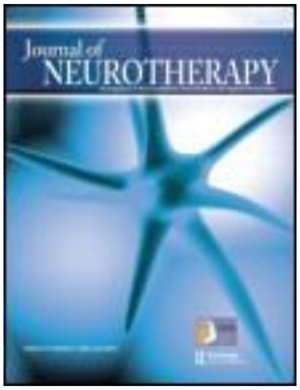

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LONG-TERM EFFECTS OF NEUROFEEDBACK TRAINING IN ANTERIOR CINGULATE CORTEX: A SHORT FOLLOW-UP REPORT

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This report is a follow-up illustrating the long-term absolute power and coherence changes in two participants that completed 30 sessions of training 14–18 Hz in the cognitive division of anterior cingulate gyrus. One female after 7 months and 1 male at 13 months agreed for follow-up EEG procedures. We obtained 3-min eyes-closed and eyes-opened baselines for comparison to pretraining eyes-closed and eyes-opened baselines. We utilized Neuroguide version 2.4 for comparisons. We compared pre- and postpsychometric scores. Analysis of variance procedures show significant differences between the pretraining baselines and follow-up baselines. There are significant differences between pre- and postworking memory and processing speed scores. LORETA neurofeedback in the anterior cingulate cortex appears to induce long-term cortical changes and produces significant positive increases in working memory and processing speed scores.

INTRODUCTION AND METHODS

Long-term effects and follow-up outcomes are by far the most arduous part of any treatment regimen or experimental design. However, for neurofeedback training these are perhaps the most important and necessary components for evidence-based outcomes. In our original research study eight subjects completed thirty-sessions of LORETA neurofeedback (LNFB) training of 14–18 Hz activity in the cognitive division of anterior cingulate (Cannon et al., 2007; Cannon et al., 2006). We were able to obtain two of the eight subjects for follow-up: one female participant 24 years of age at 7 months posttraining and one male participant 23 years of age at 13 months posttraining. We obtained 3-min eyes-closed (ECB) and eyes-opened baselines (EOB) for comparison to pre-training and post-training baselines. We also show the comparison for pre- and post-training ECB and EOB. Participants were prepared for electroencephalographic (EEG) recording using a measure of the distance between the nasion and inion to determine the appropriate cap size for recording (Electro-cap, Inc; Blom & Anneveldt, 1982). The head was measured and marked for cap placement to maintain consistency. The ears and forehead were cleaned for recording with a mild abrasive gel to remove any oil and dirt from the skin. After fitting the caps, each electrode site was injected with electrogel and prepared so that impedances between individual electrodes and each ear were $<6\ K\Omega$. The LNFB training was conducted using the 19-lead-standard international 10/20 system (FP1, FP2, F3, F4,

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We express sincere appreciation to the following: Dr. Robert Thatcher for the contribution of Neuroguide to our lab for use in research and sharing his experience and knowledge with us; Dr. Marco Congedo and Leslie Sherlin for the use of software from NovatechEEG, Inc.; Deymed Diagnostics for the use of their Truscan Acquisition system and LNFB program; ISNR for their financial support and maintaining a venue for continued research; and finally to the participants for their time and effort.
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Fz, F7, F8, C3, C4, Cz, T3, T4, T5, T6, P3, P4, Pz, O1, and O2). Data were collected and stored with a band-pass set at 0.5–64.0 Hz at a rate of 256 samples per second. All recordings and sessions were carried out in a comfortably lit, sound-attenuated room in the Neuropsychology and Brain Research Laboratory at the University of Tennessee, Knoxville. The data were collected utilizing the following frequency band-pass regions: Delta (1.0–3.5 Hz), Theta (3.5–8.0 Hz), Alpha 1 (8.0–10.0 Hz), Alpha 2 (10.0–12.0 Hz), Beta (12.0–32.0 Hz), and trained frequency (TF: 14–18 Hz).

We utilized Neuroguide version 2.4 for absolute power and coherence analyses. The Neuroguide absolute power images show the significant differences between baselines with the colors representing the probability of the obtained *F* value, the red in the images indicating $p \geq .00$, and the blue indicating $p \leq .05$. The interhemispheric coherence images show the *p* for the obtained *F* value. The size of the line indicates the probability of the obtained *F*; the thin line representing values at or less than .05, the middle size line at or less than .025, and the largest line at or less than .01. We compare pre- and postworking memory (WMI) and processing speed (PSI) index scores for each participant utilizing paired *t* tests. The comparisons in Neuroguide are planned comparisons, and thus the need for multiple comparison corrections was not utilized.

RESULTS

We report the results for each participant in the following two subsections. In these sections we discuss absolute power and coherence results. For the coherence we use the two terms *integration effect* and *differentiation effect*. Integration effect refers to increased coherence between electrodes or brain regions and posits that these regions are operating in cooperation, namely, that there is increased communication and function among regions. Differentiation effect refers to neuronal populations operating more independently thereby increasing neuronal complexity.

Participant 1

Figure 1A (1–20 Hz) and B (20–40 Hz) show the results for the follow-up–pretraining ECB comparisons. There are significant differences in delta, theta, and low-alpha frequencies globally. High alpha appears to be specific to middle occipital and frontal regions with increase in right parietal/occipital regions for 10 Hz. The trained frequency 14–18 Hz appears increased in frontal regions with a specific 15 Hz increase over the entire frontal lobe. The higher beta frequencies show increased power in superior frontal regions in 20–25 Hz, with more global effects for 25–40 Hz over the entire cortex. Figure 1C (1–20 Hz) and D (20–40 Hz) show the results for the follow-up–pretraining EOB comparisons. The results show increased delta in temporal regions and global effects for the theta frequency, especially in the 6 Hz range. Low-alpha increase is apparent in left parietal regions. The trained frequency shows increase in the 15, 16, and 17 Hz range specific to left frontal cortex. Figure 1E (1–20 Hz) and F (21–40 Hz) show the results for follow-up compared to posttraining ECB. The results indicate global increased absolute power in delta and theta frequencies and increases in low alpha over the entire frontal regions; however, more specific to the left frontal region. There is significant increase in absolute power in the trained frequency in frontal regions and in the 19 and 20 Hz range. The higher beta frequencies show increased power in most 1 Hz increments favoring frontal and right parietal areas with global increases in 25, 26, and 28 Hz specifically. Figure 1G (1–20 Hz) and H (21–40 Hz) show the follow-up–posttraining EOB comparison. There is significant increase in absolute power in delta and theta frequencies over much of the cortex and favoring frontal regions. The alpha frequency shows increased power in central and posterior regions. The trained frequency shows increased power in frontal and central regions and more specific to left temporal regions in 18, 19, and 20 Hz. The higher beta frequencies show increases specific to superior frontal and

