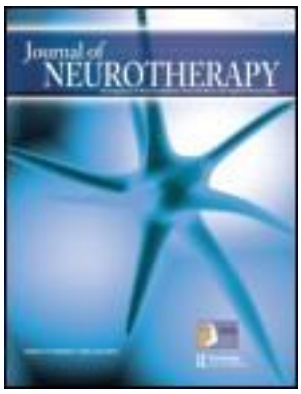

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Infrared Imaging and Neurofeedback: Initial Reliability and Validity

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Infrared Imaging and Neurofeedback: Initial Reliability and Validity

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ABSTRACT. *Introduction*. The neurological correlates underlying positive treatment outcomes for neurofeedback have been either unavailable or difficult to demonstrate. Assessment of brain-related changes associated with neurofeedback is needed to further establish its empirical basis. Infrared (IR) imaging is a noninvasive assessment of brain activity with high spatial and temporal resolution.

Method. Study 1, a reliability study, assessed the test-retest stability of IR imaging. In Validity Study 2 and 3, IR imaging assessed brain-related changes prior to and following neurofeedback and passive infrared hemoencephalography (pir HEG) training, respectively.

Results. In Study 1, high correlations occurred in pre-post comparisons for IR measures unrelated to treatment. Lower correlation between measures of IR imaging indicated changes in brain activation associated with thermoregulation following neurofeedback training. In Study 2, changes in thermal regulation occurred both within and across sessions. The change in metabolic regulation was enduring and associated with a reduction in core Autistic Spectrum Disorder symptomatology and improved cerebral connectivity. In Study 3, a significant percentage of patients with Traumatic Brain Injury increased thermal readings following pir HEG training and the change in thermal readings was associated with EEG connectivity.

Conclusion. Findings indicated that IR imaging may be a reliable and valid measure of treatment outcomes with clinical utility and sensitivity.

KEYWORDS. Autistic Spectrum Disorder, infrared imaging, near infrared spectroscopy, neurofeedback, reliability, Traumatic Brain Injury, validity

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INTRODUCTION

Neurofeedback has been found to be an effective therapeutic intervention across a wide variety of conditions including Attention Deficit Hyperactivity Disorder, epilepsy, and Traumatic Brain Injury (TBI; Linden, Habib, & Radojevic, 1996; Rossiter, 2005; Sterman, 2000; Sterman & Lantz, 2001; Thornton, 2000; Tinius & Tinius, 2001). Neurofeedback is defined in this article as a superordinate term to encompass any form of biofeedback utilized to enhance brain function including EEG biofeedback and Hemoencephalography training. Successful treatment outcomes have also been reported for alternate forms of neurofeedback as well. Carmen (2004) investigated the efficacy of passive infrared hemoencephalography (pir HEG) training in treating individuals experiencing headaches. The majority of participants increased control over migraine headaches following training. Toomim et al. (2004) also reported success in utilizing HEG training in participants with brain disorders to improve levels of impulsivity as measured by the Test of Variables of Attention. Although the aforementioned research demonstrated positive treatment outcomes from neurofeedback training, the neurological correlates underlying positive treatment outcomes have been either unavailable or difficult to demonstrate. However, infrared (IR) imaging maybe a tool to assess brain-related activation and changes. Near infrared (NIR) imaging, also known as near infrared spectroscopy (NIRS), assesses brain activation based on hemodynamic profiles (E. Gratton, Toronov, Wolf, Wolf, & Webb, 2005; Kennan, Kim, Maki, Koizumi, & Constable, 2002).

Studies Using NIRS

Research has found strong correlations between functional magnetic resonance imaging (fMRI) changes and NIRS recordings during a motor task. The blood oxygenation level dependent (BOLD) data obtained from the fMRI were compared to changes in oxyhemoglobin, deoxyhemoglobin, and total hemoglobin concentrations derived from NIRS data. The strongest correlation between BOLD fMRI and NIRS was oxyhemoglobin (Strangman, Culver, Thompson, & Boas, 2002).

