Post-therapy Functional Magnetic Resonance Imaging in Adults with Symptomatic Convergence Insufficiency

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SIGNIFICANCE: Prior studies have demonstrated the effectiveness of vergence-accommodative therapy in the treatment of convergence insufficiency (CI). These results show the changes in brain activation following therapy through the use of functional magnetic resonance imaging (fMRI).

PURPOSE: The purpose of this study was to investigate changes in brain activation following office-based vergence-accommodative therapy versus placebo therapy for CI using the blood oxygenation level-dependent signal from fMRI.

METHODS: Adults (n = 7, aged 18 to 30 years) with symptomatic CI were randomized to 12 weeks of vergence-accommodative therapy (n = 4) or placebo therapy (n = 3). Vergence eye movements were performed during baseline and outcome fMRI scans.

RESULTS: Before therapy, activation (z score ≥ 2.3) was observed in the occipital lobe and areas of the brain devoted to attention, with the largest areas of activation found in the occipital lobe. After vergence-accommodative therapy, activation in the occipital lobe decreased in spatial extent but increased in the level of activation in the posterior, inferior portion of the occipital lobe. A new area of activation appeared in the regions of the lingual gyrus, which was not seen after placebo therapy. A significant decrease in activation was also observed in areas of the brain devoted to attention after vergence-accommodative therapy and to a lesser extent after placebo therapy.

CONCLUSIONS: Observed activation pre-therapy consistent with top-down processing suggests that convergence requires conscious effort in symptomatic CI. Decreased activation in these areas after vergence-accommodative therapy was associated with improvements in clinical signs such as fusional vergence after vergence-accommodative therapy. The increase in blood oxygen level-dependent response in the occipital areas following vergence-accommodative therapy suggests that disparity processing for both depth and vergence may be enhanced following vergence-accommodative therapy.

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imaging contrast is a well-established technique called blood oxygen level–dependent signal.26

Prior literature has not investigated changes in brain activation in subjects with symptomatic convergence insufficiency in response to a stimulus with a wide range in magnitude of vergence demands after a course of office-based vergence-accommodative versus placebo therapy performed according to the Convergence Insufficiency Treatment Trial protocol.2 The purpose of this pilot study was to investigate the change in functional magnetic resonance imaging blood oxygen level–dependent response to a range of convergence demands (presented using a random-dot stereogram stimulus) in regions of the brain associated with vergence eye movements, after office-based vergence-accommodative or placebo therapy.

**METHODS**

**Recruitment**

Subjects were recruited through the clinics at The Ohio State University College of Optometry and Student Health Center, as well as through an advertisement on The Ohio State University Wexner Medical Center research Web site. All subjects signed written informed consent documents that were approved by the institutional review board at The Ohio State University; study procedures were in accordance with the Declaration of Helsinki.

**Eligibility/Baseline Entrance Testing**

Eligibility testing included the Convergence Insufficiency Symptom Survey, cover testing at distance and near, and assessment of fusional vergence ranges (negative and positive), near point of convergence, monocular accommodation of accommodation (right eye only), monocular accommodative facility (right eye only), and vergence facility. Testing was carried out using the Convergence Insufficiency Treatment Trial studies' protocols, with the subject wearing any needed refractive correction.2–27 The Convergence Insufficiency Treatment Trial criteria were used for symptomatic convergence insufficiency.5,30 Inclusion and exclusion criteria are listed in Table 1. Eligible subjects were given a brief demonstration of the visual stimulus to be completed while in the scanner.

All functional magnetic resonance imaging scans were completed at the Center for Cognitive and Behavioral Brain Imaging at The Ohio State University by a trained technician. A Siemens 3-T magnetic resonance imaging scanner was utilized, with a 12-channel head coil. Functional images were collected using the following imaging parameters: repetition time of 2500 milliseconds, echo time of 28 milliseconds, matrix size of 72 × 72, flip angle of 76°, and voxel resolution of 3 mm³, isotropic. Anatomical images were collected using the following parameters: repetition time of 1950 milliseconds, echo time of 4.44 milliseconds, matrix size of 224 × 256, flip angle of 12°, and a voxel resolution of 1.0 mm³, isotropic. Subjects viewed the computer-generated stimulus on a monitor visible to them through a mirror mounted on the head coil.