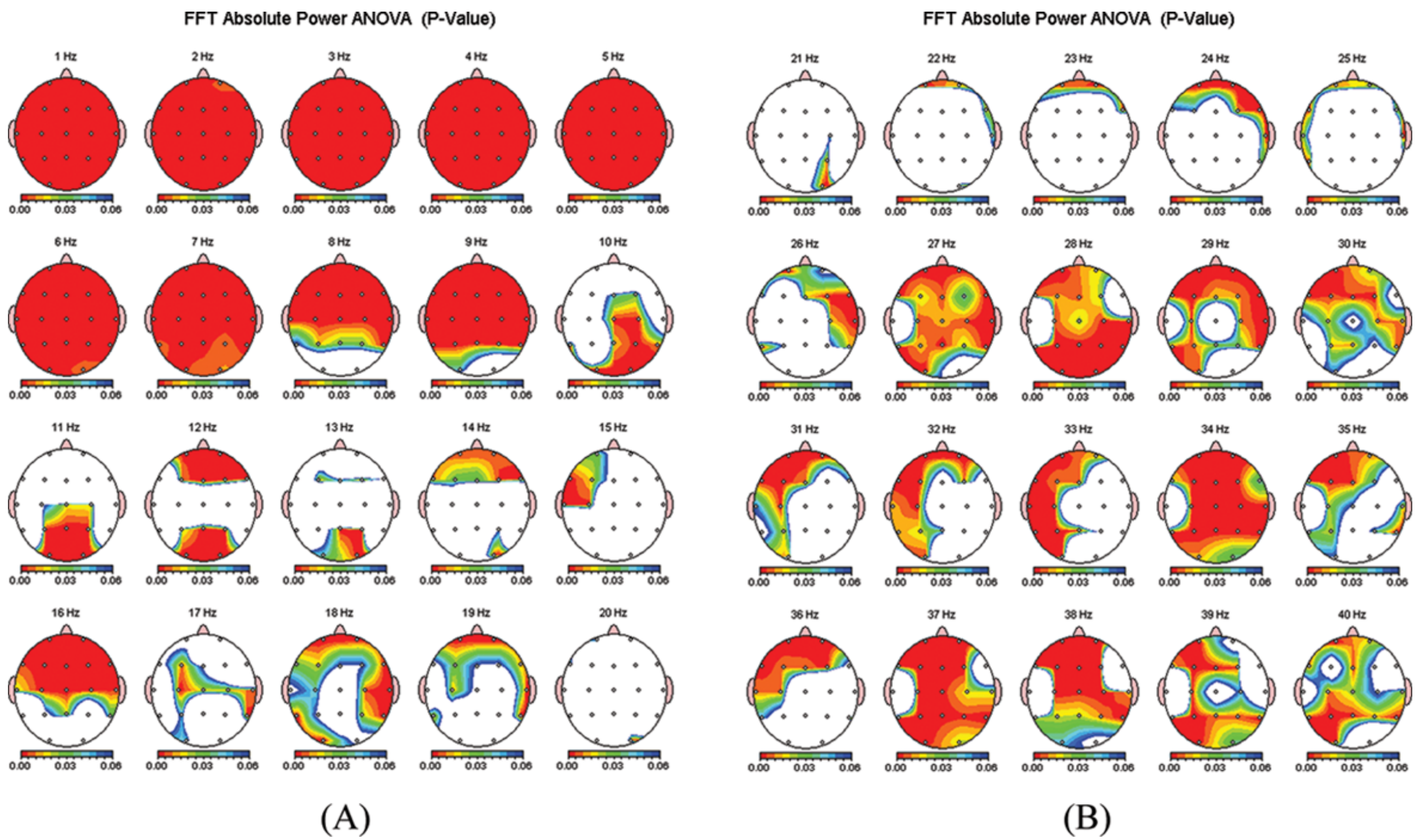
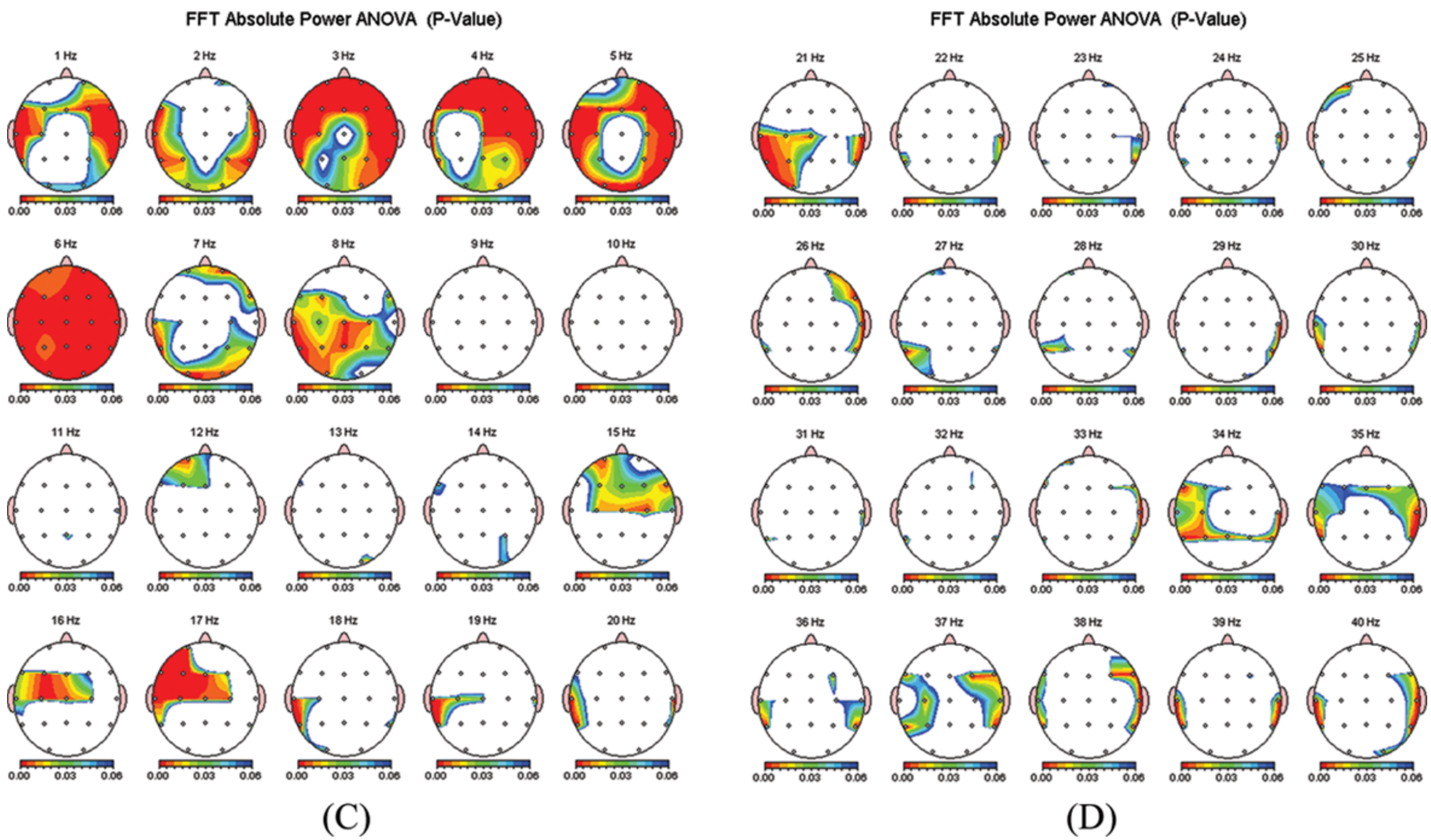


FIGURE 1. Results for follow-up compared to baseline for Participant 1 at 13 months. *Note.* In the figure from left to right and top to bottom are (A) follow-up versus pretraining eyes-closed comparison 1–20 Hz; (B) follow-up versus pretraining eyes-closed comparison 20–40 Hz; (C) follow-up versus pretraining eyes-opened comparison 1 – 20 Hz; (D) follow-up versus pretraining eyes-opened comparison 20–40 Hz; (E) follow-up versus posttraining eyes-closed baseline 1–20 Hz; (F) follow-up versus posttraining eyes-closed baseline 21–40 Hz; (G) follow-up versus posttraining eyes-opened baseline 1–20 Hz; (H) follow-up versus posttraining eyes opened baseline 21–40 Hz; (I) posttraining pretraining eyes-closed baseline 1–20 Hz; (J) posttraining pre-training eyes-closed baseline 21–40 Hz; (K) posttraining pretraining eyes-opened baseline 1–20 Hz; (L) posttraining pretraining eyes-opened baseline 21–40 Hz.



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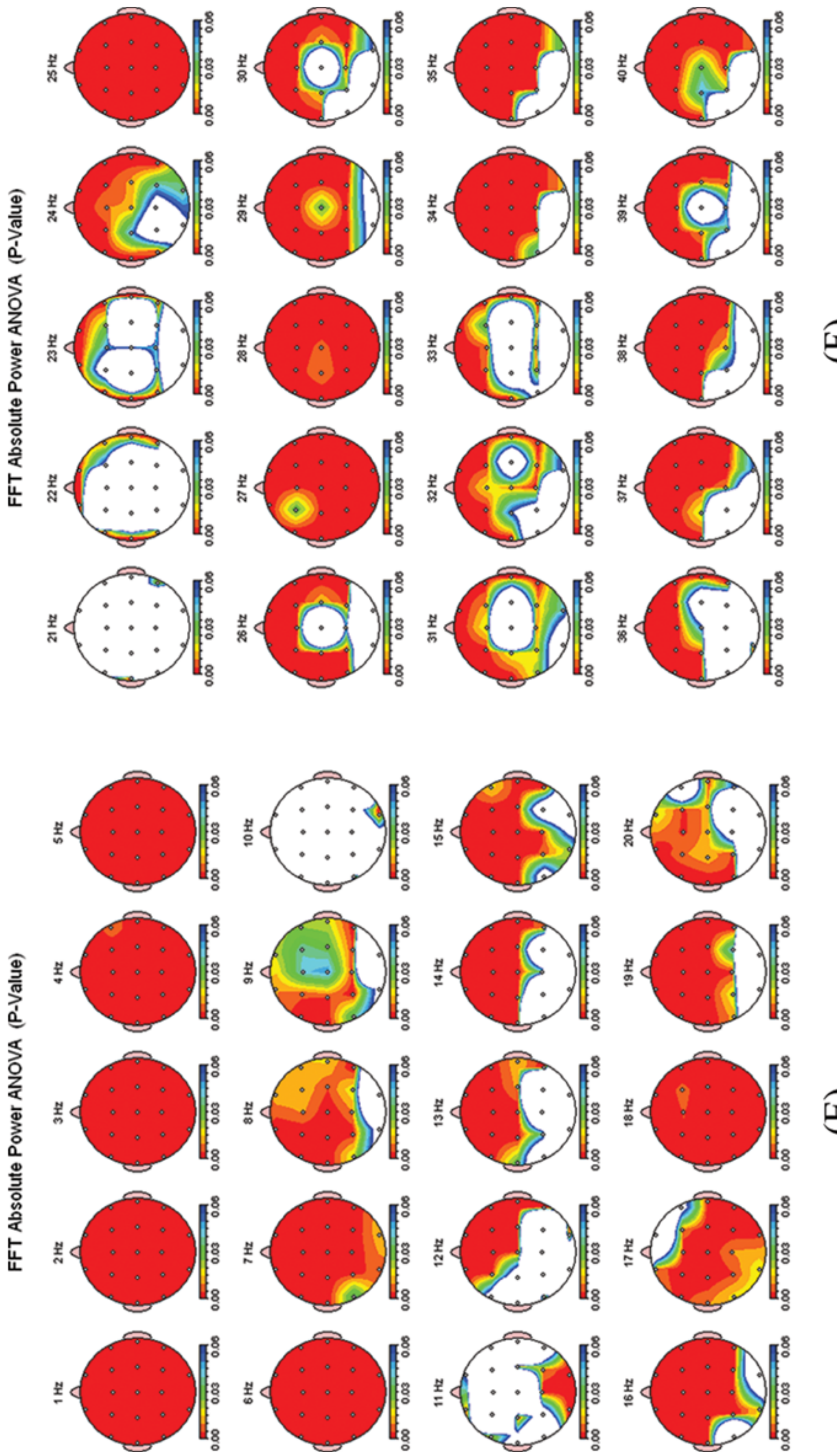

