eye drops, ensuring that the pupil diameters of both eyes, even if reacting mildly, were within the operating range of the photorefractor.

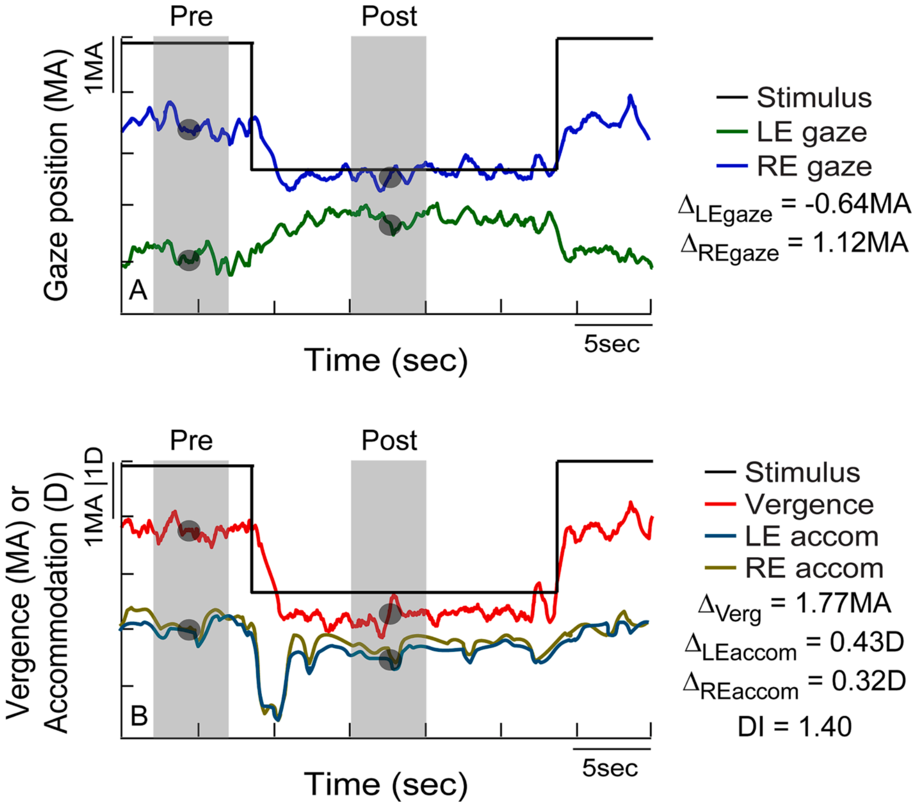

Fig. 3. Panel A) Right and left eye gaze positions plotted as a function of time to identify a valid attempt to free-fuse the stimulus in a given trial. The corresponding vergence and accommodation traces in both eyes are shown in Panel B. Downward deflection of the raw traces in the right eye and upward in the left eye show an increase in the gaze position response in panel A. Downward deflection of the raw traces in panel B indicate an increase in the magnitude of accommodation and vergence. The grey vertical bars in both panels indicate the region in the raw traces that were averaged before (pre) and after (post) stimulus presentation to calculate the magnitude of change in gaze position, vergence and accommodation in a given trial. The grey circles in each panel indicate the average value of that parameter before and after stimulus presentation. Panel B also shows the dissociation index (DI) calculated as the difference in the magnitudes of change in vergence and accommodative responses for this trial.

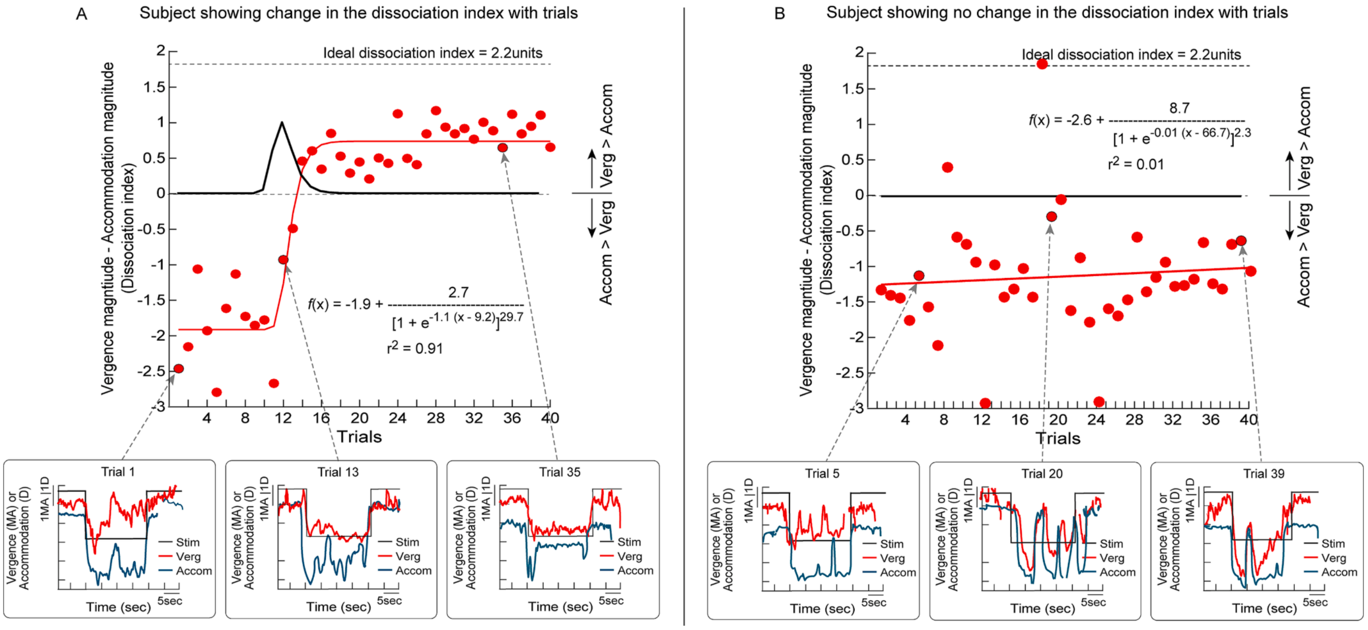

Fig. 4. The dissociation index plotted as a function of trial number in two representative subjects. Red and black curves in both panels show the best-fit logistic regression function and its derivative, respectively. The coefficients of the logistic regression fit along with its R^2 value are shown in each panel. The insets show the corresponding vergence and accommodation raw traces for representative trials from which the dissociation index was calculated. The subject in Panel A demonstrated a systematic change in the dissociation index over trials, while the subject in Panel B showed large fluctuations in both vergence and accommodation that did not show any consistent change in the dissociation index over trials.

2.3. Data analysis

2.3.1. Validity of task performance and the dissociation index

A change in monocular gaze position in the appropriate direction after stimulus presentation was used to determine if a valid attempt was made to free-fuse the stimulus (Bharadwaj & Candy, 2008). Free-fusion using convergence eye movements will result in adduction of the left and right eyes, coded as positive and negative values of gaze position change in the photorefractor output, respectively (Fig. 3A). Free-fusion using divergence eye movements results in the opposite pattern of responses. The change in gaze position was calculated by averaging 5 sec of stable data from the raw traces before and after stimulus presentation (Fig. 3A). The standard deviation of the gaze position epoch before stimulus presentation was considered as the baseline variability and the ensuing change in gaze position (and therefore the trial) was considered valid only if its magnitude exceeded the noise level.

The magnitudes of change in binocular vergence and accommodative responses to the stereogram were calculated in the valid trials in a similar manner to the gaze position responses (Fig. 3B). The difference between the magnitudes of change in vergence and accommodative responses [i.e., Vergence (MA) - Accommodation (D)] for each trial was termed the dissociation index. This index quantifies the de-coupling between the vergence and accommodative responses needed to achieve clear and single vision during the stimulus conflict of the free-fusion task. Achievement of the cyclopean percept requires that the vergence response magnitude be nearly equal to the vergence demand of 2.2 MA while the accommodative response remains nearly unchanged at plane of the computer monitor i.e., 0 D). The ideal dissociation index would therefore be 2.2 units. Smaller dissociation indices may reflect inaccuracies of vergence and/or accommodation, i.e., either vergence is too small or accommodation is too large, leading to either double or blurred cyclopean percepts, respectively. Negative values of the dissociation index would indicate that the accommodative magnitude was greater than the vergence magnitude.

2.3.2. Variation in the dissociation index across trials

Visual inspection of the data revealed that, in some participants, the dissociation index changed systematically over trials, reflecting alterations in task performance during the course of the experiment (Fig. 4). To avoid such changes from unduly influencing the outcome measures, the temporal trends in the dissociation index of each participant were fit with a five-parameter logistic regression function (Equation (2). A derivative of the best-fit regression function was then obtained and the trial number corresponding to the derivative values reaching zero was considered as the asymptote of this function. The performance in the free-fusion task was deemed to have saturated for trials beyond this asymptote. Only vergence and accommodation data from trials beyond this asymptote were averaged to describe the overall response magnitude of the participant in this task.

$$f(x) = y_0 + \frac{a}{\left[1 + e^{-b(x - x_0)}\right]^c} \tag{2}$$

Where, x_0 is the x value of the curve's midpoint, y_0 is y value of the lower asymptote, a is the height of the sigmoid between the asymptotes, b represents the steepness of the curve, and c controls the steepness and sharpness of the 'roll-offs''.

2.3.3. Statistical analyses

Analyses of all outcome variable were performed using Matlab® statistical software and SPSS® (Version 20.0, SPSS Inc, Chicago, USA). The Shapiro-Wilk test indicated that the outcome measures (percentage of correct identification, vergence magnitude and accommodation magnitude) were non-normally distributed. Hence, non-parametric tests were used for the statistical analyses. A p-value of < 0.05 was considered statistically significant. For the first aim of the main experiment, a two-step cluster analysis was performed on the data of percentage of correct identification using SPSS (Benassi, Garofalo, Ambrosini, Sant'Angelo, Raggini, De Paoli, Ravani, Giovagnoli, Orsoni & Piraccini, 2020). This analysis was set to automatically determine the number of clusters in the dataset using the log-likelihood distance between the data points assessed by the Bayesian information criterion (Benassi et al., 2020). The clusters obtained from the percentage of correct identification were further sub-clustered for their vergence and accommodative responses using the same algorithm to determine patterns of near-triadic responses.

3. Results

Qualitative feedback from the 61 study participants at the end of the experiment revealed that only a minority of participants found the free-fusion task easy to perform and correctly identify the 3D shapes in the random-dot stereograms. Those who found difficulty with the task reported inability to fuse the companion images or sustain the fused cyclopean percept and/or deblur the stereogram upon fusion. A few subjects reported an improvement in task performance with repeated trials.