A 10-second localizer scan was run, and adjustments were made accordingly to center the cerebral cortex within the scanner's imaging region. Following the localizer scan, a 7-minute anatomical scan was completed. The stimulus paradigms were then completed. All data from the scans were sent to Wright State University for analysis by examiners masked to each subject's treatment group.

Subjects wore red and blue filter glasses and viewed a red and blue random-dot stereogram target on a monitor 59 cm away through a mirror on the head coil (a constant 70-cm, reflected image). The target subtended 7.3° vertically by 6.7° horizontally and contained a central disparate square (3.3°) with approximately 480 seconds of crossed disparity relative to the background. The elements composing the random-dot stereogram subtended 2.0 minutes of arc square. The subject was instructed to look at the central square and to try to keep it single for each presentation such that a smaller square could be seen floating in front of the single, larger square. Easy and hard step convergence stimulus paradigms were presented, each of which started with 20 seconds of rest (zero

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**TABLE 1. Inclusion and exclusion criteria**

<table>
<thead>
<tr>
<th>Inclusion criteria</th>
<th>Exclusion criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>18–30 y old</td>
<td>Amblyopia, constant strabismus, vertical phoria &gt;1Δ, refractive surgery, or manifest or latent nystagmus</td>
</tr>
<tr>
<td>Best-corrected visual acuity of 20/25 or better in each eye at distance and near</td>
<td>Refractive error (not corrected by contact lenses) beyond the range of the fMRI safe trial lens set</td>
</tr>
<tr>
<td>Exophoria at near ≥4Δ greater than distance</td>
<td>Systemic diseases known to affect accommodation, vergence, or ocular motility</td>
</tr>
<tr>
<td>Receded near point of convergence of ≥6-cm break</td>
<td>Current use of any medication known to affect accommodation, vergence, or ocular motility</td>
</tr>
<tr>
<td>Reduced positive fusional vergence (less than twice the near phoria OR &lt;15 Δ; blur, or break if no reported blur)</td>
<td>History of brain injury, neurological disease, or any condition that may be in conflict with obtaining normal fMRI scans</td>
</tr>
<tr>
<td>CISS ≥21</td>
<td>Pregnancy, presence of a pacemaker, or any metallic implant that might be incompatible with fMRI safety</td>
</tr>
<tr>
<td>Accommodative amplitude ≥5 D</td>
<td>Developmental or learning disability that may interfere with treatment</td>
</tr>
<tr>
<td>Random-dot stereopsis of at least 500 seconds of arc</td>
<td>Left-handed dominance</td>
</tr>
</tbody>
</table>
| Cycloplegic refraction within the past 3 mo | \[Δ = \text{prism diopter}; \text{CISS} = \text{Convergence Insufficiency Symptom Survey}; D = \text{diopter}; \text{fMRI} = \text{functional magnetic resonance imaging}\] Modified with permission from Oechslin et al.29

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demand, i.e., the images seen by the right and left eye were overlaid), followed by 30 seconds of increasing convergence demands. Varied magnitudes of convergence demands were presented by separating the red and blue anaglyphic targets. The easy convergence step paradigm started with a $4\Delta$ demand and increased by $2\Delta$ every 6 seconds, ending with a demand of $12\Delta$. The hard step vergence paradigm started at $5\Delta$ and increased by $5\Delta$ every 6 seconds, ending with a demand of $25\Delta$. Each cycle of rest and increasing convergence demand was continued for a total of 250 seconds. Fig. 1 shows the timing pattern for the paradigms used. Subjects completed the easy vergence paradigm followed by the hard vergence paradigm.

