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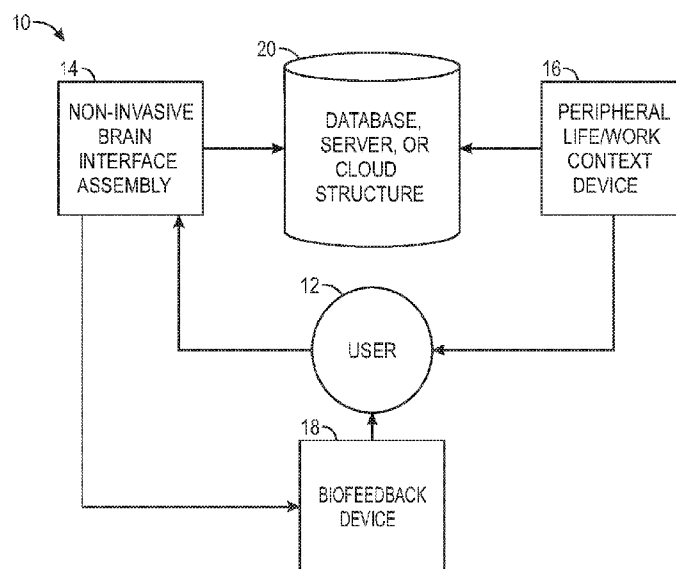


FIG. 1

(57) Abstract: A mental state awareness system (10) comprises a non-invasive brain interface assembly (14) configured for detecting brain activity of a user, a processor configured for determining a mental state of a user based on the detected brain activity, and a biofeedback device (18) configured for automatically providing biofeedback to the user indicative of the determined mental state of the user.

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**BIOFEEDBACK FOR AWARENESS AND MODULATION OF MENTAL STATE
USING A NON-INVASIVE BRAIN INTERFACE SYSTEM AND METHOD**

RELATED APPLICATION DATA

[0001] Pursuant to 35 U.S.C. §119(e), this application claims the benefit of U.S.

5 Provisional Patent Application 62/784,364, filed December 21, 2018, and U.S.
Provisional Patent Application 62/818,786, filed March 15, 2019, which are expressly
incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The present inventions relate to methods and systems for non-invasive
10 measurements in the human body, and in particular, methods and systems related to
detecting a mental state of a human and providing biofeedback of that mental state.

BACKGROUND OF THE INVENTION

[0003] It is generally known that awareness of one's subconscious mental state,
such as anxiety, focus, attention, creativity, positive or negative reflections/attitude
15 on experiences or the use of objects, the employment of certain critical cognitive
brain areas, etc., may lead to better emotional mood regulation and more objective
decision-making. However, the conscious mind typically has peripheral or no
awareness of subconscious mental states. Thus, if a person has a negative or
unhealthy mental state (e.g., anxiety) within the context of a life or work experience,
20 such person may not be aware of such mental state, and therefore, will be unable to
take corrective actions (e.g., modifying or creating a new life or work experience) in
order to alleviate or change this mental state.

[0004] There remains a need to make a person consciously aware of his or her subconscious mental state in a normal life and work environment, so that such human may better regulate his or her emotions or make more objective decisions.

SUMMARY OF THE INVENTION

- 5 **[0005]** In accordance with a first aspect of the present inventions, a mental state awareness system comprises a non-invasive brain interface assembly (e.g., an optical measurement assembly, magnetic measurement assembly, etc.) configured for detecting brain activity from a brain of a user. The non-invasive brain interface assembly may comprise, e.g., at least one detector configured for detecting energy
10 (e.g., optical energy or magnetic energy) from the brain of the user, and processing circuitry configured for identifying the brain activity in response to detecting the energy from the brain of the user. In one embodiment, the non-invasive brain interface assembly comprises a head-worn unit carrying the energy source(s), and an auxiliary non-head-worn unit carrying the processing circuitry.
- 15 **[0006]** The mental state awareness system further comprises a processor configured for determining a mental state of a user (e.g., anxiety, focus, attention, creativity, positive or negative reflections/attitude on experiences or the use of objects, and the employment of certain critical cognitive brain areas) based on the detected brain activity.
- 20 **[0007]** The mental state awareness system further comprises a biofeedback device configured for automatically providing biofeedback to the user indicative of the determined mental state of the user. In one embodiment, the biofeedback device is configured for providing/directing vibrational signals (e.g., encoded with one or more messages) to the user indicative of the determined mental state of the user through
25 peripheral somatosensation. In another embodiment, the biofeedback device is

configured for providing/directing audio or visual signals to the user indicative of the determined mental state of the user.