Kameyama, Fukuda, Uehara, and Mikuni (2004) measured changes in cerebral hemoglobin concentration during a cognitive task utilizing multichannel NIRS. The findings indicated that multichannel NIRS detected cerebral activation during cognitive tasks and clarified gender- and age-dependent differences in cerebral activation. Gender- and age-dependent differences in cerebral activation may impact on cerebral blood volume, cerebral blood flow, and cerebral glucose metabolism data. fMRI findings suggest that increased regional cerebral blood flow (rCBF) during prolonged visual stimulation can cause local changes in brain temperature and oxygen metabolism (Yablonskiy, Ackerman, & Raichle, 2000). Kennan et al. (2002) found that NIR imaging can be utilized to identify lateralization of prefrontal areas during a language task as validated by fMRI. Laterality was quantified for the fMRI by the relative number of activated voxels in each hemisphere and for NIR imaging by the total hemoglobin responses in each hemisphere. Findings suggested that NIR predicts hemispheric dominance in response to a language task consistent with fMRI, a more sophisticated and costly imaging method.

Strangman, Boas, and Sutton (2002) reported the advantages of NIR over existing brain monitoring, including excellent temporal resolution and spectroscopic information for hemodynamic events, low cost, and findings that are robust to motion artifacts. In contrast to positron emission tomography and single photon emission computed tomography, the technology is noninvasive. These benefits permit applicability of NIR to populations including small children and patients with movement disorders.

Long-Wave IR Imaging

NIR imaging is one form of assessing brain metabolic function. Another way to

assess brain metabolism is thermal imaging utilizing long-wave IR imaging, which records thermal images between 7 and 14 microns. In contrast, NIR imaging records images at less than 1 micron. In addition, NIRS records only at certain sites (usually 8–10), whereas long wave recording provides hundreds of data points over a region. NIRS includes an apparatus affixed on the head like a headband. In contrast, long-wave equipment consists of a camera picture taken at a distance.

Shevelev (1998) investigated functional imaging of the brain utilizing long-wave IR imaging. The pathological processes that were detected included depression, stress, catalepsy, and epileptic focuses. The main mechanisms of thermal responses consisted of neural activity, local units of metabolism, local cerebral blood flow, and thermoconductivity in the activated zones of the cortex.

Collins, Smith, and Turner (2004) proposed a model of local temperature changes in the brain associated with functional activation. A three-dimensional model of temperature in the human brain was produced based on a bioheat equation including the effects of metabolism, perfusion, and thermal conduction. The findings indicated changes in perfusion have a greater effect on temperature than changes in metabolism. Temperature may increase or decrease with activation accompanied by increased perfusion and metabolism as a function of specific brain locations and baseline temperature relative to blood temperature.

The aforementioned findings all point to the use of IR imaging as a valuable tool to accurately assess the level of cortical activation at baseline and following treatment. Research indicates that IR imaging is a valid and reliable measure of brain activity, metabolic processes, and rCBF (Carmen, 2004; Coben, 2005a, 2005b; Coben, Carmen, & Falcone, 2005; Toomim et al., 2004). In the research presented here, three studies were conducted to provide initial research on the reliability and validity of long-wave IR imaging as an outcome measure prior to and following neurofeedback. IR domains were consistent across all studies. The domains of assessment included minimum, maximum, and range of thermal readings.

In the first study, research was conducted on the reliability of IR imaging as an assessment of brain activation levels. In the second and third studies, we conducted research on two separate populations with known brain dysfunction to assess the clinical utility and sensitivity of IR imaging as a valid measure of changes in brain activation. In the second study, patients were diagnosed with Autistic Spectrum Disorder (ASD). IR imaging was conducted prior to and following each treatment session. IR imaging was utilized as an outcome measure to evaluate the treatment effect of assessment-guided neurofeedback. In the third study, patients participating in the research were diagnosed with TBI. IR imaging was performed prior to and following pir HEG. IR imaging was utilized as an outcome measure to evaluate the treatment effect of pir HEG. For each study, the method and results are presented. Validity Study 1 and Validity Study 2 are followed by a brief discussion of the findings. For all three studies, procedures were explained and informed consent was obtained prior to participation in the studies. An alpha level of .01 was adopted to guard against Type II associated with multiple comparisons.