3.1. Cluster analysis of task performance

Across all valid trials in the experiment, the median and [25th – 75th interquartile range (IQR)] percentage of correct identification of the 3D shape in the stereograms, vergence magnitude and accommodative magnitude was 11.11 % (0 % – 60 %), 1.24 MA (0.33 – 1.70 MA) and 0.44 D (0.14 – 0.90 D), respectively, during the free-fusion task. The two-step cluster analysis identified two clusters for the percentage of correct identification outcome variable and three clusters for the vergence variable, with ≥ 0.8 silhouette measure of cohesion and separation for both variables. This value, a measure of the goodness-of-fit of the cluster structure, indicated good quality of clusters for these outcome variables (Kaufman & Rousseeuw, 2009, van den Berge, Free, Arnold, de Kleine, Hofman, van Dijk & van Dijk, 2017). For the percentage of correct identification variable, the first and second clusters contained 18 (29.3 %) and 43 (70.5 %) participants, respectively (Fig. 5A). The median values of the percentage of correct identification were significantly different between the first [80.63 % (73.75 % – 98.44 %)] and second [0 % (0 – 12.50 %)] clusters ($p < 0.05$) (Fig. 5A). Given that data of only the valid trials in the experiment are reported here, the median percentage of correct identification of the 3D shape in the latter cohort was smaller than the chance level of 12 % in an 8-alternate forced choice task. This result indicated that fewer than 1/3rd of the study participants with normal binocular vision were successful at free-fusing to identify the 3D shape embedded in the stereograms.

In the first cluster, the median vergence and accommodative demands were 1.75MA (1.45 – 1.88MA)] and 0.40D (0.28 – 0.52D), respectively (Fig. 5B) compared with the expected values of 2.2 MA and 0 D. All these participants cross-fused to achieve single vision of the stereo pair. The vergence and accommodation response magnitudes showed larger variability in the second cluster with median values of 0.60MA (0.24 – 1.48 MA) and 0.70 D (0.13 – 1.49 D), respectively (Fig. 5C). The first vergence sub-cluster ($n = 15$; 24.5 %) showed vergence magnitudes close to the expected value [1.61 MA (1.48 – 2.25 MA)] but with high accommodative magnitudes [1.54 D (0.76 – 2.87 D)] (Fig. 5D). The second sub-cluster ($n = 4$; 8.2 %) showed relatively lower vergence magnitudes [0.78 MA (0.71 – 0.79 MA)] but with high accommodative magnitudes [1.85 D (1.64 – 2.06 D)] (Fig. 5E) and the third sub-cluster ($n = 24$; 39.3 %) showed relatively lower magnitudes of both vergence [0.27 MA (0.14 – 0.47 MA)] and accommodation [0.14 D (0.07 – 0.42 D)] (Fig. 5F).

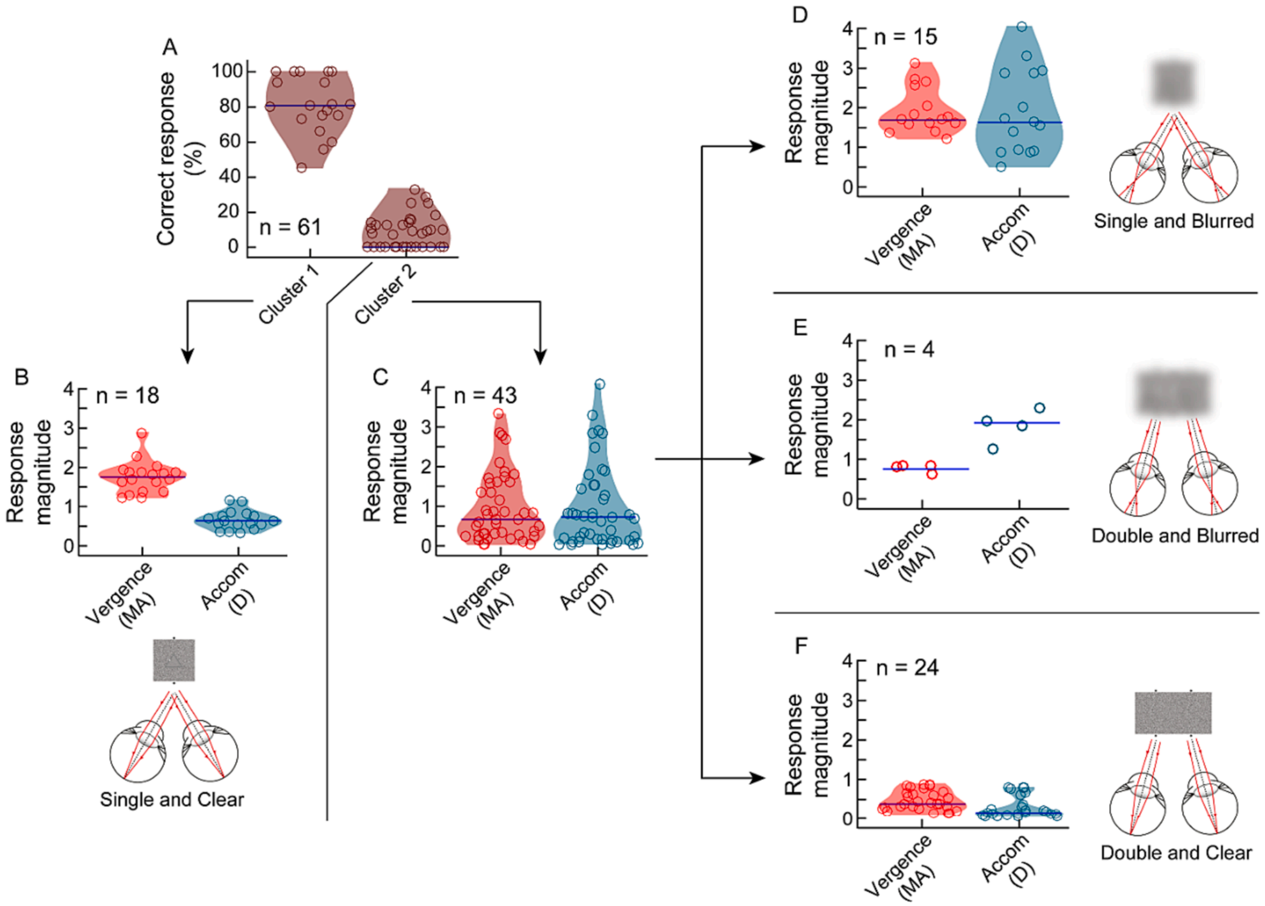

Fig. 5. Violin plots showing the results of the cluster analysis performed to segregate the outcome variables of this study. The violin plot for the percentage of correct response was constructed with a kernel density of 5 % (Fig. 5A) while all other plots were constructed with a kernel density of 0.2 MA or 0.2 D for vergence and accommodation, respectively (Fig. 5B – F). Each violin plot has been truncated at the upper and lower ends of the data distribution. The solid line within each plot shows the median value of that distribution. Individual data points within each violin plot are randomly distributed horizontally for better visualization. Violin plots are not constructed for panel E as this sub-cluster contains only 4 data points. In the violin plots for vergence and accommodation, the ordinate scale represents the change in the response magnitude from baseline condition. The ideal change in vergence and accommodative response to the free-fusion stimuli would be 2.2 MA of vergence and 0 D of accommodation. The schematic representation of the perceptual experience of participants in each cluster is included in this figure.

3.2. Raw traces of accommodation and vergence of participants in the different clusters

Fig. 6 shows raw traces of vergence and accommodation obtained from representative participants belonging to the first cluster (Fig. 5B) and to the different sub-clusters (Fig. 5D – F). The raw data of the participant in the single and clear cluster showed robust and well-sustained vergence responses following target presentation, reflecting sustained fusion of the two companion images of the stereogram (Fig. 6A). The accommodative responses, on the other hand, showed a transient increase in its magnitude in accompaniment with the vergence response but returned close to baseline values shortly thereafter (Fig. 6A). The raw data of the participant in the single and blurred sub-cluster showed sustained vergence and accommodative step responses following target presentation (Fig. 6B). The raw data of the participant in the double and blurred sub-cluster showed weak vergence response but with a larger magnitude of accommodative step response that was well-sustained throughout the stimulus presentation epoch (Fig. 6C). The raw data of the participant in the double and clear sub-cluster showed minimal change in the vergence and accommodative response following target presentation (Fig. 6D).

3.3. Relation between the percentage of correct response and the dissociation index

As noted earlier, the dissociation index is an estimate of the decoupling between vergence, and accommodation responses needed to achieve clear and single vision of the stereogram during the free-fusion task (Fig. 3B). It is expected that participants in the first cluster of Fig. 5A (i.e., those with high percentage of correct identification of the 3D shape in the stereograms) will have higher values of dissociation index, relative to those in the second cluster of Fig. 5A (i.e., those with low percentage of correct identification of the 3D shape). This was indeed found to be case, as demonstrated in the scatter diagram plotting the percentage of correct responses of each participant in the two clusters against their corresponding dissociation index (Fig. 7). The median dissociation index of the first cluster [1.33 (IQR: 0.99 – 1.53)] was also significantly different from that of the second cluster [0.03 (IQR: −0.37 – 0.31)] ($p = 0.002$). Within each cluster, there was no correlation between the percentage of correct response and the dissociation index (Spearman's rank correlation coefficient; cluster 1: $\rho = 0.06$; $p = 0.81$; cluster 2: $\rho = 0.11$; $p = 0.48$).