After completion of the baseline functional magnetic resonance imaging scan, each subject was randomized to 12 weeks of weekly office-based vergence-accommodative therapy or office-based placebo therapy. Each therapy visit consisted of 55 to 60 minutes of procedures, questions, and homework instructions. Subjects were asked to perform home reinforcement procedures 15 minutes a day, 5 days a week. Office-based vergence-accommodative therapy subjects completed therapy designed to stress vergence and accommodative abilities, and placebo subjects completed placebo therapy that did not involve vergence or accommodation beyond that involved in normal near tasks. Office-based and home reinforcement therapy procedures followed the protocol set forth by the Convergence Insufficiency Treatment Trial study. Clinical signs and symptoms of convergence insufficiency were evaluated monthly by a masked examiner. After 12 weeks of therapy, an examiner masked to the subject's assigned treatment group performed the primary outcome vision testing and functional magnetic resonance imaging scans. All vision testing and functional magnetic resonance imaging scanning procedures and paradigms were the same as those completed at baseline. Subjects were classified as either “successful,” “improved,” or “nonresponder,” as defined by the Convergence Insufficiency Treatment Trial study. Specifically, subjects were considered “successful” if the subject obtained an asymptomatic Convergence Insufficiency Symptom Survey score (≤21), normal near point of convergence (<6 cm), and normal positive fusional vergence (>15 Δ base-out and at least twice the near phoria). Subjects were classified as “improved” if the subject obtained an asymptomatic or improved Convergence Insufficiency Symptom Survey score (≤21 points or ≥10-point decrease, respectively) and achieved normal or improved near point of convergence or positive fusional vergence (near point of convergence <6 cm or improved by ≥4 cm; positive fusional vergence >15 Δ base-out and at least twice the near phoria or improved by ≥10 Δ base-out). Subjects who did not meet these criteria were classified as “nonresponders.” Anyone not classified as “successful” was offered the active vergence-accommodative treatment regimen at no cost after completion of the second functional magnetic resonance imaging scan.

Data Analysis

Functional magnetic resonance imaging data analysis and examination involved multilevel processing using FMRI Expert Analysis Tool in FMRIB Software Library (FSL version 5.0.4). Significant areas of activation during the vergence-active condition (increasing steps of convergence demand) as compared with the vergence-inactive condition (zero vergence demand) were identified. Activation before and after therapy was compared in areas previously identified as active during vergence eye movements (as listed in Table 2). In addition, exploratory analyses were performed to identify other regions with significant differences in activation before and after therapy and between the two groups. At the first level, individual functional magnetic resonance imaging data sets were preprocessed and analyzed for individual-level statistics. Each individual data set was preprocessed by performing motion correction using MCFLIRT, high-pass temporal filtering (Gaussian-weighted least-squares straight line fitting, with a cutoff = 90 seconds) was carried out to ensure that the data were free of low-frequency physiological signals. Spatial smoothing of the data was also carried out by Gaussian convolution (full-width half-maximum of 5 mm). After the preprossing steps, each individual data set was analyzed for individual-level statistics.

For statistical analysis of the individual functional magnetic resonance imaging data to assess significant activations, a general linear model was designed that described the experimental paradigm. This was done by designating a boxcar shape explanatory variable with a period of 50 seconds (20 seconds “off” and 30 seconds “on”). The explanatory variable was convolved with a double-gamma hemodynamic response to generate a predictor. This predictor, during the statistical analysis, was tested for its fitting with the time series (blood oxygen level–dependent signal change) in each voxel of the functional magnetic resonance imaging data set with a cluster-based thresholding approach for a z score of 2.3 or higher and a significance level $P < .05$. The resultant outcome z statistics maps were registered to their respective individual anatomical images and then to the standard brain template (MNI152_T1_2mm).

At the second level, the individual-level statistics from the first were grouped, and a paired $t$ test comparison was carried out.

![FIGURE 1. Timing pattern for the easy and hard vergence paradigms. Pink boxes represent a zero convergence demand for the red and blue anaglyphic target (for both easy and hard paradigms). Red, pink, and blue boxes represent increasing steps of convergence demands for the anaglyphic targets (4 Δ to 12 Δ for easy, 5 Δ to 25 Δ for hard). Modified with permission from Oechslin et al.](image)
between pre- and post-vergence-accommodative therapy, as well as between pre- and post-placebo treatment. Also, an unpaired t test was used for the comparison between the vergence-accommodative therapy and placebo groups. Given the small sample size, fixed-effect modeling was used for each group comparison. Therefore, the activation maps obtained by these group comparisons are representative only of the sample, not of a wider population.