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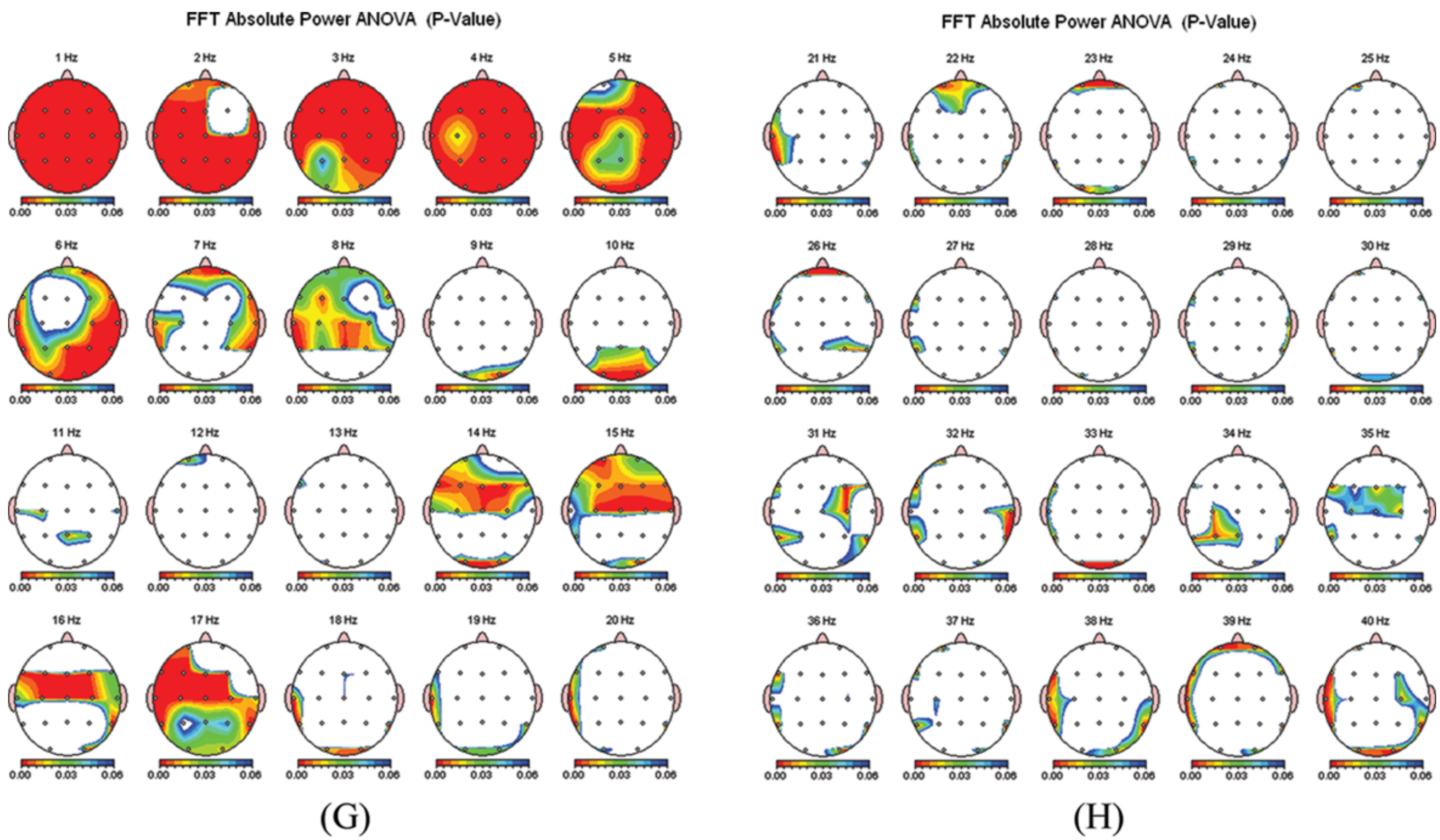

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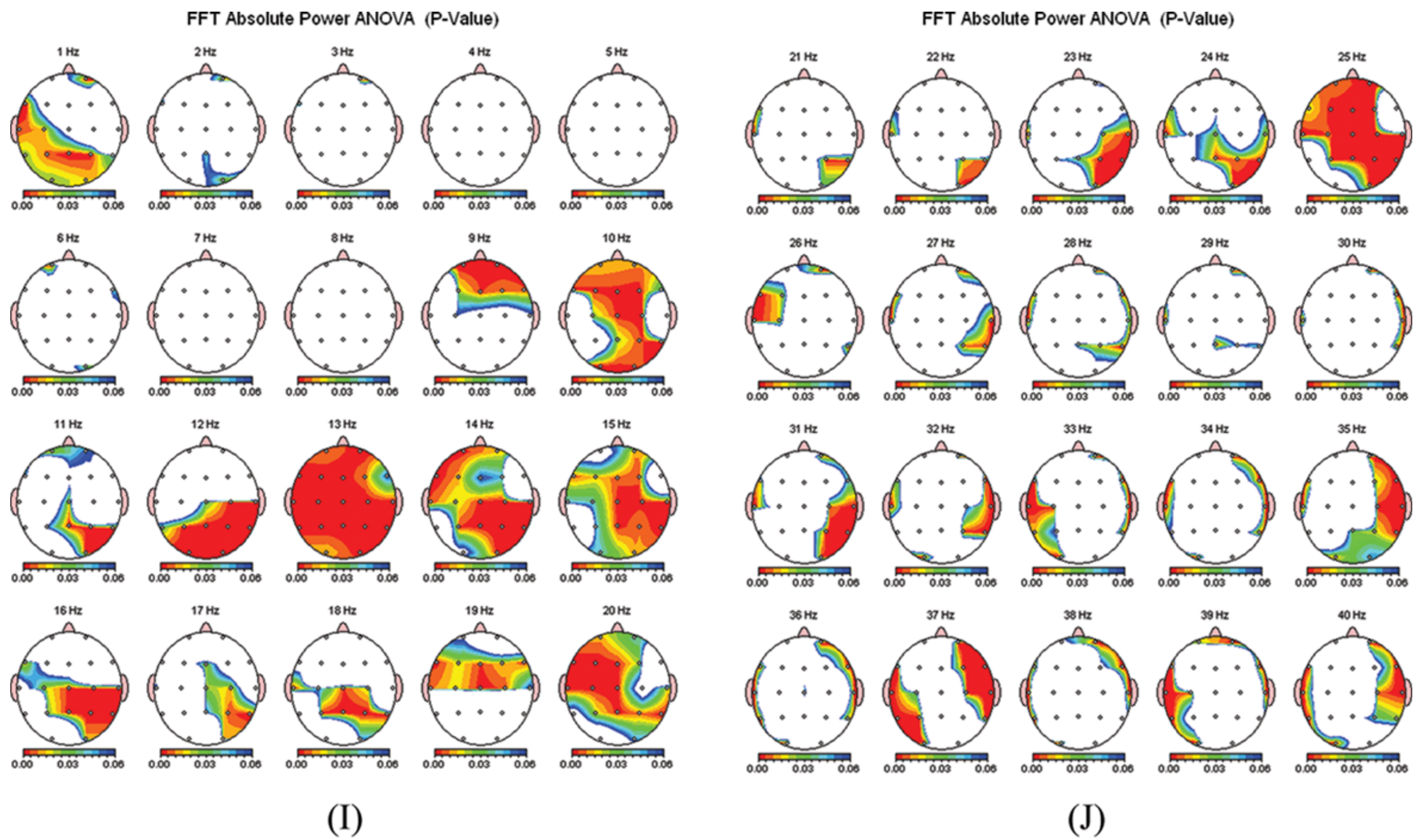

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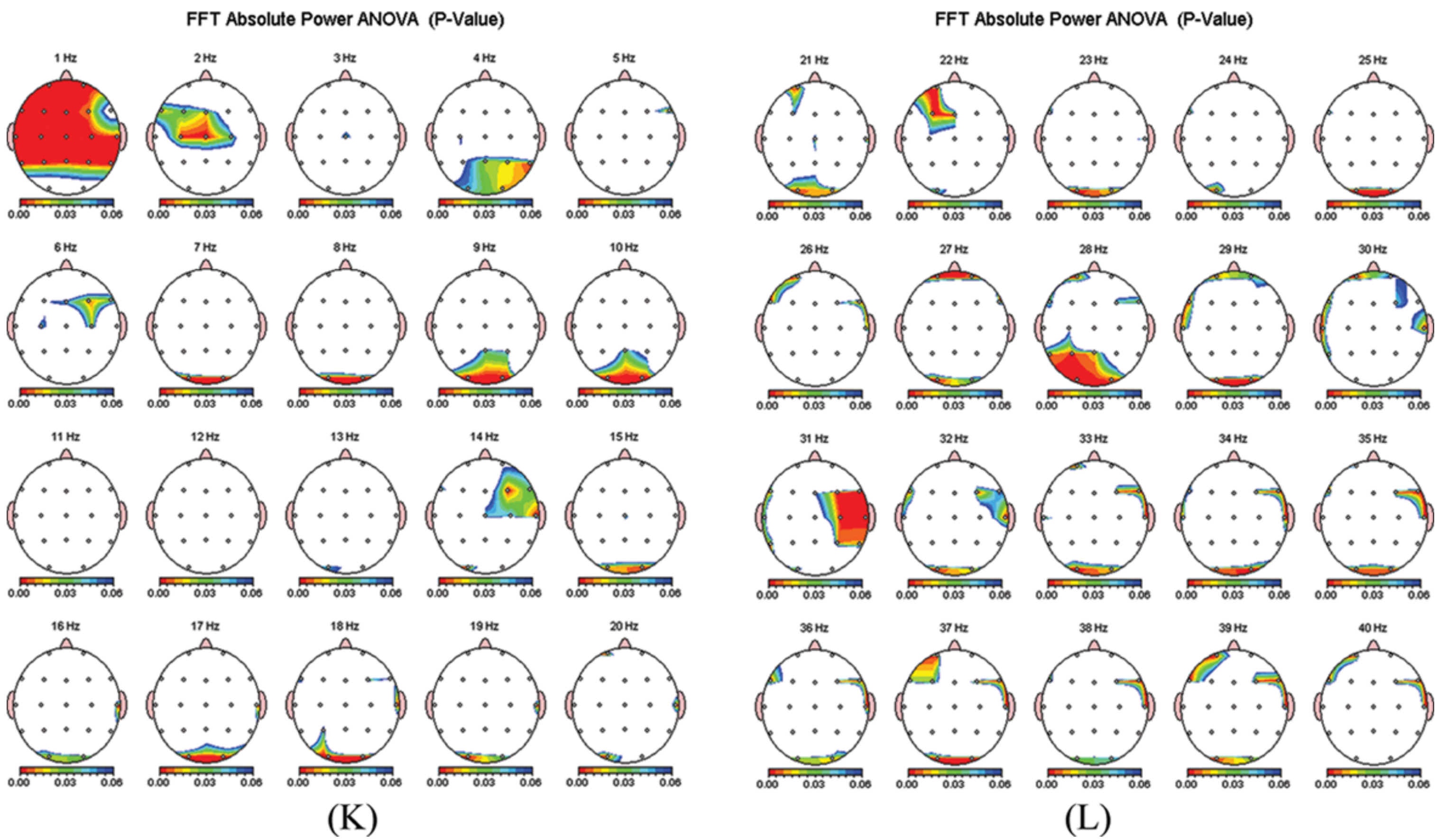