STUDY 1: RELIABILITY STUDY

Method

Participants. Forty-eight patients with various diagnoses participated in this study. All participants underwent IR imaging prior to and following neurofeedback training.

Procedure. A diagnostic interview was conducted with the patients to ascertain the core behavioral, cognitive, and social/emotional issues of concern as part of a comprehensive neurodevelopmental history. IR imaging was conducted prior to and following neurofeedback therapy sessions. Prior to treatment, two pretreatment IR images were captured 60 sec apart. Following treatment, two posttreatment IR images were

TABLE 1. Specifications for ThermoVision A20M.

Field of view	25 degrees × 19 degrees/0.3 m
Detector type	Focal plane array uncooled microbolometer
Spectral range	7.5 to 13 microns
Thermal sensitivity	At 50/60 Hz : 0.12 °C at 30 °C
Accuracy (% of reading)	± 2 °C or ± 2%
Individual emissivity settings	Individually settable
Measurement corrections	Reflected ambient, distance, relative humidity, external optics. Automatic based on user input
Power source	AC operation: AC adapter 110/220 VAC. 50/60 Hz (included). DC operation: 12/24 V nominal, <6W

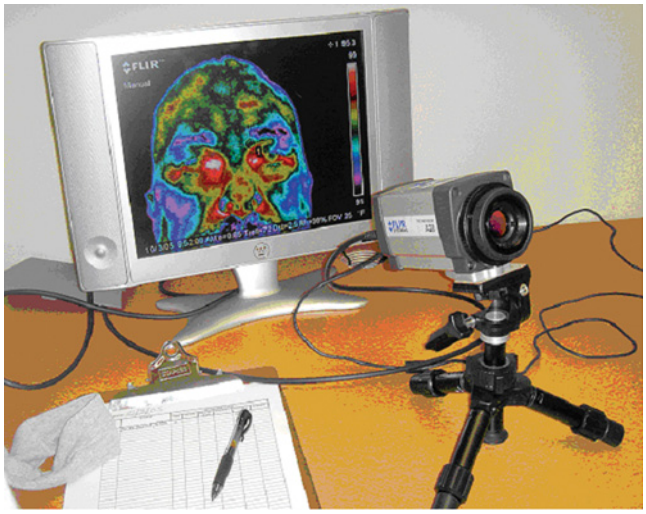
Note. Specifications were obtained from FLIR Systems Inc. (2006).

captured 60 sec apart. The images were captured 60 sec apart to assess the stability of measurement exclusive of treatment. Posttreatment images were captured 20 to 30 min after pretreatment images.

Materials. IR imaging was performed prior to and following each neurofeedback training session. The levels of thermal activity are associated with underlying metabolic activity and rCBF. IR imaging is an assessment tool that can record thermal images of multiple brain regions rather than just one area. Prior to and following neurofeedback training, an IR video system captured a thermal image of the patient. The components of the image that underwent analysis included only brain-related regions. The imaging procedure involved a camera set up approximately 1.5 ft away from the patient. The camera is aimed at the patient's face. Thermal images were color coded and ranged from black with the least thermal output to red with the greatest thermal output.

A ThermoVision A20M camera (FLIR Systems, 2006) was used for infrared imaging. (See Table 1 for camera specifications.) As part of the imaging procedure, the camera (mounted on a tripod) was set up approximately 1.5 feet from the patient and the thermal image was projected onto a screen (see Figure 1). Specifications programmed into the camera included emissivity (.90), distance (1.5 ft.), reflected temperature (72), ambient temperature (72), atmospheric transmission (1), humidity (50%, external optic temperature, 68), external optic transmission (1), and reference temperature (68).

FIGURE 1. Infrared imaging system projecting a thermal image.



Results

Reliability can be defined as the degree to which an assessment instrument provides a stable measure of the attribute it is intended to measure (Korkman, Kirk, & Kemp, 1998).