For both the first- and second-level analyses, areas that demonstrated statistical significance (z score ≥ 2.3, P < .05) were highlighted, and a Talairach Daemon atlas was used to map these areas using x, y, and z coordinates. The brain stem could not be consistently imaged on all subjects.

## RESULTS

Seven symptomatic convergence insufficiency subjects (6 females; mean age, 26.1 ± 2.5 years) were enrolled and randomly assigned to vergence-accommodative therapy (n = 4) or placebo (n = 3). Baseline descriptive statistics are shown in Table 3. Overall, the mean Convergence Insufficiency Symptom Survey was 32.6 (±9.5), mean near phoria was 10 (±4.3 Δ), mean positive fusional vergence was 13.4 (±1.5 Δ) (blur if reported or break if no reported blur), and mean near point of convergence was 8 cm (±1.5 cm). Although statistical analysis was not possible because of the small sample size, no meaningful differences in baseline findings were apparent between those subjects assigned to vergence-accommodative therapy and placebo. Mean values for each group at primary outcome are also shown in Table 3. After therapy, three of the four subjects in the vergence-accommodative therapy group were considered successful, and one was a nonresponder. Two subjects in the placebo group were considered improved after 12 weeks of therapy, and one was considered a nonresponder.

Brain slice images were generated for areas of activation (increased blood oxygen level–dependent response) pre-therapy for the vergence-accommodative therapy and placebo group averages (Figs. 2A, B). On the whole, activation can be seen in clusters mainly in the following areas: the frontal lobe (inferior frontal gyrus, precentral gyrus, medial frontal gyrus, and the superior frontal gyrus), temporal lobe (superior temporal gyrus and middle temporal gyrus), parietal lobe (inferior parietal, occipital lobe, and cerebellum (posterior lobe/declive). Before therapy, the observed mean activation was similar between the two groups.

Figs. 3A and B show the activation slices after vergence-accommodative and placebo therapies, respectively. The pre-therapy activation areas seen more anterior/rostral in Fig. 2A are now reduced in size in the post–vergence-accommodative therapy scans, with areas within the left hemisphere diminished to a greater degree than those on the right. In addition, new areas in the inferior portions of the occipital lobe were noted to show activation after

### Table 2. Observed activation in previously identified regions of interest (ROI)

<table>
<thead>
<tr>
<th>Region</th>
<th>Left</th>
<th>Right</th>
<th>Pre-therapy z</th>
<th>Post-OBVAT z</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dorsolateral prefrontal cortex</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>52</td>
<td>10</td>
<td>32</td>
<td>6.6</td>
</tr>
<tr>
<td><strong>Frontal eye field</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>−54</td>
<td>10</td>
<td>32</td>
<td>7.7</td>
</tr>
<tr>
<td><strong>Supplementary eye field</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22</td>
<td>32</td>
<td>42</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Precuneus</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>−74</td>
<td>28</td>
<td>7.0</td>
</tr>
<tr>
<td><strong>Inferior parietal lobule</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>38</td>
<td>−48</td>
<td>48</td>
<td>5.8</td>
</tr>
<tr>
<td><strong>Cerebellar vermis</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>−76</td>
<td>−30</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Statistical significance (z score ≥ 2.3, P < .05). NS = nonsignificant activation; OBVAT = office-based vergence-accommodative therapy.