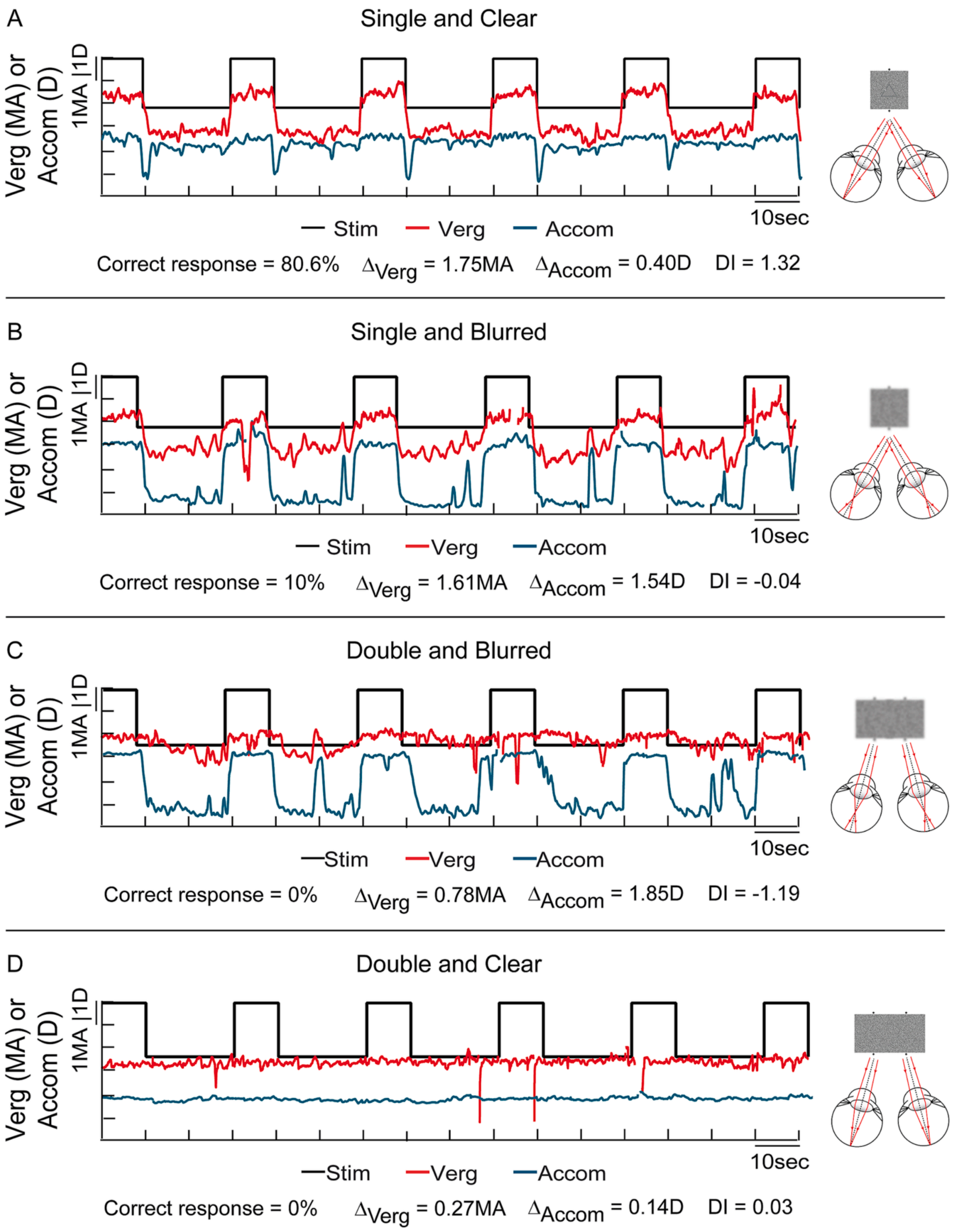

Fig. 6. Raw traces of vergence (red traces) and accommodation (blue traces) plotted as a function of time for multiple free-fusion trials (black traces) in this study. All other details of the raw traces are same as Fig. 3. Each panel shows representative raw data from one subject in each cluster or sub-cluster reported in Fig. 5. The outcome variables obtained from each of these participants are noted at the bottom of each panel.

3.4. Trial-by-trial variation in the dissociation index across study participants

The adjusted R^2 of the logistic regression equation fitted to the data of the dissociation index against trial number was > 0.4 ($p < 0.01$) in eight participants, indicating a meaningful change in the dissociation index across repeated trials (Table 2). Amongst these participants, the lower asymptote of the dissociation index (y_0) was negative in 5 participants, indicating that their accommodative response was larger than the vergence response at the beginning of the free-fusion trials. This parameter was

positive in the remaining participants, indicating that the vergence responses were equal to or larger than the accommodative response at the beginning of the free-fusion trials. The upper asymptote of this function (y_1), derived offline by adding the lower asymptote with the sigmoid height parameter (a), showed high positive values of the dissociation index in all participants, except in P6 (Table 2). Of these, the coefficients of participants P2 – P4 were close to the ideal dissociation index of 2.2, while the y1 values indicated that their vergence and accommodative responses tended in the desired direction of achieving single and clear vision of the free-fusion stimuli. The negative y_1 coefficient of participant P6 indicated a worsening of performance in the free-fusion task over trials. The steepness coefficient (b) of the logistic regression equation ranged from low to high positive values across

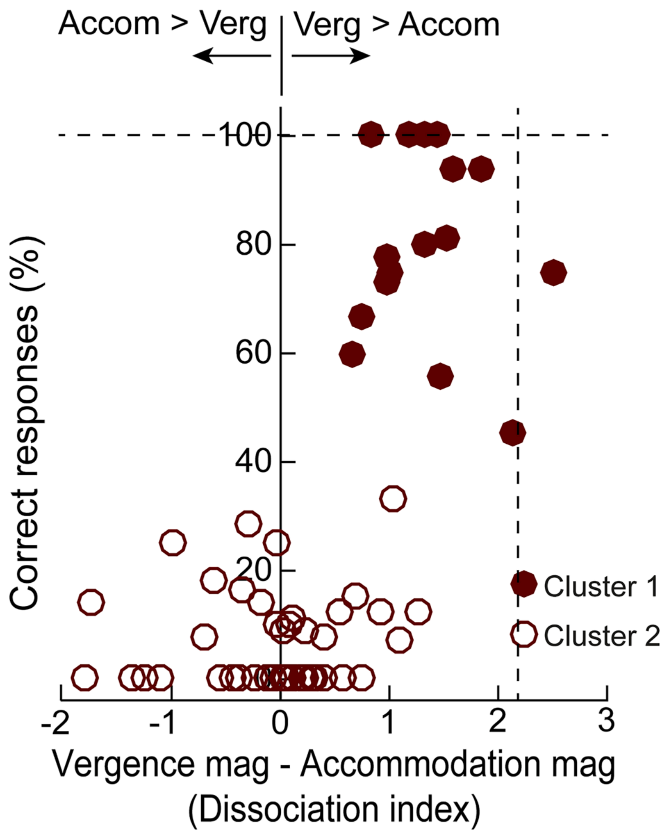

Fig. 7. Scatter diagram of the percentage of correct identification of the 3D shape plotted against the corresponding dissociation index for all participants (sub-divided into two clusters, see Fig. 5A) obtained across their valid trials in the study. The dashed horizontal and vertical lines indicate the ideal percentage of correct response (i.e., 100%) and the ideal dissociation index (2.2), respectively, in the free-fusion task employed in this study.

participants, representing non-uniform rates of change in dissociation index across trials (Table 2). There was poor correlation between the different coefficients of the logistic regression fit amongst these eight participants ($|p| \leq 0.2$, for all). The percentage of correct identification of the 3D shape in the stereograms ranged from 100 % to 7.1 % amongst these participants (Table 2), with no specific pattern related associated with the coefficients of the logistic regression fit.

The vergence and accommodation responses of one participant showed a unique pattern across the four blocks of the experiment (Fig. 8). In the first block, the responses continued to oscillate without achieving a steady-state for the entire period of stimulus presentation, reflecting their inability to achieve and maintain single and clear percept of the stereogram (Fig. 8A). The response instability decreased in the subsequent blocks of trials, with the vergence responses becoming progressively more robust and larger in magnitude than the corresponding accommodative responses (Fig. 8B – D). In the third and fourth blocks of the experiment, the raw data of accommodation also showed the characteristic transient change in response magnitude before achieving steady-state (Fig. 8C and D), similar to those shown in Fig. 6A. The dissociation index for this participant started out with a high negative value, reflecting larger magnitude of accommodation than vergence and progressively tended in the positive direction with increasing trial numbers (Fig. 8E). Despite these changes in vergence and accommodation, the percentage of correct identification of the 3D pattern was very low in this participant across trials (0 to 2 correct responses from the 1st to 4th blocks, respectively).

4. Supplementary experiments

Five supplementary experiments were conducted to explore additional aspects of the near-response behavior observed in the main experiment (Table 1). Supplementary experiments 1 – 4 were conducted to offer explanation for poor performance in the free-fusion task while supplementary experiment 5 was conducted to rule out the impact of certain artefacts on the raw data of accommodation reported here (Table 1). In general, the measurement and analysis of gaze position, vergence and accommodation in all supplementary experiments were identical to the main experiment. Since only a sub-set of subjects participated in these experiments, statistical analyses of the data were not performed. Instead, trends are described qualitatively.

4.1. Supplementary experiment 1

This supplementary experiment was conducted to rule out the possibility that the participants' difficulty in the free-fusion task was related to their general inability to generate robust vergence and accommodative responses, irrespective of the task (Table 1). The experiment also determined if accommodative vergence, stimulated by non-conflicting changes in the blur stimulus, would facilitate changes in the covarying fusional vergence of companion images used in the free-fusion task. These abilities were tested by stimulating vergence and accommodation to real-world changes in viewing distance wherein the demands on the two motor systems are consistent with each other. A subset of 5 participants (21 – 26 years of age; 3 female) who failed the main experiment and 3 participants (21 – 30 years of age; 3 female) who were successful in the main experiment, participated in this supplementary experiment. Participants fixated on a random-dot stimulus pattern (one of the companion images of the random-dot stereogram used in the main experiment) that switched four times from 1.5 m (0.67 D or MA) to 35 cm (2.86 D or MA; 2.19 D or MA of near vision demand), once every 10 s.

Fig. 9 A – F show raw data of vergence, and accommodation plotted as a function of time for three representative participants of this supplementary experiment, two of whom who failed the main experiment (Fig. 9A – D) and one who was successful in the main experiment (Fig. 9E and F). Unlike the raw data of participants who failed the main experiment (Fig. 9A and C), the raw data in the supplementary experiment showed robust vergence and accommodation responses to changes

Table 2
Coefficients of the five-parameter logistic regression equation that best-fit the data of the dissociation index as a function of trial number (Equation (1). Data from 8 of the 61 participants whose adjusted r^2 values were > 0.4 are shown in this table. The percentage of correct responses (CR) obtained from each participant in the free-fusion task is also shown in this table. The participants are arranged in descending order of the adjusted r^2 values in this table.

Participant	x_0	y_0	y_1	A	b	c	r^2	CR (%)
P1	8.30	−1.91	0.74	2.65	1.08	75.16	0.90	100
P2	−1.71	−2.98	2.21	5.18	0.22	150.83	0.80	77.8
P3	2.27	−9.40	1.64	11.04	0.11	0.25	0.65	55.6
P4	4.05	1.37	2.22	0.85	0.25	4.56	0.64	45.5
P5	17.49	0.21	8.32	8.12	0.13	27.84	0.54	60
P6	−2.08	1.19	−0.20	−1.38	0.06	9.14	0.52	75
P7	4.11	−2.72	1.05	3.78	3.97	5.96	0.47	7.1
P8	2.41	−1.64	49.85	51.49	0.03	11.37	0.43	28.6

