NeuroReport
Numero: Volume 28(3), 8 February 2017, p 123–127

Tipo de publicacion: [INTEGRATIVE SYSTEMS]
DOI: 10.1097/WNR.0000000000000734
ISSN: 0959-4965
Registro: 00001756-201703010-00002
Palabras clave: attention, convergence, eye tracking, eye vergence, gaze, human, pupil, short-term memory, visual short term memory

[INTEGRATIVE SYSTEMS]

Eye vergence responses during a visual memory task

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Received September 5, 2016
Accepted December 21, 2016

Abstract

In a previous report it was shown that covertly attending visual stimuli produce small convergence of the eyes, and that visual stimuli can give rise to different modulations of the angle of eye vergence, depending on their power to capture attention. Working memory is highly dependent on attention. Therefore, in this study we assessed vergence responses in a memory task. Participants scanned a set of 8 or 12 images for 10 s, and thereafter were presented with a series of single images. One half were repeat images – that is, they belonged to the initial set – and the other half were novel images. Participants were asked to indicate whether or not the images were included in the initial image set. We observed that eyes converge during scanning the set of images and during the presentation of the single images. The convergence was stronger for remembered images compared with the vergence for nonremembered images. Modulation in pupil size did not correspond to behavioural responses. The correspondence between vergence and coding/retrieval processes of memory strengthen the idea of a role for vergence in attention processing of visual information.

In the previous decennia it has become clear that fixation eye movements have important roles in cognitive processing of sensory information. Much attention has been given to the understanding of the functions of microsaccades or fixation saccades in conscious vision 1, attention 2, visual acuity 3, binocular disparity 4 and adjustment of gaze position 5. Eye vergence is less studied. Vergence refers to the simultaneous movement of both eyes in opposite directions to obtain a single binocular vision. In recent reports, we showed that eye vergence may play a role in orienting visual attention 6–8. This idea is in line with studies showing a significant increase in fixation disparity for dyslexic children solely when reading 9, which is suggested to be a result of the allocation of inadequate attentional resources 9,10.

Visual attention is a central determinant of further cognitive processing and interacts closely with working memory. Attention facilitates target processing during both perceptual and postperceptual stages of processing 11, and many phenomena related to visual attention are similar to working memory processes 12. In this study, we therefore tested whether eye vergence responses also occur when storing/recalling visual information into/from working memory. We recorded the gaze position of participants performing a short-term visual memory task. The results show that vergence responses for remembered images are stronger than those for forgotten images. Therefore, our results confirm the idea that eye vergence modulation correlates with increases in visual attention.

Patients and methods

Participants

Our study was approved by the Ethics Committee of the Faculty of Psychology of the University of Barcelona in accordance with the ethical standards laid down in the 1954 Declaration of Helsinki. Ten participants took part in the 8-image experiment and 10 different participants volunteered for the 12-image experiment (nine women and one man with a mean age of 21±3.16 years for the 8-image experiment, and five women and five men with a mean age of 23.1±5.64 years for the 12-image experiment).

Memory task

Participants underwent 20 trials (Fig. 1). All participants underwent the following sequence. A fixation cross is presented (during 500 ms) on a grey background. Next, the fixation cross is removed and a set of 8 or 12 peripheral images of daily objects (size of 80×80 pixels) is displayed for 10 s. In this interval the participants scan the scene, mentally recording what they are watching. Thereafter, the fixation cross is shown again (500 ms) on a grey background, and afterwards a target image appears. Participants have to respond by manually pressing a button indicating whether or not – according to their own memories – the present target was in the set. After the response, the fixation cross reappears for 500 ms, and a new target is shown. The cycle goes on until 8 or 12 loops are completed (these parts will be called ‘subtrials’). In every sequence, one half of the shown targets are repeat (‘R’) images and the other half are new (’N’). As responses can be correct or incorrect (‘C’|‘I’), the possible combinations of target type and actual response are as follows: ‘RC’ repeat target and correct response, ‘RI’ repeat target and incorrect response, ‘NC’ new target and correct response, and ‘NI’ new target and incorrect response.