Test–retest reliability is the degree to which test results can be replicated or reproduced if the same individuals are tested again under similar circumstances (Schene et al., 2000). Stability of findings was determined within two pretreatment images as well as two posttreatment images captured 60 sec apart, and between two pre- and two posttreatment images captured 20 to 30 min apart. Stability coefficients were computed using the Pearson correlation coefficient, and two-tailed probability was calculated. The coefficients for Skewness (Pre-Range1 = .51, $p = .13$) and Kurtosis (Pre-Range1 = –.45, $p = .52$) were nonsignificant indicating that data were evenly spread across the sample approximating a normal distribution. Measures of IR imaging included minimum (Min) or lowest thermal reading, maximum (Max) or highest thermal reading, and range of thermal readings across the frontal cortex.

Test–retest reliabilities. As shown in Table 2, test-retest reliability or stability reached high levels of significance for IR imaging measures ($M\ r = .903$).

Pre-/posttreatment comparisons. As shown in Table 3, the first and second pre-/posttreatment comparisons of IR imaging, test-retest stability reached levels of significance in lowest thermal reading (Min) and its variability (Range), $p < .01$ Lower correlation of IR imaging between pre and post measures ($M\ r = .468$) suggests that there were changes in brain activation (associated with thermoregulation following neurofeedback training. No significant pre-/posttreatment differences were noted for the alternate treatment group receiving Occipital Nerve Stimulation, which rules out time as an intervening variable.

TABLE 2. Pre-/post-IR imaging exclusive of treatment.

	Reliability (*r*)
Pre-min	.94**
Pre-max	.92**
Pre-range	.85**
Post-min	.95**
Post-max	.89**
Post-range	.87**

Note: Min = minimum/lowest ($n = 48$); Max = maximum, highest reading ($n = 40$).
**$p < .001$.

TABLE 3. Pre-/posttreatment IR imaging.

	Reliability (*r*)
Pre-Min1/Post-Min1	.48*
Pre-Max1/Post-Max1	.18
Pre-Range1/Post-Range1	.74**
Pre-Min2/Post-Min2	.47*
Pre-Max2/Post-Max2	.21
Pre-Range2/Post-Range2	.73**

Note: Min = minimum/lowest; Max = maximum, highest reading.
*$p < .01$. **$p < .001$.

STUDY 2: VALIDITY STUDY 1

Assessment Guided Neurofeedback for ASD

The clinical utility and sensitivity of IR imaging as an outcome measure following neurofeedback training was assessed by studies conducted with populations with known brain dysfunction. In the second study, participants were diagnosed with ASD and were treated with assessment-guided neurofeedback (Coben & Padolsky, 2007).

Method

Participants. Thirty-seven children diagnosed with ASD participated in the study and served as the experimental group. There were 12 participants in the wait-list control group similarly diagnosed with ASD. The experimental and control group were matched based on age, gender, race, handedness, other treatments, and severity of ASD as indicated by the Autism Treatment Evaluation Checklist (ATEC; Rimland & Edelson, 2000). The experimental group

received assessment-guided neurofeedback training for approximately 20 sessions. No new treatments were undertaken by any participants during the course of the study.

Procedure. A diagnostic interview was conducted with the parents to ascertain core behavioral, cognitive, and social/emotional issues of concern as part of a comprehensive neurodevelopmental history. IR imaging was conducted prior to and following each neurofeedback training session. Please see Figure 2 for an example of a pre- and post-image of a participant prior to and following neurofeedback training.

Materials. A ThermoVision A20M camera (FLIR Systems, 2006) was used for infrared imaging (see Table 1 for camera specifications). Prior to and following neurofeedback training, an IR video system captured a thermal image of the patient. The components of the image that underwent analysis included only brain-related regions. The imaging procedure involved a camera set up approximately 1.5 ft away from the patient. The camera was aimed at the patient's face. Thermal images were color coded and ranged from black with the least thermal output to red with the greatest thermal output.

NeuroCybernetics EEGer Training System (NeuroCybernetics Inc., 2006) was utilized to perform neurofeedback. Hardware included Thought Technology encoders. Sensors (Grass Silver Disc 48'' Electrodes with SafeLead protected terminals; Grass SafeLead, 2006) were applied to the patient's scalp to measure EEG activity. The signal was fed back to the patient in visual and aural form based on relative amplitude/threshold values. Frequencies which were excessively generated were inhibited and targeted frequencies were augmented.