FIGURE 1. Continued.

right central-frontal regions. Figure 1I (1–20 Hz) and J (21–40 Hz) show the results for post–pretraining eyes-closed baseline comparison. The delta frequency shows increased 1 Hz power favoring the left frontal and posterior central, whereas the remaining delta and theta frequencies show no widespread increases. The alpha frequency shows increased power in frontal, central, and right posterior/parietal regions. The 13 Hz frequency shows a global effect, whereas the trained frequency shows increased power in frontal, central, and right parietal regions. The higher beta frequencies show increased power in right parietal and left temporo-frontal regions with 25 Hz showing a near global increase. Figure 1K (1–20 Hz) and L (21–40 Hz) show the results for post–pretraining EOB comparison. The delta frequency shows increased power in 1, 2, and 4 Hz in frontal, central, and right parietal regions. The theta frequency shows increased power in the right frontal and posterior central region. The alpha frequency shows increased power in posterior central region. The trained frequency shows increases in right frontal and posterior regions. The higher beta frequencies show increased power in the left frontal, superior frontal, and posterior parietal regions. Figure 2A (ECB) and B (EOB) show the results for coherence changes between follow-up–pretraining baselines. There appears to be a global integration effect for all frequencies in this comparison. This is a possible effect of the training, in that the individual may be using more areas of the brain at any given time as compared to pretraining. Similarly the comparison of EOB shows integration effects favoring the right hemisphere and a differentiation effect in the left parietal region. Figure 2C (ECB) and D (EOB) show the results for coherence changes between follow-up–posttraining baselines. The results indicate increased coherence over the entire cortex in the delta frequency and significant increases in the theta frequency favoring the left frontal and parietal regions, with a differentiation effect in the right frontal regions. The alpha frequency shows an integration effect similar to the theta frequency. The beta frequency shows a global integration effect, with beta 1 appearing to involve more central, left regions; beta 2 appearing to involve right parietal and right and left prefrontal regions; and beta 3 producing an integration effect globally. Figure 2E (ECB) and F (EOB) show the results for the coherence changes between post–pretraining baseline comparisons. In the ECB comparison the delta frequency shows a differentiation effect in left parietal/posterior regions. The theta frequency shows increased integration of the frontal, central, and right parietal/temporal regions. The EOB comparison shows a differentiation effect in the delta frequency in frontal, central, and posterior regions. The theta frequency shows a differentiation effect in the posterior parietal regions and integration of the right fronto-temporal region. The alpha frequency shows differentiation effects in the left hemisphere and integration within the right temporo-parietal region. The beta 1 frequency shows integration of the right central, frontal, and posterior regions and differentiation in the left frontal regions. The beta 2 frequency shows an integration effect in the right frontal–temporal regions and differentiation in the left hemisphere, as does the beta 3 frequency with longer-range effects. This participant showed a mean 7.5-point increase in working memory and processing speed scores of the Wechsler Adult Intelligence Scale (3rd ed. [WAIS–III]; PsychCorp, 1997). The psychometrics utilized for pre–posttraining measures consisted of the working memory and processing speed index scores of the WAIS–III. This participants' pre-WMI score was 126 and post WMI was 136 (+10, $p < .05$). The pre-PSI score was 106 and post-PSI was 111 (+5, *ns*).

Participant 2

Figure 3A (1–20 Hz) and B (20–40 Hz) show the results for follow-up–pretraining ECB comparison. The delta frequency shows increased power in frontal and left parietal with global increase in the lower end of this frequency domain. The theta frequency shows increased power in left parieto-occipital regions. The alpha frequency shows no change. The beta

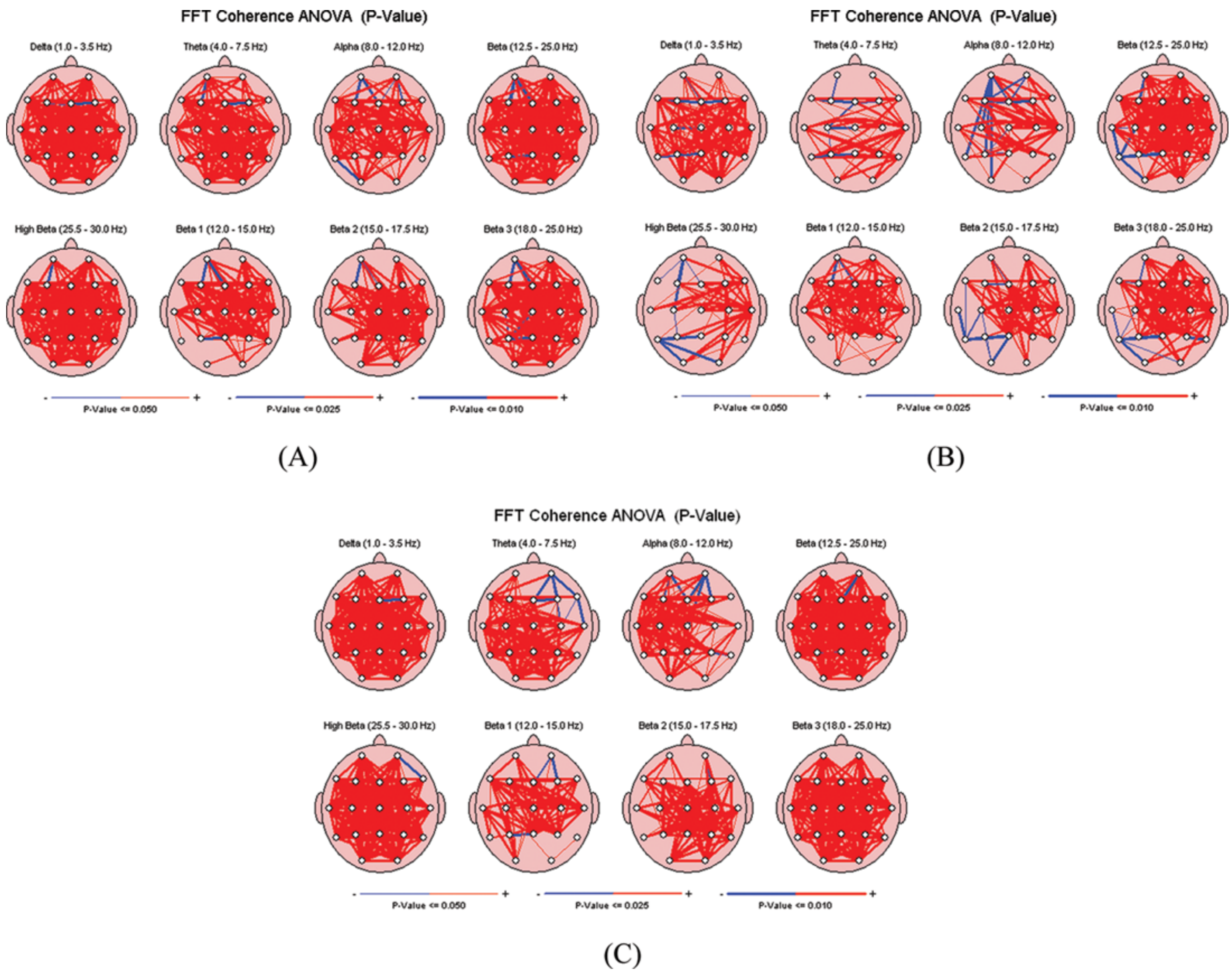
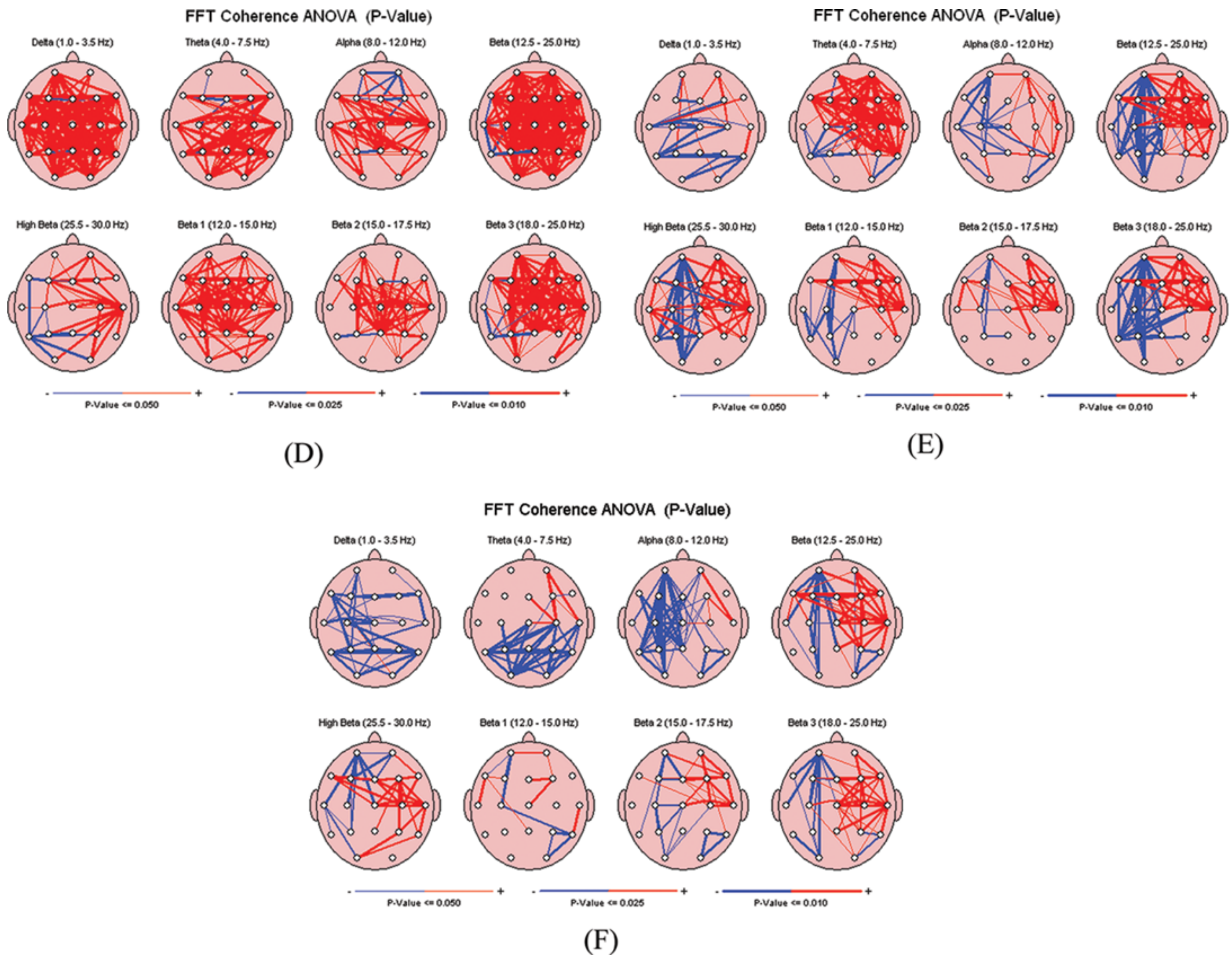