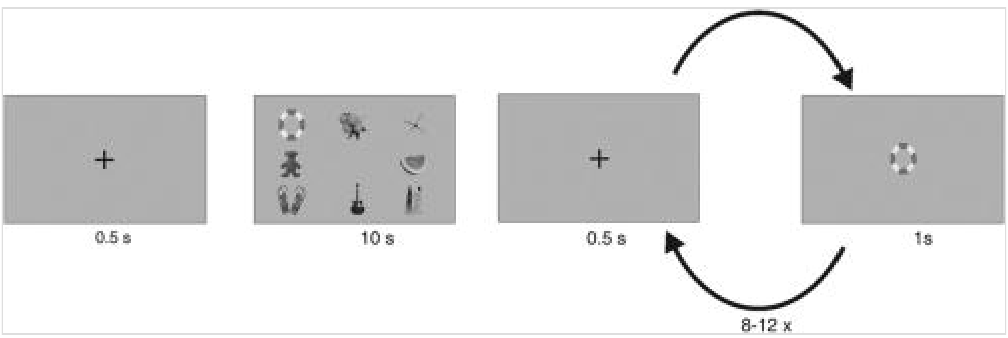

Fig. 1. Schematic illustration of the memory task. A fixation point appears for 500 ms. Next, a set of 8 or 12 peripheral images of objects is displayed. Thereafter, the fixation point is shown again, and afterwards a single target image appears. Participants have to respond indicating whether or not the present target was in the set. After the response, the fixation point reappears and a new target is shown. The cycle goes on until 8 or 12 loops are completed.

Eye recording

We used EventIDE software (Okazolab Ltd, London, UK) for presenting the stimuli. Participants sat in a dimly lit room, in front of the PC monitor at a distance of 50 cm. The display resolution was 1024×768 pixels. The participants' position of gaze was monitored using a binocular EyeLink II eye-tracking system at 500 Hz (SR Research System; SR Research Ltd, Mississauga, Ontario, Canada). To compensate for any head movements, we used a chinrest. The eye tracking equipment was calibrated for each participant at the beginning of each set (standard nine-point calibration; binocular).

Data analysis

The vergence angle was calculated by translating the gaze recordings (*X* and *Y* coordinates from both eyes), produced by the Eye Link II software, into angular measures, after finding the three-dimensional components of both eye-gaze vectors and the distance from the screen to the observer 5. The vergence point is defined as the 'near-intersection' point of the two gaze lines. For each participant, the vergence evolution data of the response time were 'normalized' by removing the offset values at the start of the selected time window and dividing by maximum absolute values of the resulting magnitudes. No normalization was applied to the 'scan time' part. Subtrials containing saccadic eye movements were excluded from the analysis. The velocity threshold value for detecting saccadic eye movements was 200°/s. Previous analysis demonstrated that microsaccades do not cause the vergence responses associated to attention 6. We applied *t*-test with the option of unknown and possibly unequal variances (Behrens–Fisher problem) for a significance level of 0.05.

Results

Performance

In the 'R' condition the participants scored on average 83 and 71% correct on the 8-image and 12-image tasks, respectively. In the 'N' condition, detection performance appeared to be slightly better (92 and 93% for the 8-image and 12-image task, respectively). Reaction times were 820/845 ms for repeated/new targets in the 8-image task, and 801/859 ms for repeated/new targets in the 12-image task.

Vergence responses during 'response time'

Vergence responses start to occur about 200 ms after the presentation of the target image, reaching a maximum around 450 ms (Fig. 2). In the 'R' condition the vergence responses appear to be stronger for correct than for incorrect behavioural responses, whereas in the 'N' condition the opposite was observed. For some participants these differences in vergence responses were statistically significant, but when the averaged angle of eye vergence across all participants was calculated significance disappeared. Therefore, to assess the relation between vergence and memory, we selected time windows of 380 ms in the 8-image task and 430 ms in the 12-image task centred on the time of the behavioural response of the participant. Averaged eye vergence responses (convergence) were seen starting before the behavioural response, reaching a maximum around response onset (Fig. 3a and b). Correct responses were associated with a higher modulation of angle of eye vergence (stronger convergence) in the 'R' condition, both for the 8-image (mean±SD: correct, 0.082±0.36; incorrect, -0.041±0.37; *t*-test2, $P=0.007$) and 12-image (mean±SD: correct, 0.13±0.35; incorrect, -0.061±0.36; *t*-test2, $P<0.00001$) tasks. In the 8-image (mean±SD: correct, 0.015±0.37; incorrect, 0.023±0.40; *t*-test2, $P=0.91$) and 12-image (mean±SD: correct, 0.024±0.34; incorrect, -0.024±0.36; *t*-test2, $P=0.35$) tasks of the 'N' condition, no significant differences were observed.