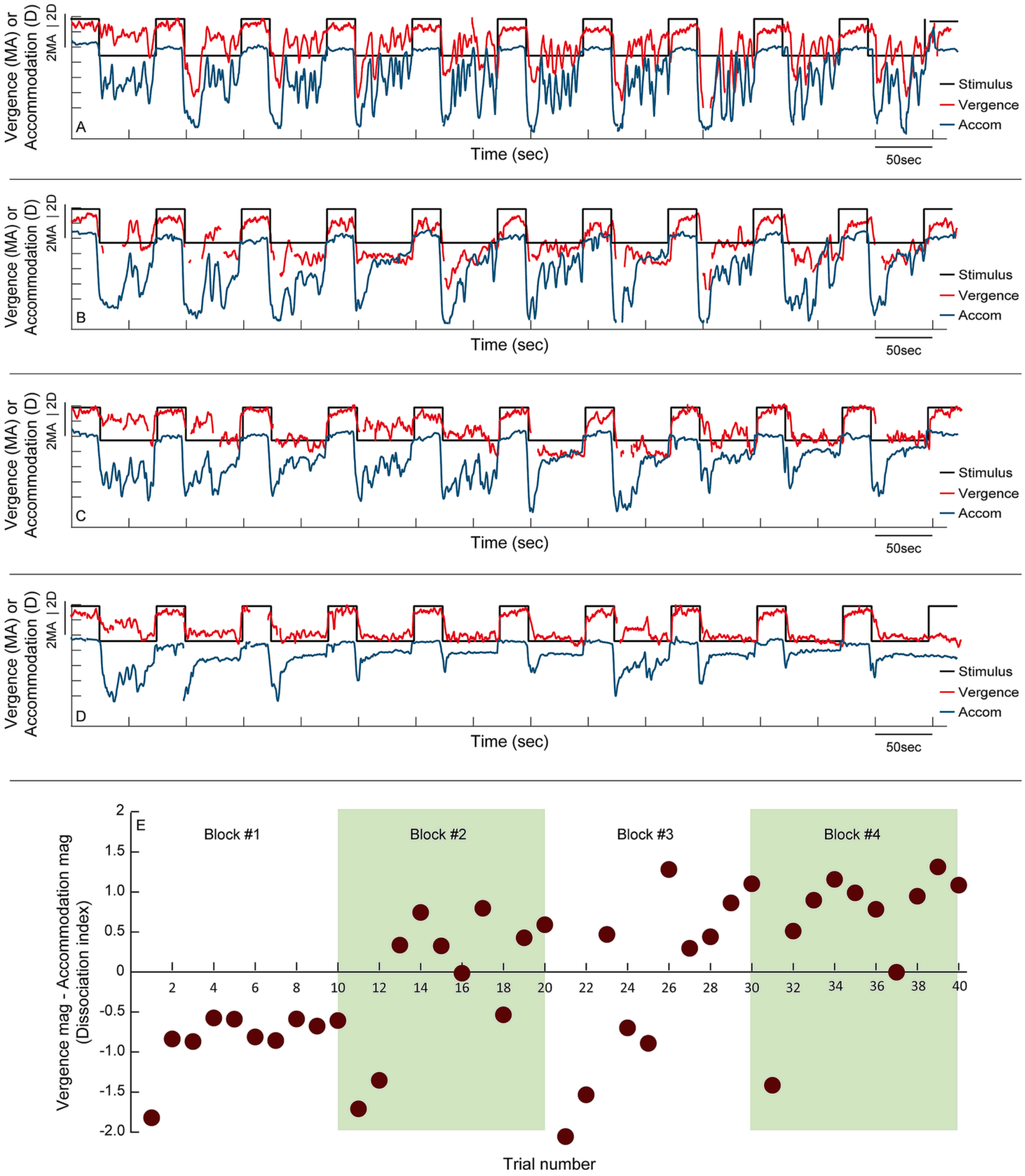

Fig. 8. Raw traces of vergence and accommodation plotted as a function of time for the four blocks of free-fusion trials from the one participant that showed a unique pattern of change in these responses over trials (panels A – D). All other details of these raw traces are same as Fig. 3. Panel E plots the dissociation index of this participant as a function of trial number. The second and fourth block of 10 trials are identified by the green boxes in this figure for ease of visualization.

in viewing distance (Fig. 9B and D). These responses were well-sustained, and their magnitudes were near-appropriate to the stimulus demand, quite unlike the main experiment wherein the responses were weak, ill-sustained and with magnitudes that were inappropriate to the stimulus demands (Fig. 9A – D). Their responses were also similar to the responses of participants who were successful in the main experiment (Fig. 9E and F). The bar diagram in Fig. 9G and H reflect the same trends across all participants of this supplementary experiment.

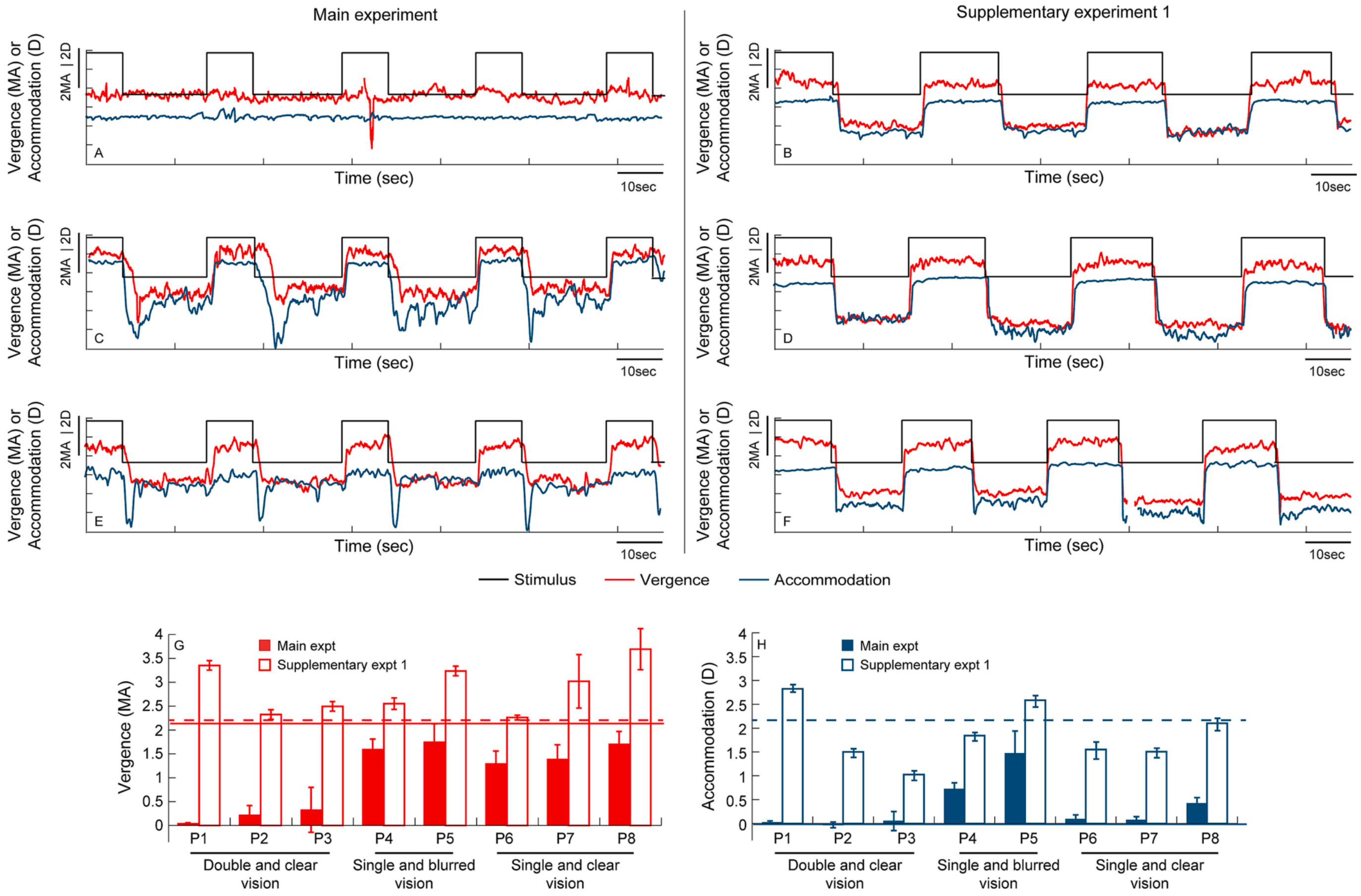

Fig. 9. Raw traces of vergence and accommodation plotted as a function of time for three representative participants in the main experiment (panels A, C and E) and in the first supplementary experiment (panels B, D and F). The first participant (panels A and B) could not perform the free-fusion task in the main experiment, the second participant (panels C and D) experienced single and blurred vision of the stereogram in the main experiment and the third participant (panels E and F) experienced single and clear vision of the stereogram in the main experiment. Bar graphs of the mean (±1S D) vergence (panel G) and accommodation (panel H) response magnitudes in the main and supplementary experiments for all study participants.

Table 3
Median (25th – 75th interquartile range) values of positive and negative relative accommodation, positive and negative relative vergence, accommodative-vergence to accommodation (AC/A) ratio, and accommodative lag, for participants who were successful and unsuccessful in the main experiment. Relative vergences (also known as positive and negative fusional vergences (Scheiman & Wick, 2013) are typically blur, break and recovery values in standard orthoptic evaluation. Since the majority of the participants in this cohort did not report blurring of the target, only the break and recovery values are reported in this table. Also, unlike the rest of the study where vergence responses are reported in units of MA, in this table vergence parameters are reported in units of prism diopters (ΔD) to be consistent with the clinical protocol (Scheiman & Wick, 2013). The cohorts in this supplementary experiment are identified in terms of their perceptual experience of viewing the stereograms in the free-fusion task of the main experiment. No subject with the experience of double and blurred experience of the stereogram could be recruited for this supplementary experiment.

Cohort	Relative Accom (D)		Relative vergence (ΔD)							
	NRA	PRA	NRV – distance		PRV – distance		NRV – near		PRV - near	
			Break	Recovery	Break	Recovery	Break	Recovery	Break	Recovery
Single and Clear (n = 9)	3.0 (3.0 to 3.3)	−4.0 (-4.0 to −3.3)	10.0 (6.0 to 14.0)	6.0 (4.0 to 8.0)	16.0 (14.5 to 19.8)	14.0 (11.0 to 16.5)	12.0 (12.0 to 16.0)	10.0 (10.0 to 14.0)	20.0 (19.5 to 26.3)	18.0 (17.5 to 21.3)
Single and blurred (n = 10)	2.6 (2.5 to3.0)	−4.3 (-4.5 to −3.5)	7.0 (6.0 to 10.0)	5.0 (4.0 to 8.0)	16.0 (14.0 to 16.0)	13.0 (12.0 to 14.0)	14.0 (11.0 to 17.0)	12.0 (9.0 to 15.0)	20.0 (20.0 to 25.0)	18.0 (16.0 to 20.0)
Double and clear (n = 10)	3.0 (2.6 to 3.0)	−4.3 (-4.5 to −4.0)	7.0 (6.0 to 9.5)	5.0 (4.0 to 7.5)	14.0 (12.0 to 17.5)	12.0 (10.0 to 14.0)	11.0 (10.0 to 13.5)	9.0 (6.5 to 11.5)	17.0 (16.0 to 20.0)	14.0 (14.0 to 17.5)

4.2. Supplementary experiment 2

This supplementary experiment determined if the failure in the free-fusion task performance is related to an abnormally limited range of vergence responses to disparity. This fusional vergence is necessary to generate dissimilar vergence and accommodative responses (Table 1) (Fincham & Walton, 1957, Fry, 1939, Ramsdale & Charman, 1988). The ability to generate dissimilar vergence and accommodative responses when both systems are under closed-loop viewing conditions is determined clinically using measures of relative vergence and relative accommodation (Fincham & Walton, 1957, Fry, 1939, Ramsdale & Charman, 1988). These measures test the ability of individuals to respond to slow ramped disparities presented at a fixed viewing distance with accurate convergence and accommodation (i.e., relative vergence range). They also measure the ability to accommodate to a gradual increase of the stimulus to accommodation while the vergence stimulus is fixed (i.e., relative accommodation range). Measurements of relative vergence and relative accommodation were obtained using standard orthoptic protocols, as described in Scheiman and Wick (2013), in a subset of 29 participants, 9 of whom were successful with the free-fusion task in the main experiment while the remaining 20 failed the task either because of a single and blurred percept of the stereogram (n = 10) and a double and clear percept of the stereogram (n = 10) (Fig. 2). This experiment tested the hypothesis that the magnitudes of relative vergence and accommodation for those who failed the task will be lower than those were successful at the task, reflecting a weaker ability of the former cohort to manage conflicts between vergence and accommodation.