FIGURE 2. Results for Participant 1 coherence comparisons at 13 months. *Note.* In the image from left to right are the comparisons for (A) follow-up versus pretraining eyes-closed baseline; (B) follow-up versus pretraining eyes-opened baseline; (C) follow-up compared to posttraining eyes-closed baseline; (D) follow-up versus posttraining eyes-opened baseline; (E) posttraining versus pretraining eyes-closed baseline; (F) posttraining versus pretraining eyes-opened baseline.



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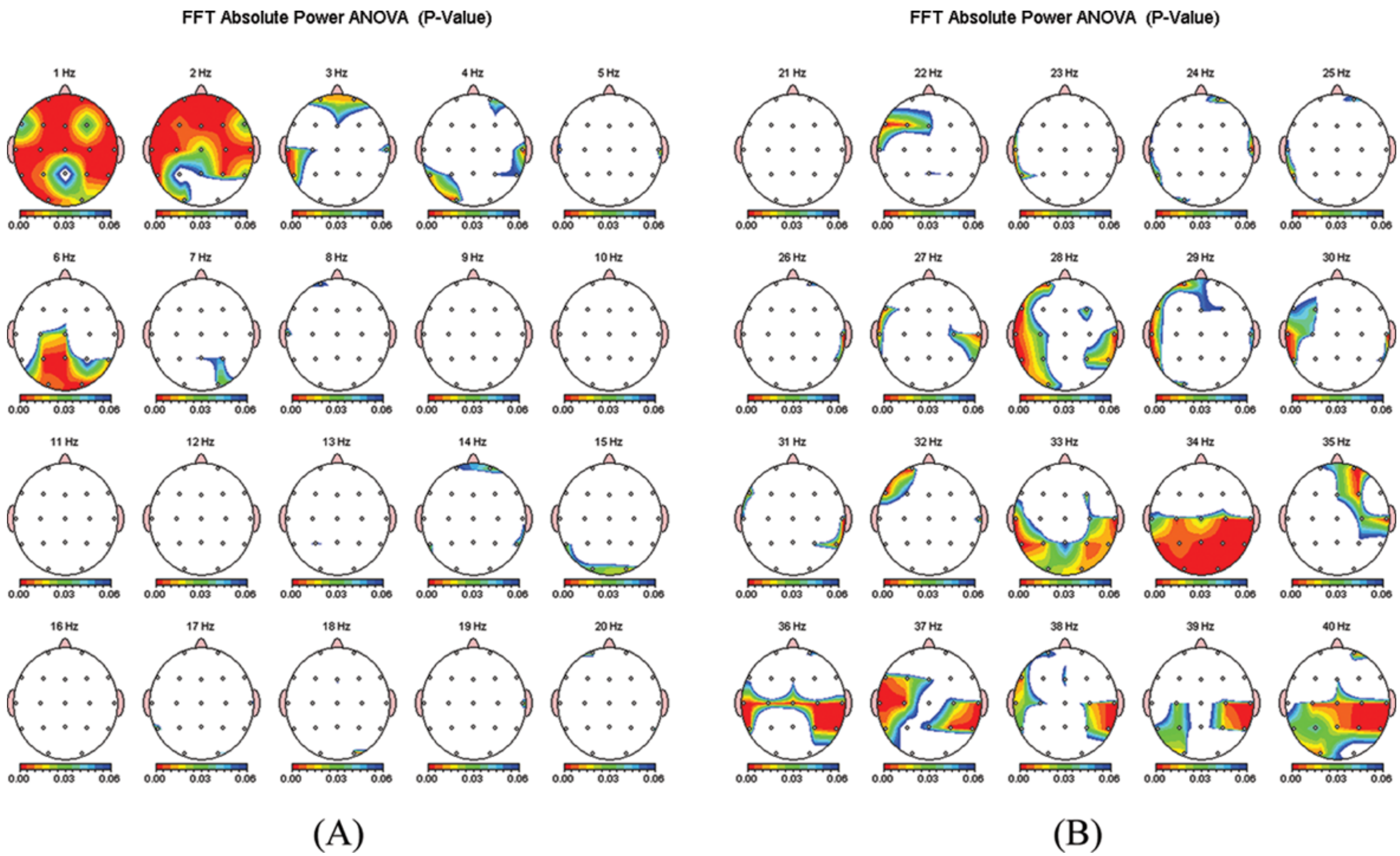
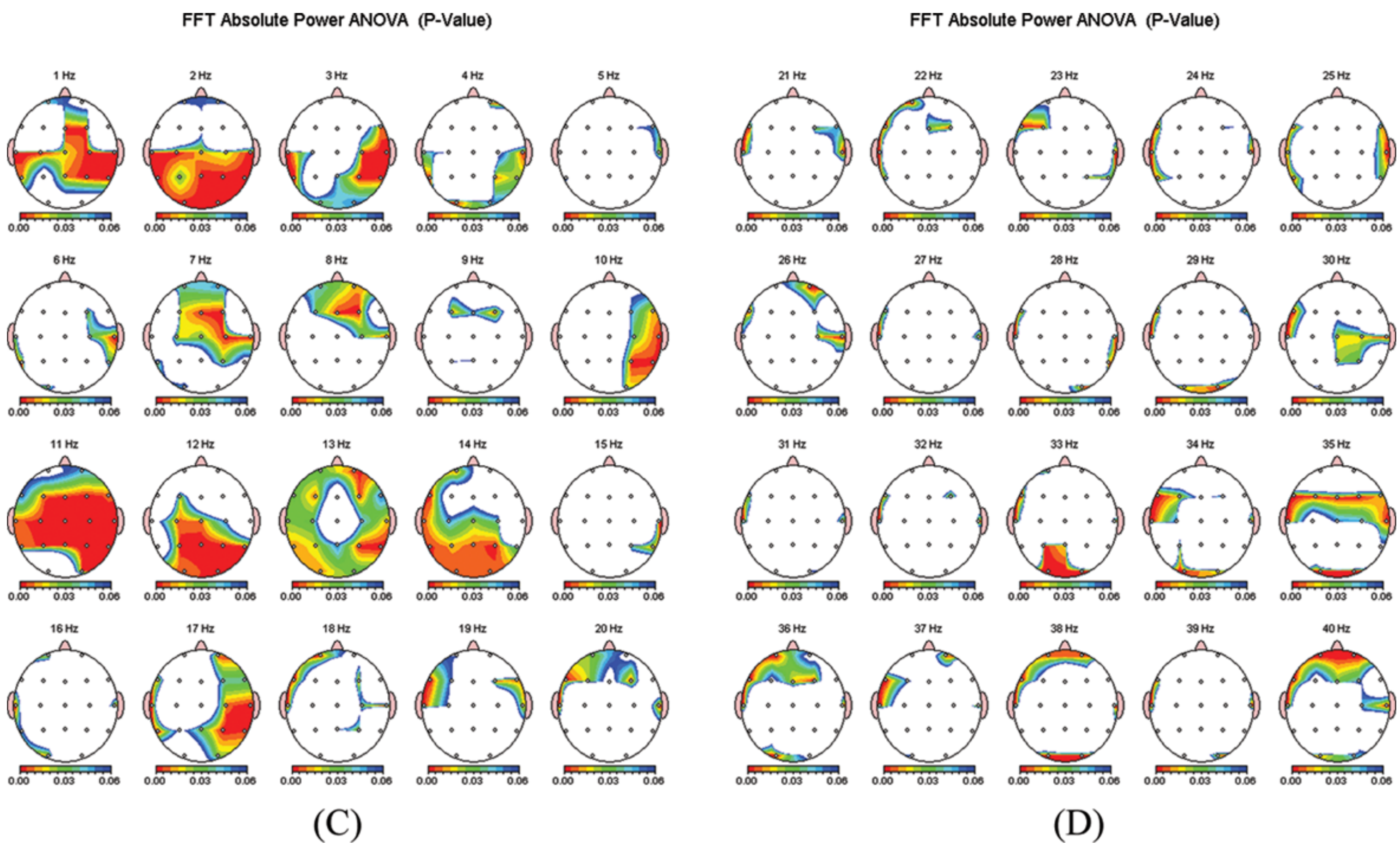


FIGURE 3. Results for follow-up compared to baseline for Participant 2 at 7 months. *Note.* In the figure from left to right and top to bottom are (A) follow-up versus pretraining eyes-closed comparison 1–20 Hz; (B) follow-up versus pretraining eyes-closed comparison 20–40 Hz; (C) follow-up versus pretraining eyes-opened comparison 1–20 Hz; (D) follow-up versus pretraining eyes-opened comparison 20–40 Hz; (E) follow-up versus posttraining eyes-closed baseline 1–20 Hz; (F) follow-up versus posttraining eyes closed baseline 21–40 Hz; (G) follow-up versus posttraining eyes-opened baseline 1–20 Hz; (H) follow-up versus posttraining eyes opened baseline 21–40 Hz; (I) posttraining pretraining eyes-closed baseline 1–20 Hz; (J) posttraining pre-training eyes-closed baseline 21–40 Hz; (K) posttraining pretraining eyes-opened baseline 1–20 Hz; (L) posttraining pretraining eyes-opened baseline 21–40 Hz.