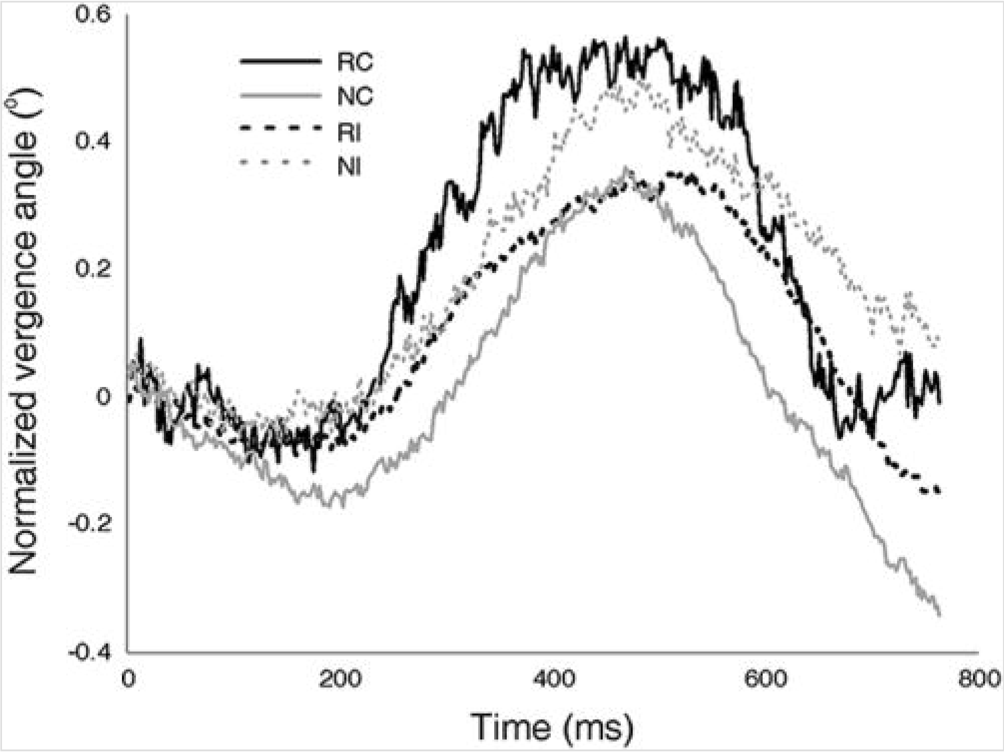

Fig. 2. Averaged time-evolutions of the 'normalized' vergence modulations after target image onset, for the 8-image experiment and for the 12-image experiment. The four curves are drawn as follows: solid black for repeated correct ('RC'), dotted black for repeated incorrect ('RI'), solid grey for new correct ('NC'), dotted grey for new incorrect ('NI'). Time is from image onset.

