ABSTRACT
Abnormal convergence eye movements (convergence insufficiency) have been reported in individuals with mild traumatic brain injury (mTBI). Convergence eye movements are a component of the near response, which includes synchronous pupil constriction and lens accommodation. This study examined dynamic coordination between divergent eye movements and pupil size in 50 control subjects and 18 subjects with acute mTBI. The results were evaluated using a step retrial disparity fusion task, using an I-PAS® virtual display platform (Neuro-Kinetik, Inc., Pittsburgh, PA). Each eye viewed a white square with red center (0.1 degrees visual angle); the task consisted of disparity shifts in the horizontal plane equivalent to symmetric, approximately ±1.4° convergence eye movement steps. Because neither stimulus luminance nor size changed, it provided a pure disparity fusion stimulus for vergence. Eye movements and pupil area were sampled with a video-sclerograph system at 100 Hz; pupil size data were normalized to responses to 0.42 to 65.4 cm²/m² homogenous illumination steps. Data were detrended prior to analysis. Visual angles (i.e., calibration phoropter) for vergence eye movements were symmetric [1.50 ± 0.10° (SE) converging; -1.50 ± 0.10° (SE) diverging] in the control subjects, the pupil constriction was -3.9 ± 2.3% (normalized area) during convergence steps and dilation was 8.1 ± 2.2% (normalized area) during divergence steps. One control subject did not perform the task; another performed eye movements without a pupil near response (data included). Both the vergence eye movement [0.63 ± 0.10° (SE) converging; -0.65 ± 0.10° (SE) diverging] and pupil modulation [-5.9 ± 2.3% (normalized area) converging; 3.5 ± 3.2% (normalized area) diverging] were reduced significantly in the mTBI group (ANOVA, p<0.05). Nine mTBI subjects were below the 93rd percentile for vergence eye movement magnitudes. The detrended pupil responses were also modeled as a sum of a high and low pass filtered representations of the vergence eye movements; R-squared values were greater (p<0.05) in the control (0.45 ± 0.08) than the mTBI group (0.21 ± 0.06). Residuals showed strong pupil habitus activity unrelated to vergence. These findings suggest that a retinal disparity vergence test has utility in objective diagnosis of convergence insufficiency in acute mTBI.

BACKGROUND
Mild traumatic brain injury (mTBI) is a major public health issue that impacts every segment of our society. One of the most difficult aspects of this disorder is making a proper diagnosis. Abnormal convergence eye movements (convergence insufficiency) have been reported in individuals with mild traumatic brain injury (mTBI). Convergence eye movements are a component of the near response, which includes synchronous pupil constriction and lens accommodation. This study examined dynamic coordination between divergent vergence eye movements and pupil size in 50 control subjects and 18 subjects with acute mTBI.

METHODS
Fifty control subjects (28.76±3.6, range: 21-45 y) and 18 mTBI patients (29.18±1.7, range: 20-43 y) were tested at University of Miami and Naval Medical Center, San Diego under IRB approval. All patients were diagnosed by medical physicians in the emergency room to have sustained a concussion; acute testing was performed 4-166 hrs after incident (mean= 57.6±36 hrs).

A battery of oculomotor tests was performed using a portable, 3D head-mounted display system with integrated eye tracking technology (I-Port® Portable Assessment System (I-PAS®), Neuro Kinetik, Inc. Pittsburgh, PA). Tests included pursuit, optokinetic, saccade and anti-saccade tasks and a vergence pursuit (0.1 Hz, ± 1.5°, 17 mTBI subjects) task. During a step retrial disparity fusion task, using an I-PAS® virtual display platform, each eye viewed a white square with red center (0.1 degrees visual angle); the task consisted of disparity shifts in the horizontal plane equivalent to symmetric, approximately ±1.4° vergence eye movement steps. Because neither stimulus luminance nor size changed it provided a pure disparity fusion stimulus for vergence. Eye movements and pupil area were sampled with a video-sclerograph system at 100 Hz; pupil size data were normalized to responses to 0.42 to 65.4 cm²/m² homogenous illumination steps. Data were detrended prior to analysis.

For control subjects, R² = 0.84 ± 0.03 for vergence model fits 0.28 ± 0.03 for the pupil model fits (to vergence eye movements). Delays were 0.26 ± 0.02 for the vergence model and 0.19 ± 0.02 for the pupil motion model. The phasic vergence response was fully rectified and symmetric, and the tonic vergence response was symmetric and the pupil gain was greater for dilation. Parameters are tabulated below:

Model Gain Parameters: Vergence and Pupil

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter</th>
<th>Tonic Gain</th>
<th>Symmetric Gain</th>
<th>Non-Symmetric Gain</th>
<th>Steady-State Medians: Vergence and Pupil</th>
</tr>
</thead>
</table>
| Control | Pupil | 0.015 ± 0.001 | 0.327 ± 0.025 | -0.102 ± 3.679 | Symmetry was tested by fixing separate gains for convergence versus divergence steps. Because neither stimulus luminance nor size changed it provided a pure disparity fusion stimulus for vergence. Eye movements and pupil area were sampled with a video-sclerograph system at 100 Hz; pupil size data were normalized to responses to 0.42 to 65.4 cm²/m² homogenous illumination steps. Data were detrended prior to analysis.

Model Fit Coefficients of Determination (R²) for Both Disparity Pursuit and Disparity Step Task Vergence Task Versus Autonomic Response Delays During Acute mTBI

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter</th>
<th>Vergence Response</th>
<th>Pupil Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>mTBI</td>
<td>0.53 ± 0.13 deg</td>
<td>0.60 ± 0.13 deg</td>
</tr>
<tr>
<td>Control</td>
<td>mTBI</td>
<td>1.300 ± 0.094 PLR</td>
<td>1.701 ± 0.043 PLR</td>
</tr>
</tbody>
</table>

CONCLUSIONS
• Binocular disparity vergence tests have utility in objective diagnosis of convergence insufficiency in acute mTBI.
• Acute mTBI can affect parameters of Binocular Disparity Resolution control, e.g., decreased vergence gain and increased vergence delay
• Acute mTBI can affect parameters of Pupillary Motor Control (decreased delay)
• Reduced pupil response magnitude in the Disparity Pursuit Task during acute mTBI is produced by the lowered vergence (Disparity Resolution) response

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DISCLOSURES
Author A.K. is an employee of, and has financial interests in Neuro Kinetik, Inc., which manufactured the equipment used in this study. The views expressed herein do not necessarily reflect the official policy or position of the Department of the Navy, Department of the Army, Department of Defense, or the U.S. Government.