Table 3 shows the median (25th – 75th interquartile range) outcomes of the orthoptic evaluation performed on participants of this supplementary experiment. The positive and negative relative vergence and relative accommodation values of those who failed the main experiment were statistically not significantly different from those who were successful in the main experiment (Table 3). The AC/A ratios of the unsuccessful cohort were not significantly different from those of the successful cohort (Table 3). Thus, motor capacity of blur driven accommodation and disparity driven convergence were not limiting factors for task performance in this study.

4.3. Supplementary experiment 3

This supplementary experiment was performed to determine if the poor performance in the free-fusion task could be attributed to the participants' inability to respond to large step changes in disparity while the blur stimulus was fixed. If accommodation innervation were allowed to change without producing blur, would step changes in vergence responses to free-fusion of stereograms improve (Table 1)? This option was achieved by repeating the free-fusion task in a subset of five participants who failed the main experiment (22 – 26 years of age; 3 female), with both their eyes cyclopleged using 1 % Cyclopentolate HCl eye drops. Cycloplegia temporarily paralyzes the ciliary muscle, preventing the optical power of the eye from changing during the free-fusion task. However, efforts of accommodation continue to stimulate accommodative vergence with cycloplegia (Pemberton & Brown, 1962, Van Hoven, 1959). This should minimize the cue-conflict and facilitate an improvement in the free-fusion task performance by allowing accommodative vergence to facilitate the step change in the vergence response just as it does with natural changes in viewing distance. Cycloplegia was confirmed ~ 60 min after instillation of the eye drops using standard clinical protocols (Yazdani, Sadeghi, Momeni-Moghaddam, Zarifmahmoudi & Ehsaei, 2018). Fig. 10 shows bar plots of the magnitude of vergence and accommodation response generated while performing the free-fusion task without and with cycloplegia and the percentage success in correctly identifying the 3D shape under each viewing condition for all five study participants. The vergence and accommodative response magnitudes were high in 4 out of 5 participants (except P2, whose accommodative magnitude was significantly smaller, relative to the vergence magnitude), with the latter exceeding the former in two

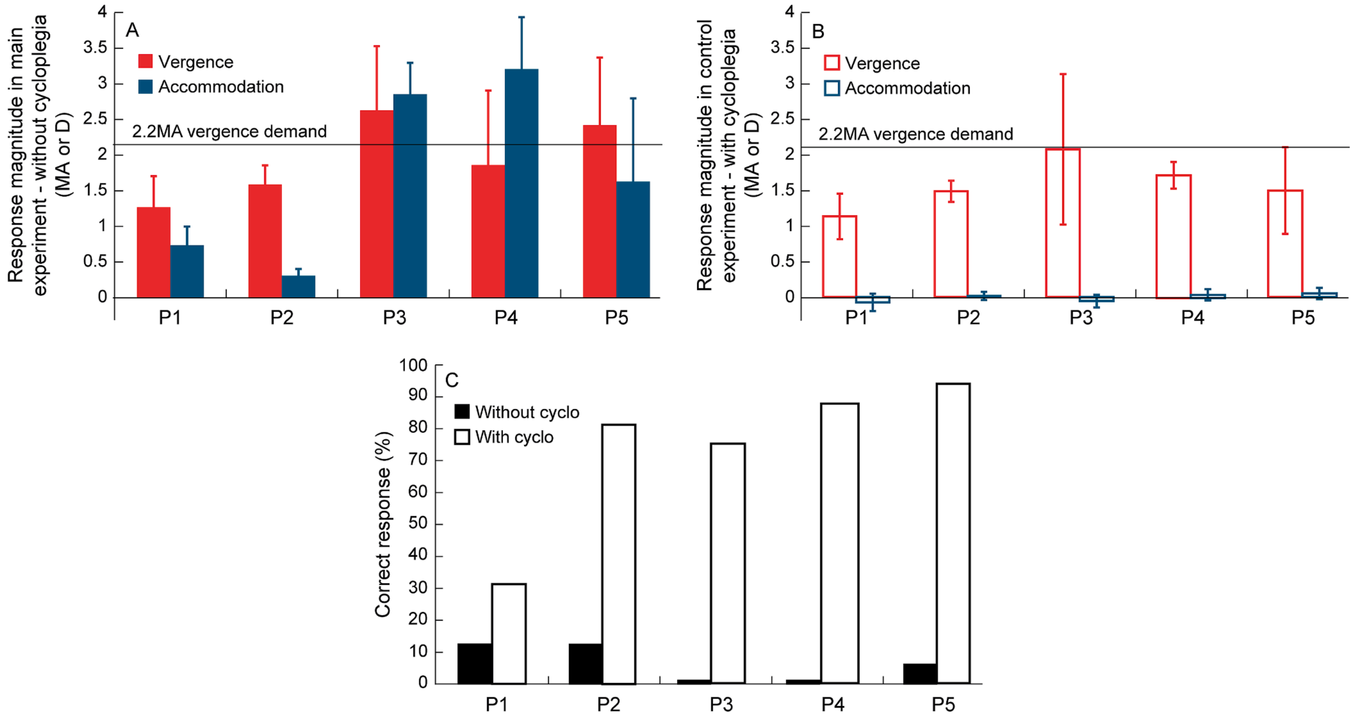

Fig. 10. Bar graphs of the mean (±1SD) vergence and accommodation response magnitudes under baseline, non-cycloplegic viewing condition (panel A) and following cycloplegia (panel B) in the five participants of the third supplementary experiment. Panel C plots bar graphs of the percentage of correct identification of the 3D shape in the stereograms under baseline, non-cycloplegic and cycloplegic viewing conditions for these participants.

participants (P3 and P4) (Fig. 10). The median (25th – 75th IQR) magnitude of vergence response, accommodative response, and dissociation index at the baseline, pre-cycloplegia viewing condition was 1.86 MA (1.59 – 2.42 MA), 1.63 D (0.74 – 2.85 D) and 0.53 (-0.23 – 0.79), respectively. Post cycloplegia, the accommodative response magnitudes were expectedly close to 0 D in all participants [median: 0.01 D (-0.06 – 0.04 D)] while their vergence response magnitudes remained similar to the pre-cycloplegia values [1.49 MA (1.48 – 1.72 MA)]. The median dissociation index also expectedly increased to 1.47 (1.44 – 1.68) following cycloplegia, relative to pre-cycloplegia values in these participants [0.53 (-0.23 – 0.79)]. The percentage of correct identification of the 3D shape increased significantly in all participants following cycloplegia [81.3 % (75.0 – 87.5 %)], relative to the baseline, pre-cycloplegia viewing [6.25 % (0.10 – 12.5 %)] (Fig. 10).

4.4. Supplementary experiment 4

This supplementary experiment determined if the difficulty in the free-fusion task performance was attributable to the magnitude of conflict between vergence and accommodation experienced by the participants in the main experiment (Table 1). The magnitude of conflict imposed in the main experiment was close to population-average limits of relative vergence and accommodation reported clinically (~2 – 2.5D and 2 – 2.5MA) (Fincham & Walton, 1957, Ramsdale & Charman, 1988). To test the hypothesis that a reduction in the magnitude of cue-conflict will produce a proportional improvement in task performance in the free-fusion task, this supplementary experiment was conducted on a subset of 8 participants (22 – 30 years of age; 4 female) by repeating the free-fusion task by lowering the magnitude of conflict imposed in the

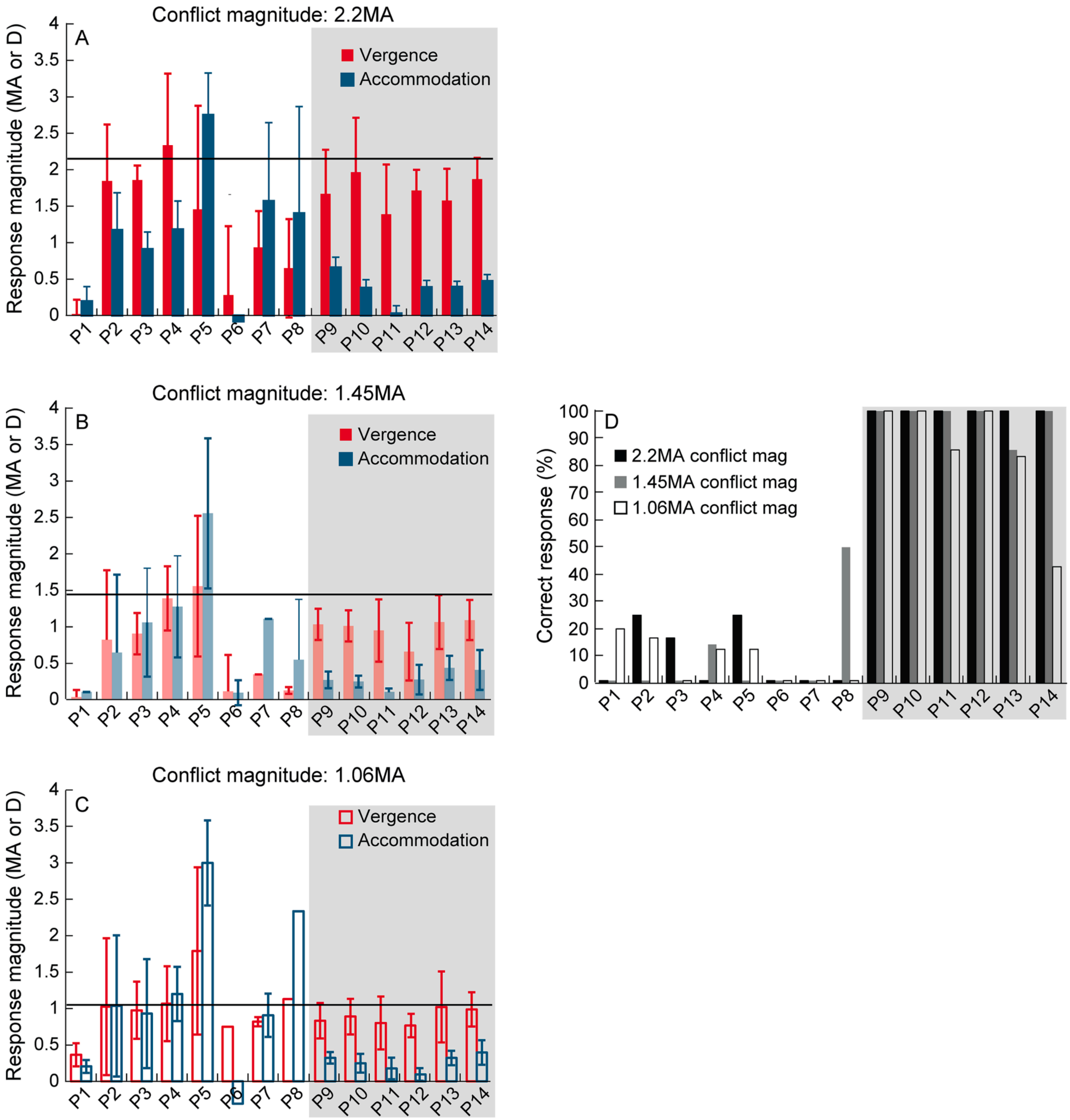

Fig. 11. Bar graphs of the mean (±1S D) vergence and accommodation response magnitudes across the three conflict magnitudes tested in 14 participants in the fourth supplementary experiment (panels A – C). Participants P1 - P8 represent those whose success rate with the free-fusion task were lower in the main experiment relative to participants P9 - P14. Panel D plots bar graphs of the percentage of correct identification of the 3D shape in the stereograms for the three conflict magnitudes in these participants.

main experiment. This was achieved by reducing the separation between the stereo pairs to 7 cm and 3.5 cm, resulting in cross-fusion convergence demands of 4.97° (or 1.45 MA for 6 cm interpupillary distance) and 3.63° (or 1.06 MA for 6 cm interpupillary distance), respectively. An additional 6 participants who achieved single and clear experience of the stereograms in the main experiment (22 – 30 years of age; 4 female) were also recruited for comparison purposes. It was hypothesized that, unlike participants who failed the main experiment, the performance of these six participants would remain unaltered with a reduction in the magnitude of conflict between vergence and accommodation.