### Table 3. Mean (SD) clinical measures at baseline and 12-week outcome examination

<table>
<thead>
<tr>
<th>Measure</th>
<th>Vergence-accommodative therapy (n = 4)</th>
<th>Placebo therapy (n = 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symptom score (CISS)</td>
<td>33.3 (12.7)</td>
<td>31.7 (4.8)</td>
</tr>
<tr>
<td>12-wk outcome</td>
<td>21.4 (4.8)</td>
<td>17.8 (3.7)</td>
</tr>
<tr>
<td>Negative fusional vergence (blur or break), Δ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>10.0 (2.8)</td>
<td>10.7 (3.1)</td>
</tr>
<tr>
<td>12-wk outcome</td>
<td>21.5 (4.4)</td>
<td>10.0 (0.0)</td>
</tr>
<tr>
<td>Positive fusional vergence (blur or break), Δ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>13.7 (2.1)</td>
<td>13.1 (0.3)</td>
</tr>
<tr>
<td>12-wk outcome</td>
<td>40.0 (8.3)</td>
<td>17.1 (4.3)</td>
</tr>
<tr>
<td>Near point of convergence break, cm</td>
<td>8.4 (1.8)</td>
<td>7.6 (1.1)</td>
</tr>
<tr>
<td>12-wk outcome</td>
<td>3.1 (0.3)</td>
<td>4.7 (1.0)</td>
</tr>
<tr>
<td>Amplitude of accommodation OD, D</td>
<td>8.6 (1.3)</td>
<td>8.4 (1.6)</td>
</tr>
<tr>
<td>12-wk outcome</td>
<td>11.8 (0.8)</td>
<td>8.7 (1.3)</td>
</tr>
<tr>
<td>Accommodative facility OD, cpm</td>
<td>5.6 (5.2)</td>
<td>14.0 (2.8)</td>
</tr>
<tr>
<td>12-wk outcome</td>
<td>17.1 (9.8)</td>
<td>17.2 (2.1)</td>
</tr>
<tr>
<td>Vergence facility, cpm</td>
<td>10.5 (2.6)</td>
<td>17.8 (0.4)</td>
</tr>
<tr>
<td>12-wk outcome</td>
<td>18.3 (2.8)</td>
<td>17.5 (2.5)</td>
</tr>
</tbody>
</table>

Δ = prism diopter; CISS = Convergence Insufficiency Symptom Survey; cpm = cycles per minute; D = diopter; OD = right eye; SD = standard deviation.
vergence-accommodative therapy when compared with the pre-therapy results. After placebo therapy, activation in the more anterior/rostral areas also appeared to decrease somewhat relative to pre-therapy, although to a lesser extent than post-vergence-accommodative therapy.

Fig. 4 shows regions where mean activation pre-therapy was significantly greater than that observed post-therapy (paired t test comparison) for both office-based vergence-accommodative therapy and office-based placebo therapy. For those assigned to vergence-accommodative therapy, regions of the brain that were more active pre-therapy versus post-therapy were more anterior and superior. Those areas that showed greater activation pre-therapy were found on the left side more than the right side of the brain.

Fig. 5 shows regions where mean activation post-therapy was significantly greater than that observed pre-therapy (paired t test comparison) for both office-based vergence-accommodative therapy and office-based placebo therapy. After vergence-accommodative therapy, areas of increased activation (compared with pre-therapy) were seen near the posterior pole of the occipital lobe, mainly in the lingual gyrus, as well as a few smaller clusters in the cuneus and posterior cingulate gyrus of the occipital lobe and the angular gyrus of the parietal lobe. For those who underwent placebo therapy, there were no areas of the brain that showed a greater activation level after placebo treatment compared with pretreatment.

Post-therapy activation was also compared between the post-vergence-accommodative therapy and post-placebo treatment groups (Fig. 6). As compared with those assigned to placebo, greater activation was observed in those assigned to vergence-accommodative therapy in the posterior, inferior portion of the occipital lobe, the lingual gyrus, and in small clusters in the superior portions of the parietal and frontal lobes. In the case of the parietal and frontal lobe activation, the increased activation in the post-vergence-accommodative therapy group was more obvious within the right hemisphere than the left side.

Changes in blood oxygen level-dependent response in regions of interest that were previously identified in the literature were also examined (Table 2). Decreased activation (lower z score) was observed across all regions of interest after vergence-accommodative therapy as compared with pre-therapy, except in the medial frontal gyrus/supplementary eye fields where there was an increase in activation after vergence-accommodative therapy.

For the hard step vergence paradigm, the overall activation pattern observed pre-therapy was similar to that of the easy step paradigm.

![Figure 2](image_url)
However, the spatial extent of the activation was slightly larger across many of the activation clusters. The post–vergence-accommodative therapy activation areas that were greater than the pre–vergence-accommodative therapy activation areas for the hard step paradigm included mainly the clusters in the posterior lingual gyrus. While these areas demonstrated increased activation (greater z score) following therapy, they were smaller in spatial extent. Observed changes in activation from pre-therapy to post-therapy with the greater demands presented during the hard step vergence (for vergence-accommodative therapy and placebo) revealed comparable patterns to those described for the easy step vergence, although post-therapy we observed greater activation but over a smaller spatial extent.