The aural reward rate (or time interval between sounds) was limited to 2 Hz. In this way, each individual sound was audible to the patient. There was a prerecorded computer sound file which typically included a short .25-sec beep providing feedback that a specified amplitude condition was met. The visual feedback consisted of simple graphics providing a continuous display of the ratio of amplitude to threshold for each stream of data. Visual feedback was provided in the following game formats: 4mation, Boxlights, Highway, Island, Jumpbox, Mazes, EEG Chomper, Space Race, Cubes, and Starlight (NeuroCybernetics Inc., 2006). (See Table 4 for specifications.)

Results

IR imaging: First session. The experimental group showed a trend toward the enhancement in the minimum or lowest thermal reading in the first session of assessment, $t(34) = -2.25$, $p = .03$ (presession $M = 93.5\,^{\circ}$F, postsession $93.9\,^{\circ}$F). There was a significant decrease in the range of thermal degrees before and after the first session of IR imaging, $t(34) = 4.52$, $p < .0001$ (presession

FIGURE 2. Pre and postinfrared images for EEG biofeedback with Ft8-Ft7-A1 potocol for a patient diagnosed with autistic spectrum disorder.

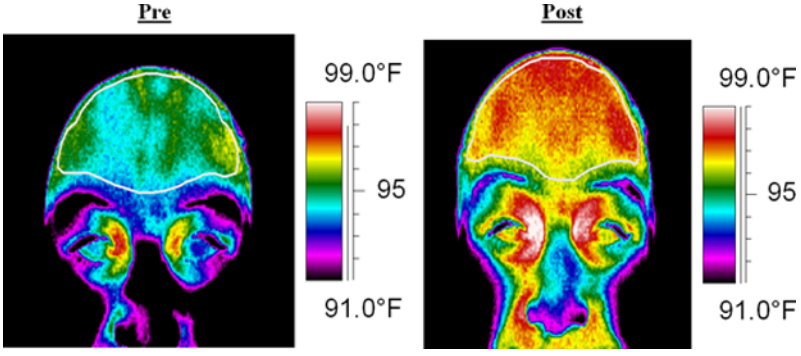


TABLE 4. Specifications for NeuroCybernetics EEGer neurofeedback training system.

Number of channels	2 channels of EEG data at 256 Hz
Sampling stored data	All sampling is done by external EEG amplifiers/converters at 256 Hz
Encoders	Thought technology encoders
Filtering	Filter coefficients were precomputed and provided in 1/8 Hz steps from 0 to 50 Hz
	Lowpass filters input can be independently specified as 0–40, 0–50, 0–30 Hz to minimize 50 or 60 Hz interference

Note. Specifications for equipment were obtained from NeuroCybernetics Inc. (2006).

M range of 3.8 °F, postsession 3.3 °F). In response to the first neurofeedback session, the experimental group elevated their metabolic activity (as reflected by increased minimum thermal reading) and decreased the variability of output.

IR imaging: Last session (approximately 20th). There was a trend toward a decrease in the maximum thermal reading following treatment within the last session, $t(33) = 2.17$, $p = .04$ (presession $M = 97.8$ °F, postsession 97.3°F) along with a significant decrease in the range of thermal degrees, $t(33) = 2.91$, $p \leq .01$ (presession *M* range 3.41 °F, postsession 3.16 °F).

Evidence of enduring change: Comparison of first and last session. IR imaging measured increases in metabolic output that resulted from neurofeedback training. Between the first and last sessions, the experimental group increased the minimum thermal reading, $t(34) = -3.31$, $p < .01$ (pretreatment $M = 93.5$ °F, posttreatment 94.3 °F) and decreased the range of thermal readings, $t(34) = 3.39$, $p < .01$ (pretreatment *M* range = 3.8 °F, posttreatment 3.4 °F). Neurofeedback training was associated with improved ASD symptoms as indicated by an 89% success rate ($p < .0001$), a 40% reduction ($p < .0001$) in core ASD symptomatology (indicated by ATEC total scores), and reduced cerebral hyperconnectivity ($p < .01$; Coben & Padolsky, 2007).