[0008] The mental state awareness system optionally comprises a peripheral device configured for providing additional life/work context to the user. In one embodiment, the peripheral device is configured for being programmed with one of a plurality of user experiences corresponding to the additional life/work context. In another embodiment, the peripheral device is configured for automatically providing the additional life/work context to the user in response to the determined mental state of the user, such that the mental state of the user is modified. The mental state

awareness system optionally comprises a database, sever, or cloud structure configured for tracking a brain activity history of the user. In this case, the processor may be configured for determining the mental state of the user further based on the tracked brain activity history of the user. The processor may be configured for determining the mental state of the user further based on tracked brain activity of a pool of users and/or tracking life/work context of the user, and acquiring meta data in depth assessment of awareness and behavior modulation patterns of the user.

[0009] In accordance with a second aspect of the present inventions, a method of making user aware of a mental state comprises detecting (e.g., optically detected, magnetically detected, etc.) brain activity from a brain of a user using a non-invasive brain interface. One method further comprises detecting energy from the brain of the user, and identifying the brain activity in response to detecting the energy from the brain of the user.

[0010] The method further comprises determining a mental state of a user (one of anxiety, focus, attention, creativity, positive or negative reflections/attitude on

experiences or the use of objects, and the employment of certain critical cognitive brain areas) based on the detected brain activity.

[0011] The method further comprises automatically providing biofeedback to the user indicative of the determined mental state of the user. In one method, providing
5 biofeedback to the user comprises providing/directing vibrational signals (e.g., encoded with one or more messages) to the user indicative of the determined mental state of the user through peripheral somatosensation. In another method, providing biofeedback to the user comprises providing/directing audio or visual signals to the user indicative of the determined mental state of the user.

10 **[0012]** The method optionally comprises providing additional life/work context to the user via a peripheral device. The additional life/work context may be provided to the user in response to the determined mental state of the user, such that the mental state of the user is modified. The method may further comprise programming the peripheral device with one of a plurality of user experiences corresponding to the
15 additional life/work context.

[0013] The method optionally comprises tracking a brain activity history of the user. In this case, the mental state of the user is may be determined further based on the tracked brain activity history of the user.

[0014] Other and further aspects and features of the invention will be evident from
20 reading the following detailed description of the preferred embodiments, which are intended to illustrate, not limit, the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The drawings illustrate the design and utility of embodiments of the present invention, in which similar elements are referred to by common reference numerals.

25 In order to better appreciate how the above-recited and other advantages and

objects of the present inventions are obtained, a more particular description of the present inventions briefly described above will be rendered by reference to specific embodiments thereof, which are illustrated in the accompanying drawings.

Understanding that these drawings depict only typical embodiments of the invention and are not therefore to be considered limiting of its scope, the invention will be described and explained with additional specificity and detail through the use of the accompanying drawings in which:

[0016] Fig. 1 is a block diagram of a non-invasive mental state awareness system constructed in accordance with one embodiment of the present inventions;

[0017] Fig. 2 is a flow diagram illustrating one method of operating the mental state awareness systems described herein;

[0018] Fig. 3 is a view of one specific embodiment of the non-invasive mental state awareness system of **Fig. 1**;

[0019] Fig. 4 is a view of another specific embodiment of the mental state awareness system of **Fig. 1**;

[0020] Fig. 5A-5D illustrate exemplary non-invasive wearable devices as used with the system of **Fig. 4**;

[0021] Fig. 6 is a view of still another specific embodiment of the mental state awareness system of **Fig. 1**; and

[0022] Fig. 7A-7C illustrate exemplary non-invasive wearable devices as used with the system of **Fig. 6**.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0023] Referring now to **Fig. 1**, a generalized embodiment of a non-invasive mental state awareness system 10 constructed in accordance with the present inventions

will be described. The non-invasive mental state awareness system 10

advantageously closes the loop between brain interfaces and self-awareness and behavior modulation.