**DISCUSSION**

This study investigated the functional magnetic resonance imaging blood oxygen level–dependent response to a range of convergence demands in previously identified regions of interest before and after office-based vergence-accommodative or placebo therapy. In addition, analyses were performed to determine whether changes occurred in other regions during convergence tasks. Because prior research has demonstrated changes in areas of the brain associated with vergence eye movements and because of the effectiveness of office-based vergence-accommodative therapy, it was hypothesized that changes in activation would be observed after therapy and between groups (real vs. placebo therapy) in previously identified regions of interest and in other areas associated with vergence eye movements.

This study showed changes in blood oxygen level–dependent response following vergence-accommodative therapy in adult subjects with symptomatic convergence insufficiency as hypothesized. In subjects assigned to vergence-accommodative therapy, much of the activation noted in the frontal lobe pre-therapy was greatly reduced in spatial extent or showed no activation post-therapy. Activation in the occipital lobe was reduced in spatial extent but increased in the posterior, inferior portion. Furthermore, a new area of activation was observed in the posterior, inferior portions of the occipital lobe, mainly in the lingual gyrus. This new area of activation was not observed post-therapy in those assigned to placebo. Less activation was generally observed after vergence-accommodative therapy.
therapy in regions of interest previously evaluated in functional magnetic resonance imaging studies (dorsolateral prefrontal cortex, frontal eye field, supplementary eye field, precuneus, inferior parietal, cerebellar vermis).

Studies using single-cell recordings in area V1 have demonstrated cells that are responsive to stereoscopic targets in macaque monkeys. Some of these cells respond to random-dot stereo targets, whereas others respond to non-random-dot stereo targets. Further, some cells respond to crossed disparities, whereas others responded to uncrossed disparities. These depth disparity-sensitive cells have also been implicated in driving vergence eye movements. Thus, the increase in blood oxygen level–dependent response in these occipital areas following vergence-accommodative therapy might suggest that disparity processing for both depth and vergence could be enhanced by vergence-accommodative therapy. The fact that activation in the occipital lobe increased and became more localized supports the results of a prior functional magnetic resonance imaging study in golf novices during imagery of completing a golf swing. The authors found that the extent of the brain area needed to complete the visualized golf swing greatly decreased in the experimental group that received physical training as compared with the control group that did not receive any training. Although Alvarez et al. reported that the spatial extent of and level of activation in regions of interest known to be used for vergence eye movements (lateral prefrontal cortex, frontal eye fields, supplementary eye fields, parietal eye fields, and the cerebellum) increased post-therapy, this study found a smaller spatial range and decrease in activation in these areas following therapy. The differences in results may be attributable to methodological differences. Specifically, the stimulus to convergence in the current study was a random-dot stereogram at a fixed distance (thus targeting fusional vergence), whereas the stimuli used by Alvarez et al. were light-emitting diodes at various distances (thus potentially stimulating multiple forms of vergence including proximal). In addition, the current study utilized larger magnitudes of convergence demands (comparable to near demands experienced during typical near viewing) and the accommodative-vergence therapy administered followed the Convergence Insufficiency Treatment Trial office-based vergence-accommodative therapy protocol, which has been shown to be the most effective therapy treatment.

Many brain areas known to be used during attentional tasks were discovered to be active pre-therapy when examining all the

FIGURE 4. Red/yellow clusters show regions where average group activation pre-therapy was significantly (z score ≥ 2.3, P < .05) greater than that observed post-therapy (paired t test comparison) for both office-based vergence-accommodative therapy (OBVAT) and office-based placebo therapy (OBPT). Greatest differences in activation is represented by yellow clusters. R denotes right side of the brain.
FIGURE 5. Red/yellow clusters show regions where average group activation post-therapy was significantly (z score ≥ 2.3, \( P < .05 \)) greater than that observed pre-therapy (paired t-test comparison) for both office-based vergence-accommodative therapy (OBVAT) and office-based placebo therapy (OBPT). Greatest differences in activation is represented by yellow clusters. R denotes right side of the brain.