STUDY 3: VALIDITY STUDY 2

pir HEG for TBI

In the third study, patients were diagnosed with TBI and received pir HEG training (Coben, 2005b).

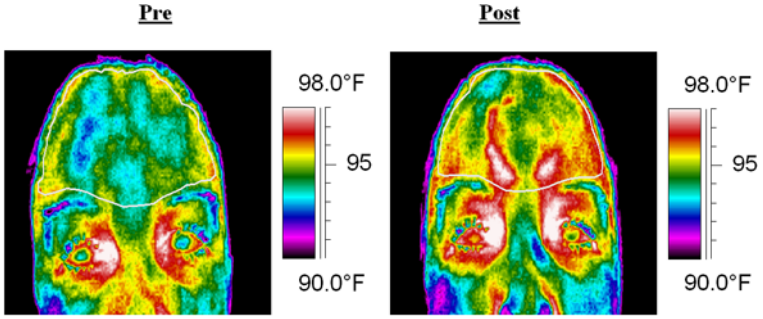
Method

Participants. Thirty-two patients sent to our treatment facility with a diagnosis of TBI and no other previous neurological or psychological difficulties participated in the study. Patients participating in the study received approximately 20 sessions of pir HEG over Fpz. Two control groups were available for comparison. Control groups were matched for gender, age, race, and education. Control group 1 underwent occipital nerve stimulation for TBI ($n = 7$) and control group 2 received individual psychotherapy ($n = 10$).

Procedure. A diagnostic interview was conducted with the patients to ascertain the core behavioral, cognitive, and social/emotional issues of concern as part of a comprehensive neurodevelopmental history. IR imaging was conducted prior to and following each training session for the experimental group. For control group 1 and 2, IR imaging was conducted at the initiation and completion of the study. See Figure 3 for a sample of pre- and posttreatment images taken before and after a pir HEG session.

Materials: Assessment instruments. A ThermoVision A20M camera from FLIR Systems (2006) was used for infrared imaging. A description of the procedure in capturing IR images appears previously, in the validity study. The pir HEG equipment (developed by Carmen, 2001) had sensor assembly that mounted on the forehead with soft Velcro straps to hold it in place. Increases in pir HEG signal are associated with a composite of thermal activity generated by brain cells, vascular supply, and

FIGURE 3. Pre- and postinfrared images for pir HEG protocol for a patient diagnosed with traumatic brain injury.



vascular return. The addition of threshold-based control of a VCR and/or DVD player provided operant reinforcement of target brain activity. The objective was to increase the pir HEG signal to exceed the threshold setting for the movie to continue or resume playing. Maximum output of infrared radiation was associated with mental states of low anxiety and frustration while maintaining a high degree of sustained concentration. It is believed that prefrontal pir HEG training tends to suppress disregulated activity throughout the brain, not just frontally (Carmen, 2001, 2004).

Results

IR imaging: First session and last session. There was a significant increase in the lowest thermal reading pre-/posttreatment in the initial IR imaging session, $t(26) = -3.99$, $p < .001$ (presession $M = 91.8$°F, postsession 93.5°F) as well as the highest thermal reading, $t(26) = -3.06$, $p < .01$ (presession Mrange = 96.8°F, postsession 97.5°F). Significant enhancement of thermal readings were also noted in comparisons of the lowest thermal reading, $t(25) = -3.39$, $p < .01$ (presession $M = 92.6$°F, postsession 93.7°F) and highest thermal reading in the final IR imaging session, $t(25) = -3.07$, $p < .01$ (97.1 °F, 97.7 °F, respectively).

IR imaging: Comparison of first to last session. Eighty-seven percent of TBI patients increased thermal readings following treatment ($p < .01$; sign test). Significant changes in range of thermal readings were observed in the initial assessment, $t(26) = 3.56$, $p < .01$ (presession M range = 5.1 °F, postsession 4.1 °F), and a trend for the final assessment, $t(25) = 2.30$, $p = 0.03$ (4.5 °F compared to 4.0 °F, respectively). A linear regression revealed an association between IR imaging presession minimum readings in the first and last session and changes in EEG connectivity ($r^2 = .20$, $p < .02$).