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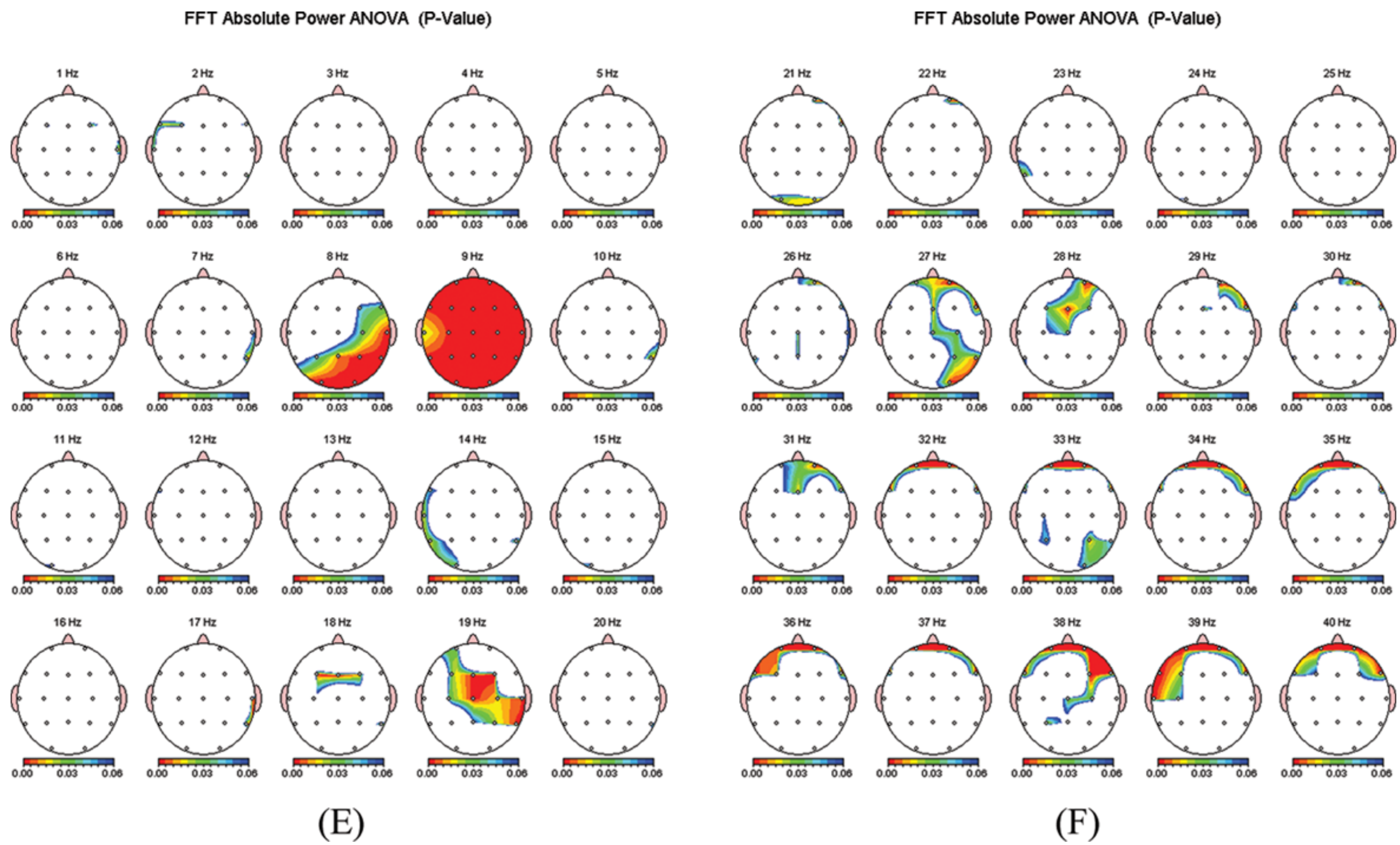

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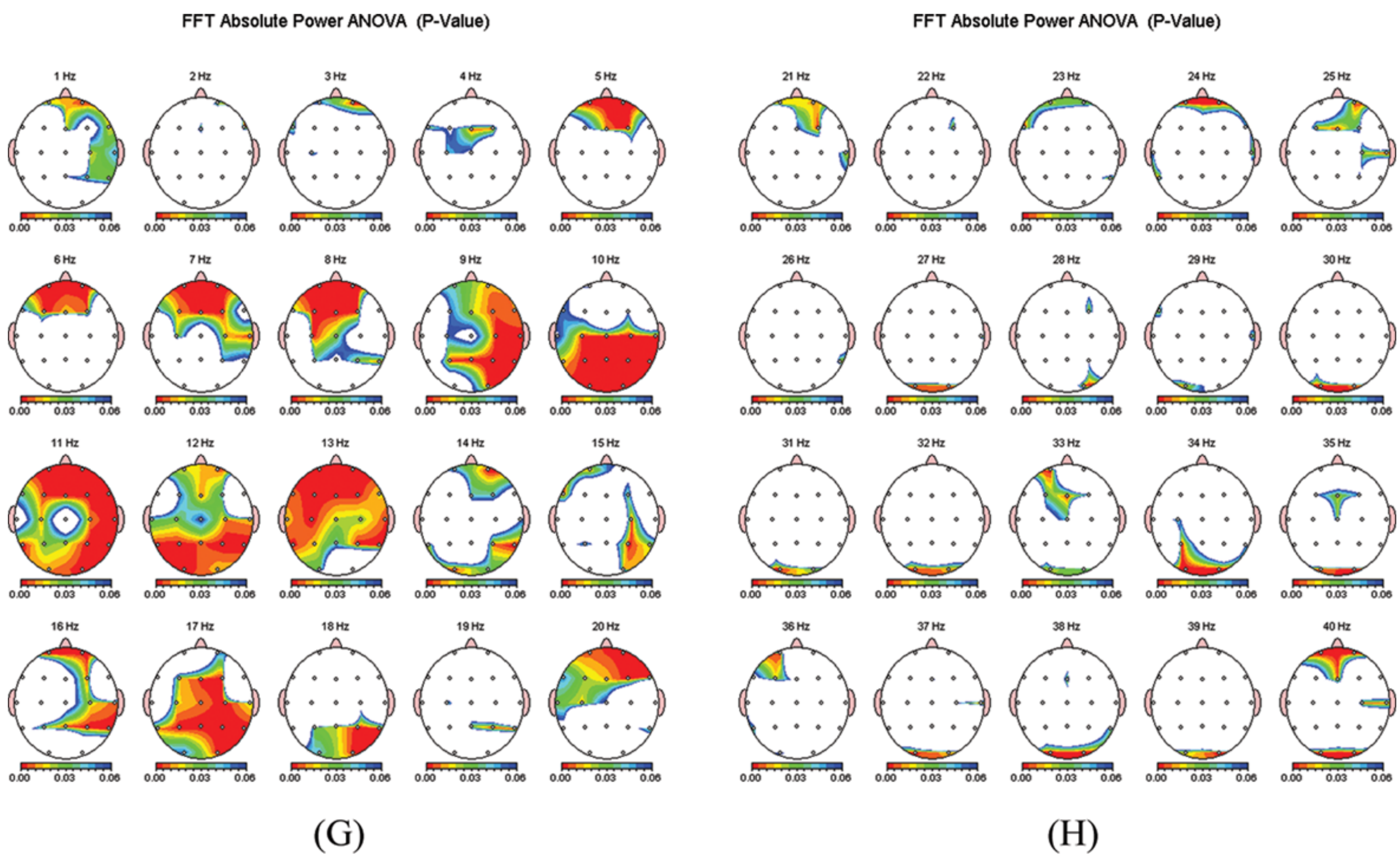