Fig. 11 plots bar diagrams of the vergence and accommodative response magnitudes and the percentage of correct identification of the 3D shape obtained across for all three conflict magnitudes. In this figure, participants P1 - P8 represent those whose success rate with the free-fusion task were lower (i.e., they belonged to the second cluster in Fig. 5A) relative to participants P9 - P14 whose success rates were higher (i.e., they belonged to the first cluster in Fig. 5A). Across all three conflict magnitudes, the vergence response of participants P9 - P14 were close to the corresponding vergence demands [median (25th – 75th IQR); 1.69 MA (1.60 – 1.83 MA) for 2.2 MA conflict magnitude; 1.02 MA (0.96 – 1.06 MA) for 1.45 MA conflict magnitude; 0.86 MA (0.81 – 0.96 MA) for 1.06 MA conflict magnitude] while their accommodative responses were small and invariant of the conflict magnitude [0.39 D (0.38 – 0.45 D) for 2.2 MA conflict magnitude; 0.27 D (0.25 – 0.37 D) for 0.90 MA conflict magnitude; 0.29 D (0.20 – 0.32 D) for 0.60 MA conflict magnitude] (Fig. 11A – C). The dissociation indices were smaller than the expected value of 2.2, 1.45 and 1.06 for all three conflict magnitudes [1.34 (1.22 – 1.39), 0.72 (0.64 – 0.76) and 0.62 (0.59 – 0.68), respectively]. Expectedly from the vergence and accommodative responses, the percentage of correct identification of the 3D shapes were high and invariant of the conflict magnitude in participants P9 to P14 [100 % (100 – 100 %) for 2.2 MA conflict magnitude; 100 % (100 – 100 %) for 1.45 MA conflict magnitude; 92.9 % (83.9 – 100 %) for 1.06 MA conflict magnitude] (Fig. 11D).

The results of accommodation and vergence were quite different from the aforementioned trends in participants P1 - P8 (Fig. 11A – C). The pattern was quite idiosyncratic across these eight participants but uniform across conflict magnitudes in each participant (Fig. 11A – C). The vergence and accommodative responses were attenuated in participants P1 and P6 across conflict magnitudes, the accommodative response exceeded the vergence response in participants P5, P7 and P8 across conflict magnitudes and the accommodative response was equal to or slightly smaller than the vergence response in participants P2, P3 and P4 (Fig. 11A – C). The dissociation indices were close to zero in these participants across conflict magnitude. Median values of vergence, accommodation and dissociation index are not reported here, given the heterogeneity in response patterns across these eight participants. The percentage of correct identification of the 3D was also quite low in these participants across all three conflict magnitudes [1.0 % (1.0 – 18.8 %) for 2.2 MA conflict magnitude; 1.0 % (1.0 – 4.3 %) for 1.45 MA conflict magnitude; 6.8 % (1.0 – 13.5 %) for 1.06 MA conflict magnitude] (Fig. 11D).

4.5. *Supplementary experiment 5*

Participants with high levels of success in the free-fusion task invariably showed a transient change in accommodation along with the vergence response following stimulus presentation (Fig. 3B, 4A and 6A). To determine if this transient change in accommodation was related to an artefact of eye movements recorded by the photorefractor (Table 1), a

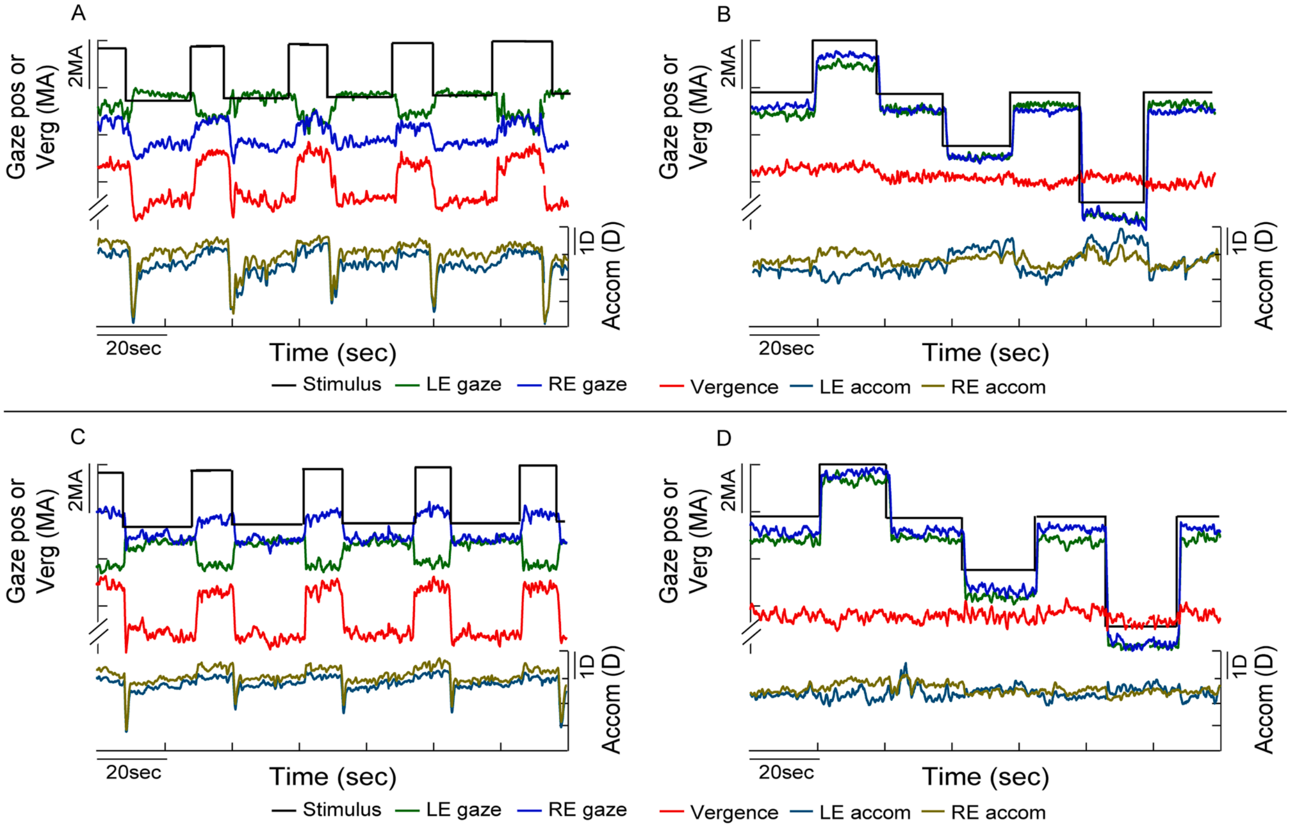

Fig. 12. Raw traces of gaze position, vergence and accommodation plotted as a function of time for two participants in the fifth supplementary experiment. Panels A and C show data in the free-fusion task while panels B and D show data in the version task. The ordinate axis scales are different for the gaze position/vergence traces and the accommodation traces. The raw traces have been vertically shifted for better representation of the individual data trends, without any alternation in their horizontal alignment.

subset of 5 participants (22 – 25 years of age; 4 female) who showed such transients generated versional shifts in gaze position between four targets location placed at a separation of 6.5° from each other at 150 cm viewing distance. The first target location corresponded to the left end of the target display monitor, the second to the center of the monitor, the third to the right end of the monitor and the fourth to a target placed beyond the right end of the monitor. The experiment started by the participants fixating on the second target location (i.e., center of the monitor) for a period of 10 sec, changing their gaze position to the first target location for another 10 sec and returning to the second target location for another 10 sec. This sequence was repeated for the third and the fourth target locations.

Fig. 12 plots raw traces of gaze position, vergence, and accommodation as a function of time for two representative participants in the free-fusion task of the main experiment (panels A and C) and in the versional gaze shift task of this supplementary experiment (panels B and D). The raw data from the free-fusion task showed the characteristic transient change in accommodation of both eyes following every stimulus presentation (Fig. 12A and C). These transients were larger in magnitude for the first participant (panel A) relative to the second (panel C). The gaze position of both eyes and vergence responses were robust and fully sustained for the duration of stimulus presentation in both participants (Fig. 12A and C). On the contrary, the raw traces obtained from these participants in the version task only showed robust changes in the gaze position of both eyes that were scaled with the magnitude of the version demand (Fig. 12B and D). The vergence response was expectedly flat throughout the experimental session (Fig. 12B and D). The accommodation traces did not show any evidence of transients like those seen in the free-fusion task and remained flat throughout the experimental session (Fig. 12B and D). Given that this supplementary experiment was conducted with only a small number of participants, no quantitative analyses have been carried out on this dataset.

5. Discussion

5.1. Summary of results

a. Less than 1/3rd of the study participants with normal binocular vision (18 out of 61) were successful in free-fusing to identify the 3D shape embedded in the stereograms (Fig. 5A).

b. Participants successful in this task fused the companion images using vergence eye movements while maintaining their accommodation close to the stimulus plane of (Fig. 5B, 6A and 7). The unsuccessful participants showed three patterns of vergence and accommodation that indicated their inability to manage conflicting demands on vergence and accommodation: i) successful fusion of the companion images using vergence eye movements but excessive accommodation (Fig. 5D and 6B); ii) inability to sustain the fusion of the companion images (Fig. 8); iii) unsuccessful fusion of the companion images with or without excessive accommodation (Fig. 5E and F and 6C and D).

c. The unsuccessful participants could successfully converge and accommodate to naturalistic changes in viewing distance (Fig. 9), had clinical binocular vision parameters similar to their successful counterparts, and, as in previous studies (Bharadwaj & Candy, 2009, Fincham & Walton, 1957, Ramsdale & Charman, 1988), successfully managed conflicting vergence-accommodation demands imposed using optical prisms and lenses (Table 3).

d. Eliminating the vergence-accommodation conflict using cycloplegia resulted in a significant improvement in the free-fusion task performance in the unsuccessful participants, relative to the main experiment (Fig. 10). The magnitude of vergence-accommodation conflict, however, did not appear to influence the free-fusion task performance (Fig. 11).

e. Task performance of a few participants improved with repeated attempts at the free-fusion task (Fig. 4A and 8, Table 2). Their initial free-fusion responses showed challenges in achieving stable vergence and accommodation while these responses progressively resembled the pattern of vergence and accommodation in successful participants with repeat trials (Fig. 8, Table 2).