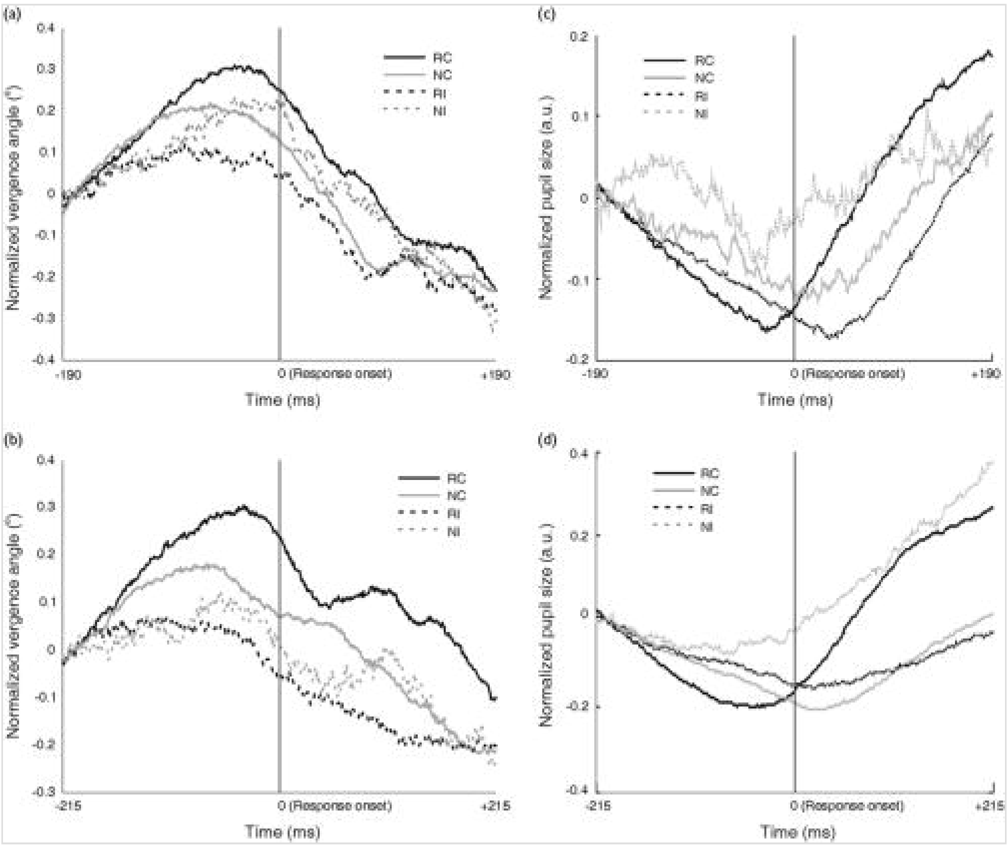

Fig. 3. Averaged time-evolutions of the 'normalized' vergence and pupil modulations around the response time. Vergence responses for the 8-image experiment (a) and for the 12-image experiment (b), and pupil sizes for the 8-image experiment (c) and for the 12-image experiment (d). The four curves are drawn as follows: solid black for repeated correct ('RC'), dotted black for repeated incorrect ('RI'), solid grey for new correct ('NC'), dotted grey for new incorrect ('NI'). Time is from response onset.

Vergence reponses during 'scan time'

We also assessed vergence differences during the 'scan time' – that is, while the image set is shown and the participant is visually scanning the scene trying to store its contents into her/his memory. We therefore calculated the vergence responses to fixated images that were repeated during 'response time'.

The vergence values show that the mean for 'RC' was, in both experiments, higher than the mean for 'RI'. Correct responses were associated to higher vergence responses during scan time both for the 8-image (mean±SD: correct, 6.37±0.24; incorrect, 6.29±0.26; *t*-test2, P=0.0094) and 12-image (mean±SD: correct, 6.68±0.60; incorrect, 6.55±0.46; *t*-test2, P<0.0024) tasks.

Duration gaze fixation

We also assessed fixation duration during the 'response time'. Fixation duration, however, was not predictive for the behavioural outcome as the mean fixation duration to an image for 'RC' was not significantly different from that for 'RI', both in the 8-image (mean±SD; 'RC': 282±196 ms; 'RI': 184±158 ms; P=0.92) and in the 12-image task (mean±SD; 'RC': 254±144 ms; 'RI': 268±202 ms; P=0.39).

Pupil size

Pupil size relates to attention, memory and changes as a function of cognitive load. We therefore analysed pupil size from the left eye using the same data set that was used for the vergence calculation (Fig. 3c and d). Pupil constricted before behavioural response onset and dilated afterwards. However, clear differences in pupil size between conditions 'RC' and 'RI' was not observed, neither in the 8-image task (-0.00805±0.44 vs. 0.04646±0.44, P=0.47) nor in the 12-image task (-0.02223±0.43 vs. -0.08756±0.44, P=0.07). As regards 'N' condition, no significant differences were found in the 8-image task between correct and incorrect subtrials (-0.0736±0.44 vs. 0.00289±0.43, P=0.33), whereas this difference was significant in the 12-image task (-0.1172±0.44 vs. 0.03899±0.39, P=0.008).