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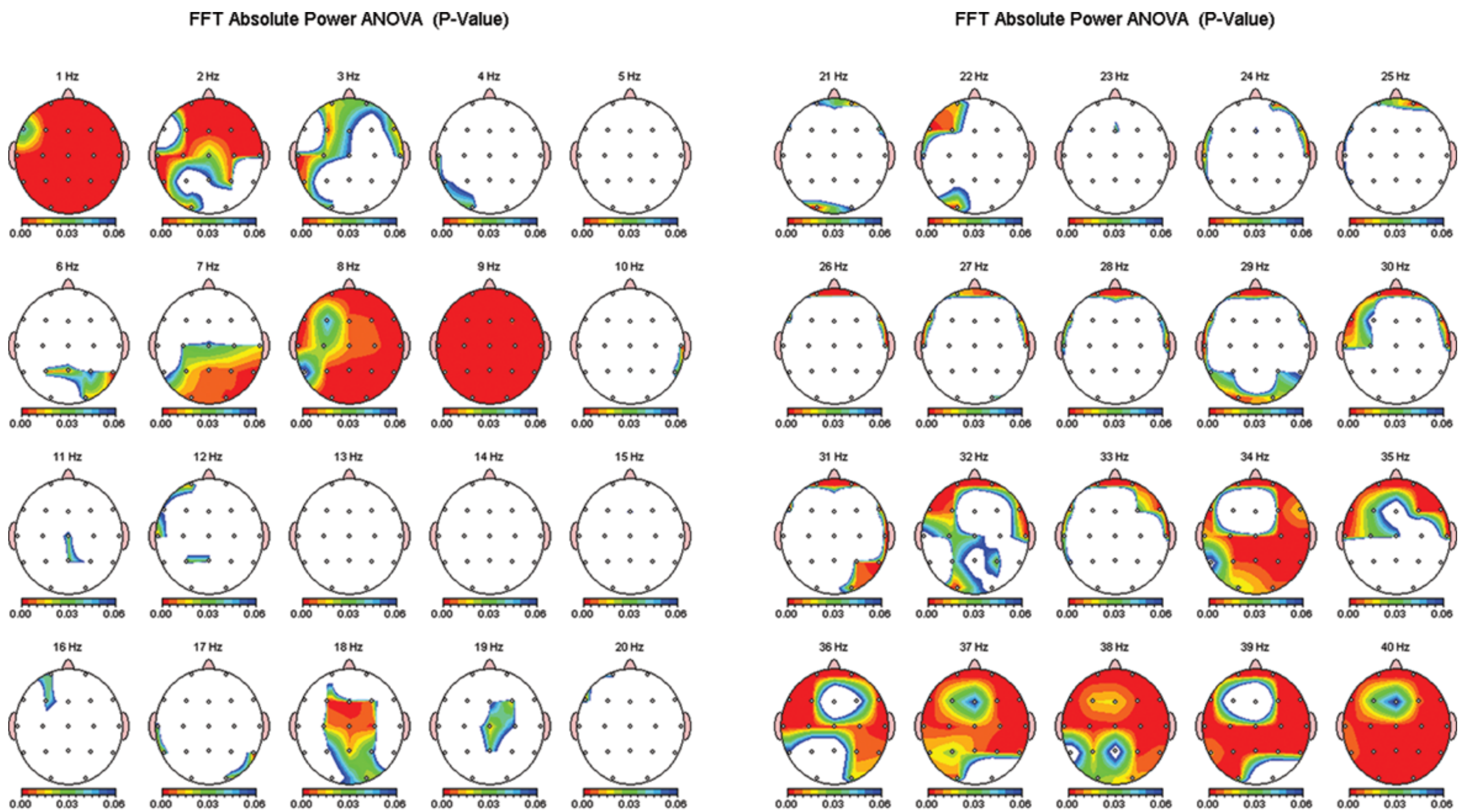

(I)

(J)

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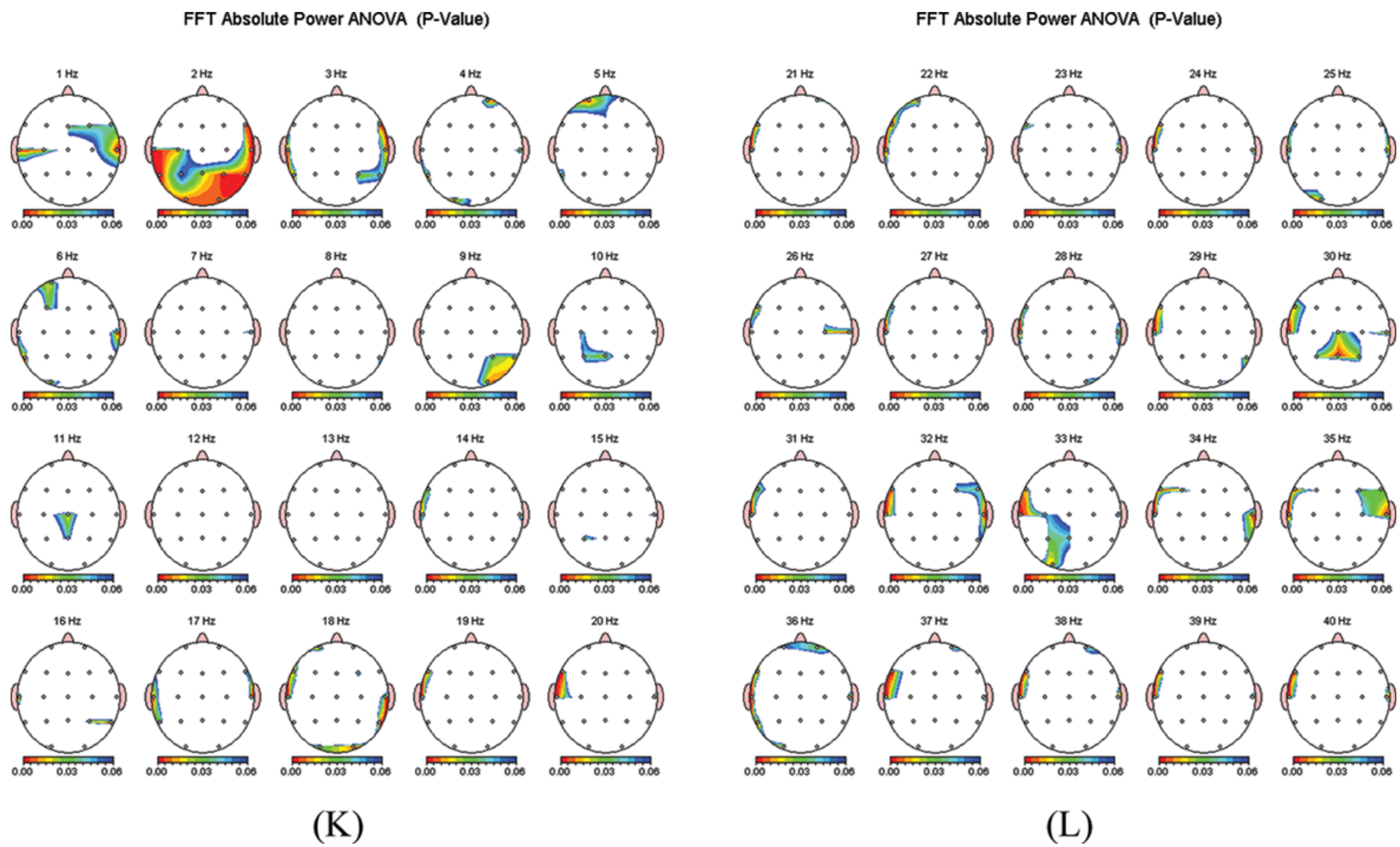

FIGURE 3. Continued.

frequency shows increased power in left and right frontal, right parietal, and occipital cortices. This may reflect network specific increases in absolute power. Figure 3C (1–20 Hz) and D (21–40 Hz) show the results for the follow-up–pretraining EOB comparisons. There is increased delta power in fronto-central, parietal, and occipital regions. The theta frequency shows increased power in temporal and parietal regions in the right hemisphere. The alpha frequency shows a more global increase as do bands within the trained frequency. The beta frequency shows increases to specific regions in superior frontal, temporal, and occipital regions. Figure 3E (1–20 Hz) and F (21–40 Hz) show the results for the follow-up–posttraining ECB comparison. The delta and theta frequencies show no significant differences. The alpha frequency shows a right posterior increase and a global increase in absolute power at 9 Hz. The trained frequency shows increased power in the left temporal at 14 Hz and central (Fz) increase in 18 Hz and 19 Hz from left frontal and central to right temporal/parietal regions. The higher beta frequencies show increases superior frontal regions. Figure 3G (1–20 Hz) and H (21–40 Hz) show the results for the follow-up–post-EOB comparison. There is significant increased power globally in delta and theta frequencies, whereas the alpha frequency shows increase in central and posterior regions. The trained frequency shows increased power in fronto-central regions and the left frontal region in 17 Hz. The higher beta frequencies show increased power in superior frontal and posterior regions. Figure 3I (1–20 Hz) and J (21–40 Hz) show the results for the post–pretraining ECB comparison. The delta frequency shows increased power globally at 1 Hz and in frontal regions. The theta frequency shows increased power n right posterior regions, while the alpha frequency shows increase in 8 and 9 Hz globally. The trained frequency shows increased power in central regions at 16 Hz. The higher beta frequencies show increased power in superior frontal regions; however, in the higher beta 34–40 the increased power appears to include much of the cortex. Figure 3K (1–20 Hz) and L (21–40 Hz) show the post–pretraining EOB comparison. The delta region shows increased power in posterior and temporal regions. The theta frequency shows increased power in left frontal regions. The alpha frequency shows increased power in right parietal regions. The trained frequency shows increase in fronto-temporal regions. The higher beta frequencies show increase in left frontal, central posterior, right temporal-parietal regions. Figure 4A (ECB) and B (EOB) show the results for the coherence changes between follow-up and pretraining baselines. The ECB (A) comparison shows a differentiation effect for the delta frequency, whereas theta, alpha, and beta show integration effects globally; of particular interest is the how the beta 2 and high beta frequencies appear to integrate specific sites. The EOB (B) comparison shows a differentiation effect that appears to involve more regions than the ECB comparison. These effects are prominent in frontal, temporal, and central regions. An integration effect appears to favor the areas except for the right prefrontal cortex. The beta 1 and 2 frequencies show integration effects for specific sites. Figure 4C (ECB) and D (EOB) show the coherence changes between follow-up–posttraining baselines. The ECB (C) comparison shows a differentiation effect in frontal-central-parietal regions with and integration effect occurring in the left temporal and parietal regions. The theta frequency shows and integration effect in left anterior–posterior regions, whereas the right frontal shows a differentiation effect with left frontal-central regions. The alpha frequency shows an integration effect in the left parietal and a differentiation effect in right frontal regions. The beta frequencies tend to follow the other frequencies showing an integration effect in left posterior regions and a differentiation effect within the right frontal region. The EOB (D) comparison shows a larger differentiation effect in delta, theta, alpha, and beta frequencies specific to the frontal lobes, whereas integration shows effects in left temporo-parietal regions. Figure 4E (ECB) and F (EOB) show the post–pretraining comparisons. The ECB