[0024] The mental state awareness system 10 comprises a non-invasive brain interface assembly 14 configured for detecting brain activity of a user 12. As will be discussed in further detail below, the brain interface assembly 14 can be optically-based, magnetically-based, or based on any other modality that enables it to non-invasively detect brain activity of the user 12 (i.e., through the intact skin and skull of the user 12), through the use of sensitive electronics, as will be described below, and is designed to be worn by the user 12. As will also be discussed in further detail below, the non-invasive brain interface assembly 14 is portable in that it can be worn by the user 12. The brain interface assembly 14 is also configured for determining a mental state (such as, e.g., anxiety, focus, attention, creativity, positive or negative reflections/attitude on experiences or the use of objects, the employment of certain critical cognitive brain areas, etc.) of the user 12 based on the detected brain activity, although this function can be performed by other processing components in the mental state awareness system 10, as described in further detail below.

[0025] The mental state of the user 12 may be determined based on the detected brain activity in any one of a variety of manners. In one embodiment, a univariate approach in determining the mental state of the user 12 may be performed, i.e., the brain activity can be detected in a plurality (e.g., thousands) of separable cortical modules of the user 12, and the brain activity obtained from each cortical module can be analyzed separately and independently. In another embodiment, a multivariate approach in determining the mental state of the user 12 may be performed, i.e., the brain activity can be detected in a plurality (e.g., thousands) of

separable cortical modules of the user 12, and the full spatial pattern of the brain activity obtained from the cortical modules can be assessed together.

[0026] Any one of a variety of models can be used to classify the mental state of the user 12, and will highly depend on the characteristics of brain activity that are input
5 onto the models. Such characteristics of brain activity may typically be extracted from the spatiotemporal brain activity that is captured, and can include, e.g., location of signal, fine grained pattern within or across locations, amplitude of signal, timing of response to behavior, magnitude of frequency bands of the signal (taking the Fourier transform of the time series), ratio of magnitude of frequency bands, cross-
10 correlation between time series of signal between two or more locations captured simultaneously, spectral coherence between two or more locations captured simultaneously, components that maximize variance, components that maximize non-gaussian similarity, etc. The characteristics of brain activity selected to be input into the models must be considered in reference to univariate and multivariate
15 approaches, since the univariate approach, e.g., focuses on a single location, and therefore will not take advantage of features that correlate multiple locations. The characteristics of the brain activity can be extracted from preprocessed raw data recorded during situations of patterns of thought and perception in everyday life, which are characterized by a continually changing stream of consciousness. The
20 preprocessing of the raw data typically involves filtering the data (either in the time domain or the frequency domain) to smooth, remove noise, and separate different components of signal.

[0027] Selecting a model will be heavily dependent on whether the data is labeled or unlabeled (meaning is it known what the user is doing at the time that the brain
25 activity is detected), as well as many other factors (e.g., is the data assumed to be

normally distributed, is the data assumed relationship linear, is the data assumed relationship non-linear, etc.) Models can include, e.g., support vector machines, expectation maximization techniques, naïve-Bayesian techniques, neural networks, simple statistics (e.g., correlations), deep learning models, pattern classifiers, etc.

5 **[0028]** These models are typically initialized with some training data (meaning that a calibration routine can be performed on the user to determine what the user is doing). If no training information can be acquired, such models can be heuristically initialized based on prior knowledge, and the models can be iteratively optimized with the expectation that optimization will settle to some optimal maximum or
10 minimum solution. Once it is known what the user is doing, the proper characteristics of the neural activity and proper models can be queried. The models may be layered or staged, so that, e.g., a first model focuses on pre-processing data (e.g., filtering), the next model focuses on clustering the pre-processed data to separate certain features that may be recognized to correlate with a known activity
15 performed by the user, and then the next model can query a separate model to determine the mental state based on that user activity.