Discussion

Here, we show eye vergence responses in a memory task. Vergence responses start 200 ms and peak around 450 ms after stimulus onset, which is rather late in terms of visual processing. The timing may indicate that vergence occurs during more perceptual or attentive stimulus processing, which is in line with the observation that stronger vergence responses were observed for images that are correctly remembered compared with the responses for forgotten images. This predictive power appears to be applicable not only to the task of recalling an image but also to the process of storing visual memory. These findings support the idea of a link between eye vergence and attention/perception 6–8, and emphasize the importance of fixation eye movements in cognitive processing of sensory information 1–5. In the current study, vergence responses peak just before the manual response. This may indicate that vergence relates to the behavioural action. However, a manual response was always required, which suggests that the differential vergence responses to remembered and nonremembered images cannot be attributed to the manual response. Moreover, predictive vergence responses were seen during the scanning period when images were stored in memory. The vergence responses mimic figure-ground modulation, which is also stronger for perceived and memorized stimuli and peaks just before behavioural response onset (see Wierda *et al.* 13 and ref. herein).

Pupil is modulated by a variety of cognitive processes, including attention 13 and memory 14. We also observed constriction of the pupils; however, remembered images did not elicit a stronger constriction compared with forgotten images. Except for novel images in the 12-image task, we observed significant differences in pupil size between correct and incorrect responses. This is in line with a role of cognitive load and novelty in pupil control 14. The lack of a clear correlation between pupil size and behaviour indicates that the change in pupil size is not an explanatory factor for the modulation of the angle of vergence, which is in agreement with our previous results 6.

Precise binocular coordination does not always happen and disparity is frequently observed during gaze fixation 15. Uncrossed fixation disparity when the right eye fixates further to the right compared with the left eye is more prevalent 16, and thus the eyes may converge after the presenting of an image to align both eyes. It may be speculated that in this way the visual system obtains a better retinal image, which aids the subsequent cognitive processing of the stimulus. Alternatively, it was proposed 6 that vergence responses may have a role in the change in cortical state necessary for processing perceptual information 17.

Neurons in the midbrain reticular formation of the brainstem control eye vergence 18–20. The reticular formation forms a part of a neural circuit including the frontal and parietal regions of the cerebral cortex 21–23 and cerebellum 24,25 that control eye vergence movements. All these areas are also known for their involvement in visual attention. Thus, at a neural level there seems to be a close link between vergence and attention.

In conclusion, we observed vergence responses during a memory task that predict behavioural responses, which supports the idea of a role for eye vergence in visual attention.

Acknowledgements
This research was supported by grants to HS from the Catalan Government (SGR2009-308) and from Spanish Ministry of Economy (PSI201457454-P).

Conflicts of interest

Hans Super is shareholder of Braingaze that exploits the patented findings described in the paper.

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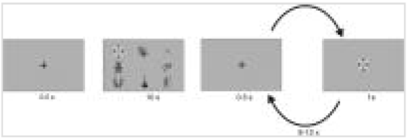

Fig. 1

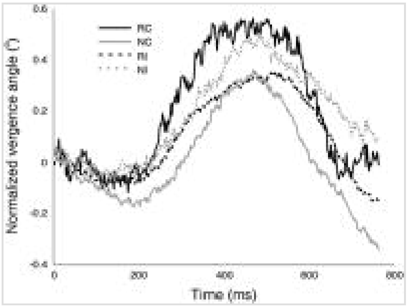

Fig. 2

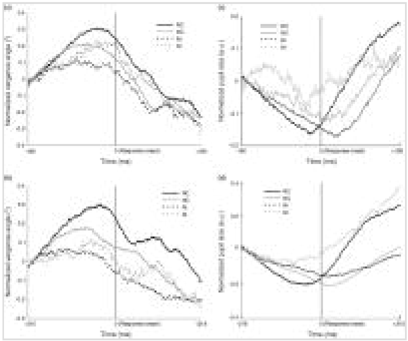

Fig. 3

Volver al principio