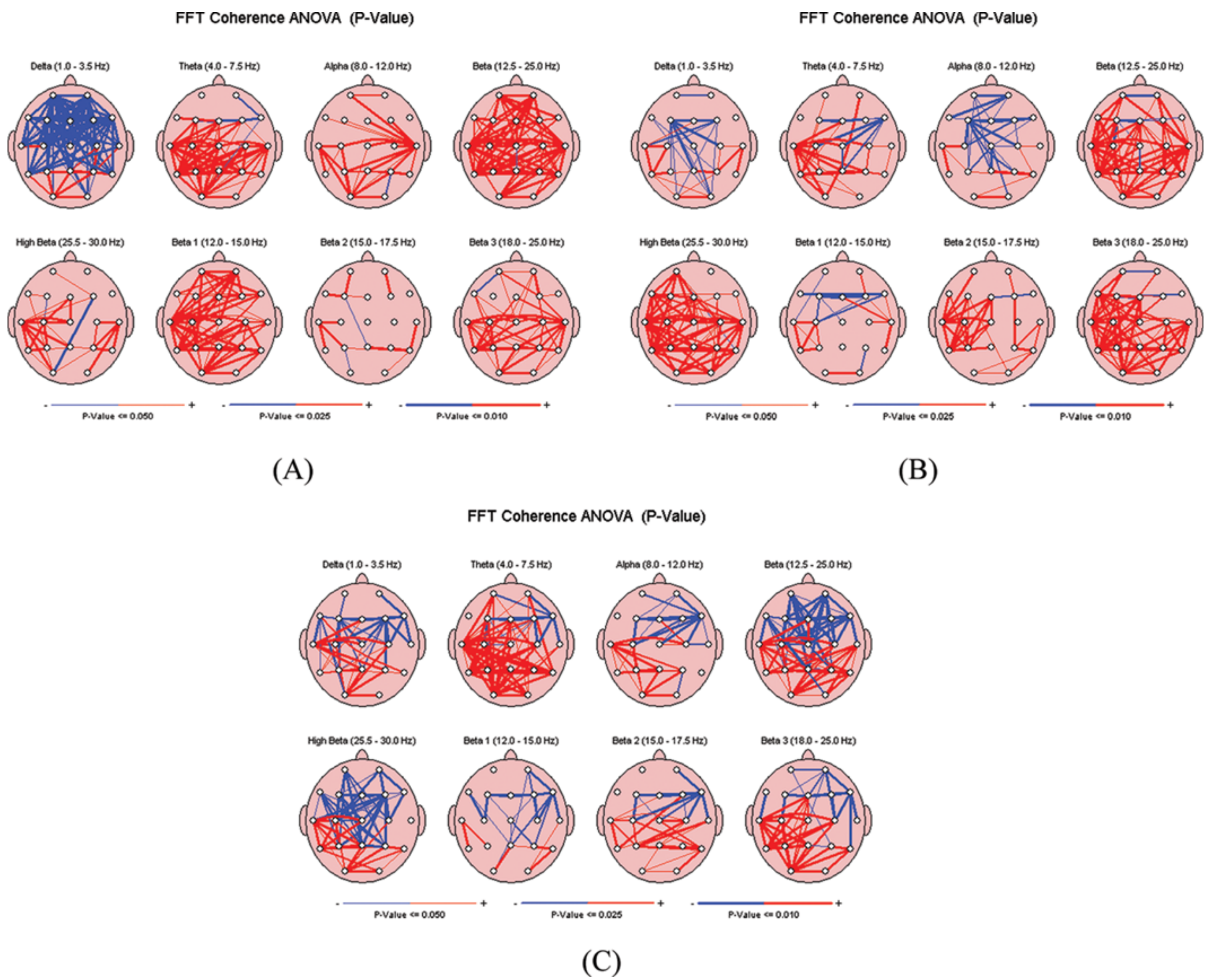

FIGURE 4. Results for Participant 2 interhemispheric coherence comparisons at 7 months. *Note.* In the image from left to right are the comparisons for (A) follow-up versus pretraining eyes-closed baseline; (B) follow-up versus pretraining eyes-opened baseline; (C) follow-up versus posttraining eyes-closed baseline; (D) follow-up versus posttraining eyes-opened baseline; (E) posttraining versus pretraining eyes-closed baseline; (F) posttraining versus pretraining eyes-opened baseline.

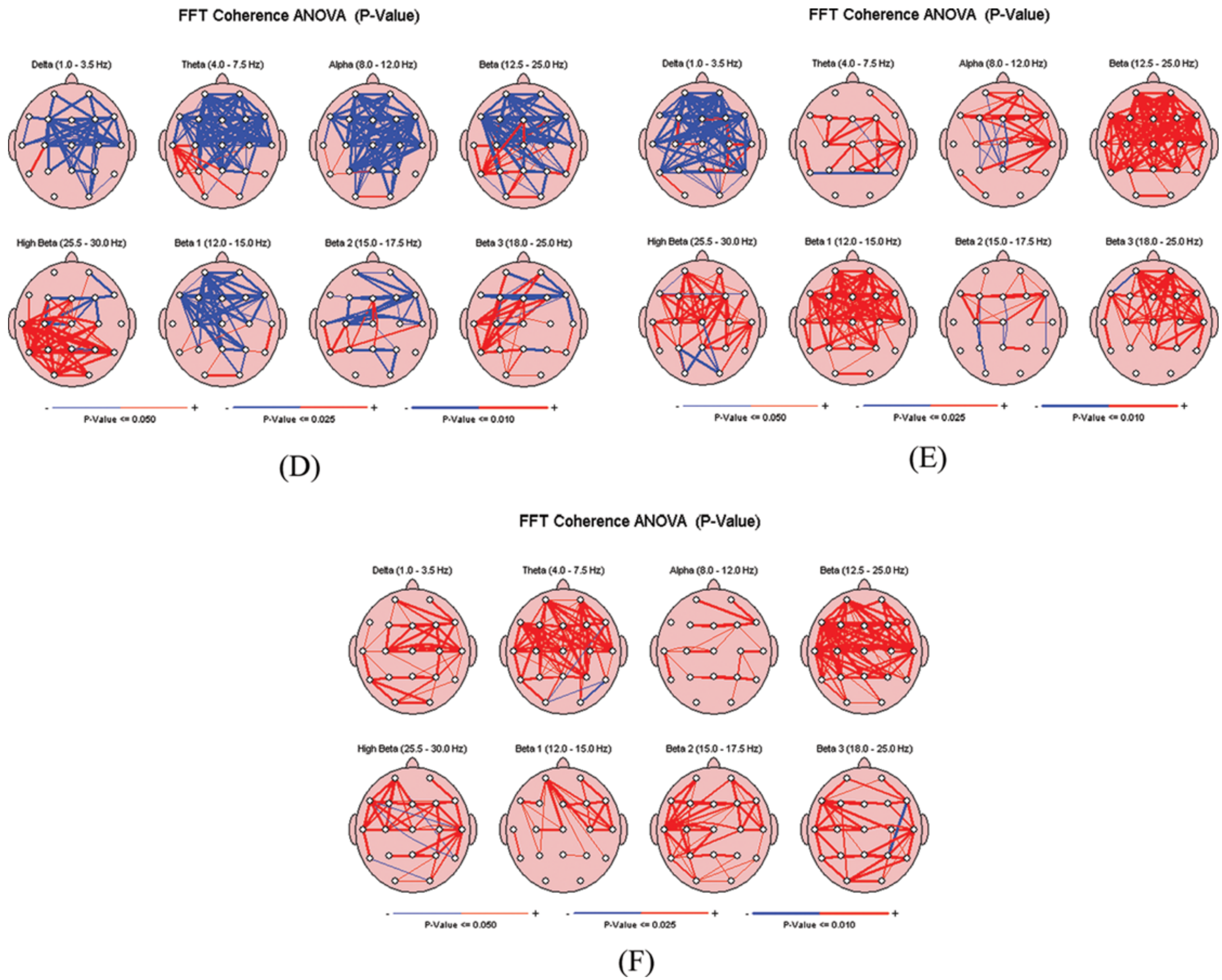

FIGURE 4. Continued.

(E) comparison shows neuronal differentiation within the frontal lobes with specific regions integrating. The theta frequency shows specific integration effect in frontal, temporal, and parietal regions, with differentiation occurring in posterior parietal regions. The alpha and beta frequencies show widespread integration with specific differentiation in posterior central regions. The EOB (F) comparison shows significant integration effects in all frequencies throughout the cortex and apparent specificity of cooperation between neuronal populations in the alpha and beta 1 frequencies. This participant showed a mean 16-point increase in working memory and processing speed scores of the WAIS–III. The psychometrics utilized for pre–posttraining measures (Cannon et al., 2007; Cannon et al., 2007; Congedo, Lubar, & Joffe, 2004) consisted of the working memory and processing speed index scores of the WAIS–III. This participants' pre-WMI score was 109 and post-WMI was 130 (+21, $p < .01$). The pre-PSI score was 117 and post-PSI was 128 (+11, $p < .05$).

DISCUSSION AND CONCLUSION

The data suggest that LNFB produces significant long-term changes in both absolute power and coherence. The increased power in specific frequencies may indicate a global integration effect, as indicated by the coherence changes, namely, delta power is associated with encoding and retrieval processes; theta and alpha are associated with encoding, retrieval, attention, and working memory processes; and beta power is associated with higher order executive processing. The differences between the three comparisons are of particular interest, most noticeably the follow-up compared to posttraining baselines. One might expect there to be minimal changes after training is concluded; however, this does not appear to be the case. In fact, it appears as if the change in absolute power and coherence initiated by LNFB in anterior cingulate cortex progresses on a continuum, because it is shown that EEG remains relatively stable over time (Keil, Stolarova, Heim, Gruber, & Müller, 2003; Näpflin, Wildi, & Sarnthein, 2007). The subjects reported no deleterious effects during the span between recordings; similarly, both subjects reported retaining information more easily and experiencing less anxiety and stress after the training. It would have been beneficial to this study to arrange for a 1-year follow-up for all subjects to include psychometric testing. This will be an aim of future studies. The data indicate, at least with these two participants, that LNFB may have initiated positive changes in memory, attention, and cognition as well as affective processing, which may be a direct result of influencing neural pathways or circuits involving the cognitive division of the anterior cingulate cortex. Similarly, it may be that the integration and differentiation of neuronal populations indicate strengthening of neural networks, which may reflect the very essence of the neurofeedback process. In-depth analysis of the cortical regions apparently influenced by this training is an area for future research.

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