Discussion

IR imaging is a reliable assessment procedure which is sensitive to brain activation as indicated by thermoregulation. In the reliability study, we demonstrated that, when comparisons of IR imaging measures were obtained exclusive of therapy, correlation coefficients had great stability indicating that little change in brain activation as reflected by thermal readings occurred. Lower correlations between pre-/postreadings of IR imaging suggests that there were changes in brain activation associated with thermoregulation following neurofeedback training. These findings indicated that IR imaging should be considered a reliable method of assessing brain function and may be sensitive to the effects of neurofeedback.

The clinical utility, validity, and sensitivity of IR imaging as an outcome measure following neurofeedback training were assessed by conducting studies utilizing populations with known brain dysfunction. In the validity study with patients diagnosed as ASD, IR imaging revealed changes in brain activation

following assessment-guided neurofeedback. These changes coincided with improvements in neurobehavioral, neuropsychological, and neurophysiological measures.

In the validity study with patients diagnosed as TBI, IR imaging provided further evidence of changes in brain activation following pir HEG training. Global improvements in brain connectivity were associated with changes in IR imaging findings suggestive of enhanced cerebral blood flow.

Other research has also reported an association between cortical activation and metabolic measures of brain activity. G. Gratton, Goodman-Wood, and Fabiani (2001) utilized findings from optical imaging, MRI, and electrophysiological recordings to support a linear relationship between neuronal activity integrated over time and the amplitude of hemodynamic response to visual stimulation of the medial occipital region. Fiege et al. (2005) reported that EEG alpha amplitudes were associated with fMRI BOLD signal decrease in occipital regions. This inverse relationship between EEG alpha amplitude and BOLD signals in primary and secondary visual areas was associated with reduced brain metabolism. Moosmann et al. (2003) found that NIRS and EEG measurements had a positive cross-correlation in the occipital cortex between alpha activity and concentration of deoxygenated hemoglobin. Alpha activity in the occipital cortex was associated with metabolic deactivation.

In our research, IR imaging measured changes in brain states that occurred as a result of neurofeedback treatment, which has been shown to enhance brain activity. When brain activity improves, metabolic and temperature changes are expected as well. IR imaging assesses changes in brain activity in a rapid and unobtrusive manner. Shevelev (1998) described long-wave IR imaging as an assessment tool that produces two-dimensional, contact-free, dynamic noninvasive recording of background and evoked cortical activation. High spatial and temporal resolution as well as sensitivity were reported.

Other researchers (Strangman, Boas, et al., 2002) reported on the advantages of NIR imaging over existing brain monitoring including excellent temporal resolution and spectroscopic information for hemodynamic events, low cost, and findings that are robust to motion artifacts. These benefits permit applicability of NIR to populations including small children and patients with movement disorders (Strangman, Boas, et al., 2002).

The results presented here show that IR imaging is a reliable and valid means of assessing brain activation and changes that occur as a result of targeted brain intervention therapies. Future research into therapies that seek to enhance brain activity and functioning may use IR imaging as a reliable and valid outcome measurement. The importance of this should not be underemphasized. This indicates that moment-to-moment changes and responses to therapeutic interventions can be determined while they are occurring or shortly thereafter. When utilized in a clinical setting, IR imaging can determine the treatment effect of neurofeedback training. IR imaging can assess the maximal beneficial duration of sessions and evaluate therapeutic improvement over time.

Future research should be conducted to replicate these findings with larger sample sizes across a variety of brain-related disorders as well as age ranges. In addition to long-wave IR imaging, NIRS has been utilized as a measure of changes in brain activation. NIRS has excellent temporal resolution and spectroscopic information for hemodynamic events, low cost, and findings that are robust to motion artifacts (Strangman, Boas, et al., 2002). Although long-wave IR imaging may be used as a pre- and postmeasure, it is difficult to apply this technology to training in the moment. NIRS, however, can measure and track brain-related changes as they are occurring during neurofeedback or any task performance.

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