[0029] As will be described in further detail below, the training data or prior knowledge of the user may be obtained by providing known life/work context to the user. Altogether, the models can be used to track mental state and perception under
20 natural or quasi-natural (i.e., in response to providing known life/work context to the user) and dynamic conditions taking in the time-course of averaged activity and determining the mental state of the user based on constant or spontaneous fluctuations in the characteristics of the brain activity extracted from the data.

[0030] A set of data models that have already been proven, for example in a
25 laboratory setting, can be initially uploaded to the mental state awareness system

10, which system will then use the uploaded models to determine the mental state of the user. Optionally, the mental state awareness system 10 may collect data during actual use with the user, which can then be downloaded and analyzed in a separate server, for example in a laboratory setting, to create new or updated models.

5 Software upgrades, which may include the new or updated models, can be uploaded to the mental state awareness system 10 to provide new or updated data modelling and data collection.

[0031] Further details regarding determining the mental state of a person based on detected brain activity can be found in a variety of peer-reviewed publications. See,

10 e.g., Lee, B.T., Seok, J.H., Lee, B.C, Cho, S.W., Chai, J.H., Choi, I.G., Ham, B.J., “Neural correlates of affective processing in response to sad and angry facial stimuli in patients with major depressive disorder,” Prog Neuropsychopharmacol Biol Psychiatry, 32(3), 778-85 (2008); A.C. Felix-Ortiz, A.C., Burgos-Robles, A., Bhagat, N.D., Leppla, C.A., Tye, K.M., “Bidirectional modulation of anxiety-related and social
15 behaviors by amygdala projections to the medial prefrontal cortex,” Neuroscience 321, 197-209 (2016); Beauregard, M., Levesque, J. & Bourgouin, P., “Neural correlates of conscious self-regulation of emotion,” J. Neurosci. (2001): 21, RC165; Phan, K. L., Wager, T., Taylor, S. F. & Liberzon, I., “Functional neuroanatomy of emotion: a meta-analysis of emotion activation studies in PET and fMRI,”
20 Neuroimage, 16, 331–348 (2002); Canli, T. & Amin, Z., “Neuroimaging of emotion and personality: scientific evidence and ethical considerations,” Brain Cogn., 50, 414–431 (2002), McCloskey, M. S., Phan, K. L. & Coccaro, E. F., “Neuroimaging and personality disorders,” Curr. Psychiatry Rep., 7, 65–72 (2005); Pridmore, S., Chambers, A. & McArthur, M., “Neuroimaging in psychopathy,” Aust. N. Z. J. Psychiatry, 39, 856–865 (2005); Heekeren, H. R., Marrett, S., Bandettini, P. A. &
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Ungerleider, L. G., "A general mechanism for perceptual decision-making in the human brain," Nature, 431, 859–862 (2004); Shin LM, Rauch SL, Pitman RK.

Amygdala, Medial Prefrontal Cortex, and Hippocampal Function in PTSD, Ann N Y Acad Sci., 1071(1) (2006); Lis E, Greenfield B, Henry M, Guile JM, Dougherty G.,

5 "Neuroimaging and genetics of borderline personality disorder: a review," J Psychiatry Neurosci., 32(3), 162–173 (2007); Etkin A, Wager TD, "Functional neuroimaging of anxiety: a meta-analysis of emotional processing in PTSD, social anxiety disorder, and specific phobia," Am J Psychiatry, 164(10), 1476–1488 (2007);

Etkin A. Functional Neuroimaging of Major Depressive Disorder: A Meta-Analysis

10 and New Integration of Baseline Activation and Neural Response Data, Am J Psychiatry, 169(7), 693–703 (2012); Sheline YI, Price JL, Yan Z, Mintun MA,

"Resting-state functional MRI in depression unmasks increased connectivity between networks via the dorsal nexus, Proc Natl Acad Sci., 107(24), 11020–11025 (2010);

Bari A, Robbins TW, "Inhibition and impulsivity: Behavioral and neural basis of

15 response control," Prog Neurobiol., 108:44–79 (2013); Kagias, Konstantinos et al. "Neuronal responses to physiological stress," Frontiers in genetics, 3:222 (2012).