5.2. Implication of results for the free-fusion task

The success rates with the free-fusion task shown in Fig. 5A match well the previous report of Cisarik et al. (2012). These indicate that, contrary to popular belief, free-fusion of companion images is a non-trivial task and outside the habitual capabilities of most human adults with normal sensorimotor binocular vision. This is a somewhat disappointing result, for the operational advantage of these stimuli in being able to demonstrate complex binocular vision phenomena without the need for anaglyphs or polarizers or a dichoptic set-up is significantly counteracted by the task difficulty. Users of such stimuli in scientific papers/presentations, popular science forums or in classroom settings must therefore be aware of this limitation and optimize the stimulus/task to maximize the audience's experience of binocularity. Potential ways of achieving this include a clear instruction set about the task, as acknowledged by Cisarik et al. (2012), adding fusion guides/locks around the stimuli to facilitate free-fusion (Fig. 1) and, hypothetically, by free-fusing the companion images through optical interventions that extend the depth of focus of the eye to minimize any retinal image blur arising from excessive accommodation [e.g., pinholes (Campbell & Weir, 1953, Marcos, Moreno & Navarro, 1999) or presbyopia correcting extended-depth of focus contact lenses (Molina-Martin, Pinero, Martinez-Plaza, Rodriguez-Vallejo & Fernandez, 2023)], in turn minimizing the vergence-accommodation conflict. pinholes or extended-depth of focus contact lenses that A variant of the last strategy involved eliminating the accommodative response through cycloplegia, and this indeed resulted in a significant improvement in task performance of those who failed the main experiment in this study (Fig. 10C). Along these lines, absolute presbyopes may be hypothesized to perform the free-fusion task better than non-presbyopes and incipient presbyopes. Absolute presbyopes should not experience any conflict between vergence and accommodation during the free-fusion task due to their inability to accommodate while pre-presbyopes or incipient presbyopes might experience increased levels of conflict due to their active accommodation and/or increased myodiopter needed to mold an aging lens (Atchison, 1995, Schor & Bharadwaj, 2005). These issues need further investigation in the future.

Unlike Cisarik et al (2012), who obtained self-reported measures of task performance in their participants, the ability of participants to resolve suprathreshold (250 arc sec) disparity-defined shapes was used as a defining measure of task success (Fig. 5A). Similar surrogate measures have been adopted previously while investigating the impact on vergence-accommodation conflicts on visual discomfort (Kim, Kane & Banks, 2014). While this measure of success was overall higher in those who could dissociate vergence and accommodation (Cluster 1 in Fig. 5A) relative to those who could not (Cluster 2 in Fig. 5A), the correlation between the success rate and the dissociation index was only moderate (Fig. 7). This result indicates that the vergence and accommodative behavior can only provide a gross estimate of the perceptual experience of depth by the participant in this task. For the first cluster, this indicated that a near-ideal dissociation index was not necessary or did not guarantee 100 % correct identification of the 3D shape in the stereograms. This could be so because the residual vergence and accommodative errors (i.e., fixation disparity and accommodative lag; not quantified in this study) may have negatively impacted the matching of corresponding features in the random-dot stereogram or may have created a blurred percept, both of which would negatively impact stereo performance (Badcock & Schor, 1985, McKee, Verghese & Farell, 2005, Schmidt, 1994, Westheimer & McKee, 1980). This result also broadly aligns with previous reports of deficient depth perception when vergence and accommodative demands are in conflict with each other (e.g., virtual reality displays; (Banks, Kim & Shibata, 2013, Maiello, Chessa, Solari &

Bex, 2014). Poor correlation between the two variables is somewhat expected in the second cluster, for all values of the dissociation index in this cluster represented a non-ideal behavior that precluded correct identification of 3D shape in the stereograms (Fig. 7).

That free-fusion may be learnt through practice is a silver lining for, in principle, participants may be "taught" this task ahead of time through appropriate instructions or training paradigms (Fig. 4A and 8, Table 2). "Teaching" the art of free-fusion also forms the starting point for many clinical vision therapy paradigms aimed at managing binocular vision dysfunctions with non-optimal vergence/accommodation relationships (Press, 2008). In these paradigms, patients are successfully taught to free-fuse and calibrate their vergence responses using specific instruction sets and feedback (e.g., by creating awareness of physiological diplopia that is associated with binocular vergence eye movements) (Press, 2008). Higher levels of binocularity are trained only after these patients demonstrate robust free-fusion capabilities. The participants with a natural learning curve in this study all had different magnitudes of vergence and accommodation at the start but tended towards the ideal response pattern by the end of the experimental session (Fig. 4A and 8, Table 2). This behavior may be akin to learning the free-fusion task and calibrating their near-triadic responses as in vision therapy, albeit with no specific instructions or feedback there. The present study used a standard instruction set for all participants and did not encourage/penalize them based on their responses. Future studies could address the impact of variations in the instruction set on the free-fusion task performance.

5.3. Vergence-accommodative responses during free-fusion

The vergence demand in the free-fusion task exceeded the upper retinal disparity limit for stereo (Schor & Wood, 1983, Tyler, 1975) and fusional vergence (Rashbass & Westheimer, 1961). This suggests that volitional processes may dominate the initiation of the free-fusion response, and reflex processes may function to complete free-fusion, which could be achieved in two possible ways. In the first scheme, free-fusion responses may be initiated through the direct volitional effort of the vergence system. This procedure is associated with a brief pulse of input to accommodation through the CA crosslink, resulting in the accommodative transients observed in this study (Fig. 6A) (Schor, 1986). Following this, the resultant accommodative error is corrected by blur-driven accommodation, without stimulating the negative-feedback of convergence accommodation, or through a temporary disconnection of the CA crosslink. In the second scheme, free-fusion responses may be initiated by a volitional pulse of accommodative effort even while there is no explicit stimulus to accommodation or instructions from the investigators to free-fuse by blurring the stimulus. This voluntary effort may manifest as the accommodative transients in Fig. 6A and may drive the vergence responses through the AC crosslink to correct the large initial disparity (McLin & Schor, 1988). Such a volitional accommodative effort would be a habituated response that is thought to supplement the limited motor range of disparity during gaze shifts to naturalistic changes in viewing distance (Fry, 1939, McLin & Schor, 1988, Morgan, 1968, Provine & Enoch, 1975). When the target is fused or nearly-fused, the resultant blurred image is corrected by replacing accommodative vergence with disparity vergence or voluntary vergence, allowing accommodation to relax (McLin & Schor, 1988, Rashbass & Westheimer, 1961). The latter vergence response would not influence accommodation if the CA cross link is disconnected. The current study does not distinguish between these two possibilities, even while the former scheme may be more intuitive than the latter considering the free-fusion task requirement. However, a detailed study of the dynamics of the two systems would clarify the issue (Semmlow & Heerema, 1979, Semmlow & Wetzel, 1979, Semmlow, Berard, Vercher, Putteman & Gauthier, 1994). Interestingly, similar accommodative transients at the beginning of large step changes in vergence have also been observed for prism-induced retinal disparity stimuli (Bharadwaj & Candy, 2009). Thus, the pattern of vergence-accommodation interaction observed in the present study may not be unique for free-fusion but may reflect a more generalized response to situations with vergence-accommodation conflicts. Given the conventional organization of crosslinks, wherein the outgoing link branches before the incoming link merges (Schor, 1986), all these scenarios will benefit by having only one direction of crosslink active at any given time under closed loop conditions. This will ensure that the two cross links do not interfere with one another and reduce their effective gains and accuracy while managing conflicting vergence and accommodative demands. All these aspects are currently being investigated in the laboratory through additional experiments and analyses of the existing dataset.

That optimal free-fusion required to obtain single and clear vision of the stereogram was observed in only a minority of participants (Fig. 5A), suggests that generation of the aforementioned volitional responses may not be within the routine capabilities of most participants (Cisarik et al., 2012). Many participants who had difficulty with the free-fusion showed unstable vergence and accommodative responses during attempted free-fusion, potentially reflecting a poor calibration of volitional vergence (Fig. 4B, middle inset and Fig. 8A). Perhaps the vergence motor command generated by the internal representation of the stimulus demand was too high and this combined with the vergence-accommodation crosslink operating in a negative-feedback framework in the final common pathway resulted in these instabilities (Read et al., 2022). This calibration could be potentially learnt through practice, as could be seen from the vergence and accommodative responses achieving a more optimal behavior in Fig. 8B – D. The time course and bandwidth of such a learning needs systematic exploration in the future. This also raises the question of whether the ones who performed the task well from the beginning were innately good at programming such volitional responses or have learnt it through prior experience, outside of the present study. The majority of participants who did well in the free-fusion task from the beginning (Cluster 1 in Fig. 5A) were all optometry students who have prior experience with free-fusion as part of their training program. Therefore, the possibility of learning this task through prior experience cannot be ruled out.

5.4. Free-fusion task performance and clinical binocular vision measurements

Both Cisarik et al. (2012) and the present study showed no significant differences in the clinical measures of vergence and accommodation between participants who were successful or unsuccessful at the free-fusion task (Table 3). This result is interesting for two reasons. First, they imply that no single measure of motor binocular vision that is routinely evaluated in an orthoptic examination can act as a marker for differentiating individuals who may or may not be successful at the free-fusion task. Perhaps the various orthoptic measures of binocular vision need to be collectively analyzed using comprehensive measures of the zone of clear and single binocular vision to gain insights into the free-fusion task performance (Grosvenor, 2007, Shibata, Kim, Hoffman & Banks, 2011). Second, the results imply that the clinical measures of conflict management may not fully represent the nature of the conflict experienced during the free-fusion task. For instance, the clinical measures of relative vergence and accommodation introduce disparity and defocus gradually (typically in steps of 2–3 D of disparity or 0.5 D of defocus) so that at any given point in time the conflict magnitude is small compared to the large step change in conflict magnitude experienced in the free-fusion task. The latter may be outside the bandwidth of visual system, thus resulting in unsuccessful free-fusion task performance. However, several previous studies have found visually-healthy adults to successfully manage the vergence-accommodation conflict to relatively large step changes in stimulus demands (Bharadwaj & Candy, 2009, Fincham & Walton, 1957, Ramsdale & Charman, 1988). These results reinforce the notion that the relatively poor performance in the free-fusion task may not arise from the motoric inability to manage vergence-accommodation conflicts but from the inability to generate well-calibration volitional vergence/accommodation response, as discussed above.