FIGURE 6. Unpaired t-test comparison between average group activation after office-based vergence-accommodative therapy (OBVAT) versus average group activation after office-based placebo therapy (OBPT). Red/yellow clusters represent regions where activation post-OBVAT was significantly (z score ≥ 2.3, \( P < .05 \)) higher compared with activation post-OBPT. Greatest differences in activation is represented by yellow clusters. R denotes right side of the brain.
Functional magnetic resonance imaging scan data. These attentional areas include multiple locations throughout the dorsal frontal, lateral prefrontal, and parietal cortices, including the following: medial intraparietal sulcus, precuneus, superior parietal lobule, supplementary eye fields, frontal eye fields, dorsolateral prefrontal cortex, inferior frontal sulcus, temporal parietal junction, inferior parietal lobule, and middle frontal gyrus. These attentional brain areas also have been shown to have a connection with eye movements. In addition, many of these areas are connected to each other as the dorsal-frontoparietal network and the ventral-frontoparietal network. The dorsal-frontoparietal network is bilateral and connects the superior parietal lobes, intraparietal sulcus, and frontal lobes. This network is associated with attention that is top-down, meaning a person must think about attending to a stimulus before an action is taken. On the other hand, the ventral-frontoparietal network is located in the right hemisphere and connects the temporal parietal junction, inferior parietal lobule, and ventral frontal lobe. This network is associated with attention that is bottom-up, meaning that the stimulus itself draws the attention of a person and then causes an action. Before vergence-accommodative therapy, frontal and parietal lobe areas of activation were observed on both the left and right sides of the brain (Fig. 2). The bilateral activation in these areas suggests that the dorsal system was active prior to therapy and by extension that subjects were engaged in top-down processing. On the other hand, following vergence-accommodative therapy, the activation (shown in Figs. 3 and 4) was reduced on both sides of the brain compared with pre-therapy, but the reduction was more substantial on the left side of the brain. This imbalance in the decreased activation for the right and left sides of the brain suggests that after therapy subjects had a relative decreased reliance on the (bilateral) dorsal system, which is associated with top-down processing but continued reliance on the (right-sided) ventral system, which is associated with bottom-up processing as this system appears to remain active. Overall, these results may suggest that top-down–driven attentional areas (associated with the dorsal-frontoparietal network) are activated during convergence in those with symptomatic convergence insufficiency. Furthermore, this suggests that convergence in those with convergence insufficiency may require conscious effort. Extra vergence effort may be associated with visual fatigue. A decrease in the need for extra vergence effort in those assigned to vergence-accommodative therapy is supported by the observed improvements in clinical findings (positive fusional vergence, near point of convergence, and vergence facility). On the other hand, improvements in symptoms were observed in both groups after therapy. It is unknown whether the improvement in symptoms in the placebo group was due to a placebo effect, response bias, or regression to the mean. In addition, a poor association between clinical signs and symptoms as measured by the Convergence Insufficiency Symptom Survey has been previously reported.

Strengths of the current study include use of a stimulus with a wide range of convergence demands presented at a fixed distance, the use of a therapy regimen shown to be effective for the treatment of symptomatic convergence insufficiency, and the inclusion of a placebo control. A limitation of the current study is the small number of subjects (n = 7). However, the subjects who went through vergence-accommodative therapy all showed the same general pattern before versus after therapy (decreased frontal areas of activation and a focusing of activation posteriorly).

In summary, after office-based vergence-accommodative therapy in those with symptomatic convergence insufficiency, the blood oxygen level–dependent response from functional magnetic resonance imaging while viewing a random-dot stereogram with increasing convergence demand showed a decrease in the spatial extent and magnitude of activation in frontal attentional areas, a decrease in the spatial extent of activation in much of the occipital lobe, and an increase in the amount of activation in the posterior, inferior occipital lobe. Observed activation pre-therapy that appeared to be associated with the dorsal-frontoparietal network, and therefore top-down driven attention, suggests that convergence requires conscious effort in those with symptomatic convergence insufficiency. The increase in blood oxygen level–dependent response in the occipital areas following office-based vergence-accommodative therapy suggests that disparity processing for both depth and vergence may be enhanced following vergence-accommodative therapy.

REFERENCES