CRediT authorship contribution statement

Chandrika Ravisankar: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Christopher W. Tyler:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision. **Clifton M. Schor:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision. **Shrikant R. Bharadwaj:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors thank all the volunteers that participated in this study. The authors also thank Dr Jameel Rizwana Hussaindeen, Ms. Bidisha Bhattacharya, and Mr. Sabyasachi Goswami for help with data collection in the first and second supplementary experiment and Ms. Preetirupa Devi for the stereogram shown in Fig. 1A. Thanks also to Profs. Simon Grant and Martin S. Banks for insightful feedback during the study. The study was financially support through the Hyderabad Eye Research Foundation, L V Prasad Eye Institute and by a grant from the Cognitive Science Research Initiative, Department of Science and Technology, Govt. of India to Dr Shrikant R. Bharadwaj (Grant #DST/CSRI/2021/265). Dr Shrikant R. Bharadwaj was also supported by the Fulbright-Nehru Academic and Professional Excellence fellowship, offered by the United States-India Educational Foundation (USIEF), during the manuscript preparation phase of this study.

References

Atchison, D. A. (1995). Accommodation and presbyopia. *Ophthalmic & Physiological Optics, 15*(4), 255–272.

Badcock, D. R., & Schor, C. M. (1985). Depth-increment detection function for individual spatial channels. *Journal of the Optical Society of America. A, 2*(7), 1211–1216.

Banks, M. S., Kim, J., & Shibata, T. (2013). Insight into Vergence-Accommodation Mismatch. *Proc SPIE Int Soc. Optical Engineering, 8735*.

Benassi, M., Garofalo, S., Ambrosini, F., Sant'Angelo, R. P., Raggini, R., De Paoli, G., … Piraccini, G. (2020). Using Two-Step Cluster Analysis and Latent Class Cluster Analysis to Classify the Cognitive Heterogeneity of Cross-Diagnostic Psychiatric Inpatients. *Frontiers in Psychology, 11*, 1085.

Bharadwaj, S. R., & Candy, T. R. (2008). Cues for the control of ocular accommodation and vergence during postnatal human development. *J Vis, 8*(16), 14.1–16. https://pubmed.ncbi.nlm.nih.gov/19146280/.

Bharadwaj, S. R., & Candy, T. R. (2009). Accommodative and vergence responses to conflicting blur and disparity stimuli during development. *Journal of Vision, 9 (11), 4*, 1–18.

Bharadwaj, S. R., Roy, S., & Satgunam, P. (2020). Spasm of Near Reflex: Objective Assessment of the Near-Triad. *Investigative Ophthalmology & Visual Science, 61*(8), 18.

Bharadwaj, S. R., Sravani, N. G., Little, J. A., Narasaiah, A., Wong, V., Woodburn, R., & Candy, T. R. (2013). Empirical variability in the calibration of slope-based eccentric photorefraction. *Journal of the Optical Society of America. A, Optics, Image Science, and Vision, 30*(5), 923–931.

Campbell, F. W., & Weir, J. B. (1953). The depth of focus of the human eye. *The Journal of Physiology, 120*(4), 59P–60P.

Candy, T. R. (2019). The Importance of the Interaction Between Ocular Motor Function and Vision During Human Infancy. *Annu Rev Vis Sci, 5*, 201–221.

Cisarik, P., Davis, N., Kindy, E., & Butterfield, B. (2012). A comparison of self-reported and measured autostereogram skills with clinical indicators of vergence and accommodative function. *Perception, 41*(6), 747–754.

Eadie, A. S., & Carlin, P. J. (1995). Evolution of control system models of ocular accommodation, vergence and their interaction. *Medical & Biological Engineering & Computing, 33*(4), 517–524.

Esteve-Taboada, J. J., Del Aguila-Carrasco, A. J., Bernal-Molina, P., Ferrer-Blasco, T., Lopez-Gil, N., & Montes-Mico, R. (2016). Effect of Phenylephrine on the Accommodative System. *Journal of Ophthalmology, 2016*, 7968918.

Fincham, E. F., & Walton, J. (1957). The reciprocal actions of accommodation and convergence. *The Journal of Physiology, 137*(3), 488–508.

Fry, G. A. (1937). An experimental analysis of the accommodation-convergence relation. *American Journal of Optometry, 14*(11), 402–414.

Fry, G. A. (1939). Further experiments on the accommodative convergence relationship. *American Journal of Optometry, 16*, 325–334.

Gonzalez-Perez, M., Susi, R., Antona, B., Barrio, A., & Gonzalez, E. (2014). The Computer-Vision Symptom Scale (CVSS17): Development and initial validation. *Investigative Ophthalmology & Visual Science, 55*(7), 4504–4511.

Grosvenor, T. P. (2007). Management of anomalies of refraction and binocular vision. In T. P. Grosvenor (Ed.), *Primary Care Optometry* (pp. 251–273). St. Louis: Butterworth Heinemann Elsevier.

Kaufman, L., & Rousseeuw, P.J. (2009). Finding groups in data: an introduction to cluster analysis. (John Wiley & Sons.

Kim, J., Kane, D., & Banks, M. S. (2014). The rate of change of vergence-accommodation conflict affects visual discomfort. *Vision Research, 105*, 159–165.

Maiello, G., Chessa, M., Solari, F., & Bex, P. J. (2014). Simulated disparity and peripheral blur interact during binocular fusion. *Journal of Vision, 14*(8), 13.

Marcos, S., Moreno, E., & Navarro, R. (1999). The depth-of-field of the human eye from objective and subjective measurements. *Vision Research, 39*(12), 2039–2049.

McKee, S. P., Verghese, P., & Farell, B. (2005). Stereo sensitivity depends on stereo matching. *Journal of Vision, 5*(10), 783–792.

McLin, L. N., Jr., & Schor, C. M. (1988). Voluntary effort as a stimulus to accommodation and vergence. *Investigative Ophthalmology & Visual Science, 29*(11), 1739–1746.

Molina-Martin, A., Pinero, D. P., Martinez-Plaza, E., Rodriguez-Vallejo, M., & Fernandez, J. (2023). Efficacy of Presbyopia-Correcting Contact Lenses: A Systematic Review. *Eye & Contact Lens, 49*(8), 319–328.

Morgan, M. W. (1968). Accommodation and vergence. *American Journal of Optometry and Archives of American Academy of Optometry, 45*(7), 417–454.

Ntodie, M., Bharadwaj, S. R., Balaji, S., Saunders, K. J., & Little, J. A. (2019). Comparison of Three Gaze-position Calibration Techniques in First Purkinje Image-based Eye Trackers. *Optometry and Vision Science, 96*(8), 587–598.

Pemberton, J. W., & Brown, D. J. (1962). Accommodative convergence. A study of the effect on the AC/A ratio of partial cycloplegia induced by systemic medication (orphenadrine citrate). *Archives of Ophthalmology, 68*, 348–352.

Press, L.J. (2008). Applied Concepts in Vision Therapy. 1 (p. 384): Optometric Extension Program Foundation.

Provine, R. R., & Enoch, J. M. (1975). On voluntary ocular accommodation. *Perception & Psychophysics, 17*(2), 209–212.

Ramsdale, C., & Charman, W. N. (1988). Accommodation and convergence: Effects of lenses and prisms in 'closed-loop' conditions. *Ophthalmic & Physiological Optics, 8*(1), 43–52.

Rashbass, C., & Westheimer, G. (1961). Disjunctive eye movements. *The Journal of Physiology, 159*(2), 339–360.

Read, J. C. A., Kaspiris-Rousellis, C., Wood, T. S., Wu, B., Vlaskamp, B. N. S., & Schor, C. M. (2022). Seeing the future: Predictive control in neural models of ocular accommodation. *Journal of Vision, 22*(9), 4.

Roorda, A., Campbell, M. C., & Bobier, W. R. (1995). Geometrical theory to predict eccentric photorefraction intensity profiles in the human eye. *Journal of the Optical Society of America. A, Optics, Image Science, and Vision, 12*(8), 1647–1656.

Scheiman, M., & Wick, B. (2013). *Clinical Management of Binocular Vision: Heterophoric, Accommodative, and Eye Movement Disorders, 1*, (p. 705)..

Schmidt, P. P. (1994). Sensitivity of random dot stereoacuity and Snellen acuity to optical blur. *Optometry and Vision Science, 71*(7), 466–471.

Schor, C. M. (1986). The Glenn A. Fry award lecture: Adaptive regulation of accommodative vergence and vergence accommodation. *American Journal of Optometry and Physiological Optics, 63*(8), 587–609.

Schor, C. M. (2009). Neuromuscular plasticity and rehabilitation of the ocular near response. *Optometry and Vision Science, 86*(7), E788–E802.

Schor, C. M., & Bharadwaj, S. R. (2005). A pulse-step model of accommodation dynamics in the aging eye. *Vision Research, 45*(10), 1237–1254.

Schor, C. M., & Wood, I. (1983). Disparity range for local stereopsis as a function of luminance spatial frequency. *Vision Research, 23*(12), 1649–1654.

Semmlow, J., & Heerema, D. (1979). The synkinetic interaction of convergence accommodation and accommodative convergence. *Vision Research, 19*(11), 1237–1242.

Semmlow, J., & Wetzel, P. (1979). Dynamic contributions of the components of binocular vergence. *Journal of the Optical Society of America, 69*(5), 639–645.

Semmlow, J. L., Berard, P. V., Vercher, J. L., Putteman, A., & Gauthier, G. M. (1994). The interactive processes of accommodation and vergence. *Bulletin de la Société Belge d'Ophtalmologie, 253*, 135–146.

Shibata, T., Kim, J., Hoffman, D. M., & Banks, M. S. (2011). The zone of comfort: Predicting visual discomfort with stereo displays. *Journal of Vision, 11*(8), 11.

Sravani, N. G., Nilagiri, V. K., & Bharadwaj, S. R. (2015). Photorefraction estimates of refractive power varies with the ethnic origin of human eyes. *Scientific Reports, 5*, 7976.

Tyler, C. W. (1975). Spatial organization of binocular disparity sensitivity. *Vision Research, 15*(5), 583–590.

Tyler, C. W., & Clarke, M. B. (1990). The autostereogram. *Stereoscopic Displays and Applications, SPIE, 1256*, 182–197.

van den Berge, M. J. C., Free, R. H., Arnold, R., de Kleine, E., Hofman, R., van Dijk, J. M. C., & van Dijk, P. (2017). Cluster Analysis to Identify Possible Subgroups in Tinnitus Patients. *Frontiers in Neurology, 8*, 115.

Van Hoven, R. C. (1959). Partial cycloplegia and the accommodation convergence relationship. *American Journal of Optometry and Archives of American Academy of Optometry, 36*(1), 22–39.

Venkataramanan, K., Gawde, S., Hathibelagal, A. R., & Bharadwaj, S. R. (2021). Binocular fusion enhances the efficiency of spot-the-difference gameplay. *PLoS One1, 16*(7), e0254715.

Westheimer, G., & McKee, S. M. (1980). Stereoscopic acuity with defocussed and spatially filtered retinal images. *Journal of the Optical Society of America. A, Optics, Image Science, and Vision, 70*(7), 772–778.

Wu, Y., Thibos, L. N., & Candy, T. R. (2018). Two-dimensional simulation of eccentric photorefraction images for ametropes: Factors influencing the measurement. *Ophthalmic & Physiological Optics, 38*(4), 432–446.

Yazdani, N., Sadeghi, R., Momeni-Moghaddam, H., Zarifmahmoudi, L., & Ehsaei, A. (2018). Comparison of cyclopentolate versus tropicamide cycloplegia: A systematic review and meta-analysis. *J Optom, 11*(3), 135–143.