[0032] The mental state awareness system 10 further comprises an optional

peripheral life/work context device 16 (e.g., a Smartphone or tablet computer)

configured for incorporating known life/work context (e.g., GPS tracking, calendar

20 scheduling, means for listening to music, means for listening to a lecture, means for learning a language, means for engaging in video conversations with others located in remote locations, etc.) to promote, adjust and/or calibrate the experience of the user 12.

[0033] For example, based on this known life/work context provided to the user 12

25 via the peripheral life/work context device 16, the quasi-natural conditions that are

contributed to or promoting the actual mental state of the user 12 can be known or better assessed to more accurately determine this mental state.

[0034] As another example, the peripheral life/work context device 16 may provide the known life/work context to the user 12 to automatically promote, adjust, regulate, and/or calibrate the mental state of the user, e.g., anxiety, fear, alertness. For example, if the determined mental state of the user 12 is anxiety, then the peripheral life/work context device 16 may change a music selection to a more soothing melody.

[0035] The experience of the user 12 can also be individually programmed using a manual selection or manual input on the peripheral life/work context device 16 by the user 12. For example, a variety of individual experiences, such as reading, meditation, taking a nap, watching a television program, watching a live theater or musical performance, or the option for programming any other type of individual experience, can be available from the peripheral life/work context device 16 through a menu of selectable options in order to promote, adjust, regulate and/or calibrate the mental state of the user 12. Such experiences can be selected or individually programmed by the user 12, and can be made available through the graphical user interface of the peripheral device 16 through a button, tab, or icon, e.g., through the use of a radio button or similar selectable options, representing one of a set of options of individual experiences.

[0036] The mental state awareness system 10 further comprises a biofeedback device 18 configured for automatically providing biofeedback to the user 12 indicative of the mental state determined by the brain interface assembly 14. In the preferred embodiment, the biofeedback device 18 is configured for providing/directing vibrational (or haptic) signals indicative of the determined mental

state of the user 12 through peripheral somatosensation, e.g., to areas of the user's 12 skin, e.g., arm, wrist, hand, finger, etc., to provide the user 12 convenient awareness recognition of the determined mental state. The biofeedback device 18 may encode different messages by how the vibrations are constructed or modulated in amplitude or frequency. In one embodiment, the vibrations encode speech, e.g., conversations or speech envelopes, or encode speech at a word level, e.g., single vowel, single word, or a combination of single words and vowels. In another embodiment, the vibration modalities may be encoded to mental state type, level, urgency, or other user-relevant information.

[0037] As such, the biofeedback device 18 can serve as brain input through the peripheral nervous (PNS) or sympathetic nervous system (SNS), thereby closing the loop that connects the user's 12 subconscious mental state via brain interfaces by the brain interface assembly 14 to the user's 12 conscious awareness of such mental state. In alternative embodiments, the biofeedback device 18 may be configured for providing/directing audio or visual feedback to the user 12 that may be encoded to signal urgency, levels of mental states, or other user-relevant information, which likewise serves as brain input through the audio or visual nervous system, thereby closing the loop that connects the user's 12 subconscious mental state to the user's 12 conscious awareness of such mental state.

[0038] The mental state awareness system 10 also optionally comprises a database, server, or cloud structure 20 configured for tracking the brain activity of the user 12. For example, the database, server, or cloud structure 20 may be configured to collect raw data (e.g., brain activity data) generated by the brain interface assembly 14. Furthermore, the database, server, or cloud structure 20 (independently of or in conjunction with the mental state determination functions of the brain interface

assembly 14) may be configured for performing a data analysis of the raw data in order to determine the mental state of the user 12.

[0039] For example, if the raw data obtained by the user 12 is being anonymized and stored in the database, server, or cloud structure 20, the data models can be
5 pooled across various users, which deep learning algorithms would benefit from.

The database, server, or cloud structure 20 may be configured for performing cross-correlation analysis of the signal data analysis in order to reduce the pool size of the database and focus subject averaged data to a pool that is similar to the user. Most likely, each user will have a portion of their model optimized to them, but then

10 another portion takes advantage of patterns extracted from a larger pool of users. It should also be appreciated that each user may perform any variety of an infinite number of activities. Thus, even if a user is properly calibrated, such calibration will only be for a small set of infinite possibilities. Generalizing models may comprise various variabilities and optimizing may be difficult. However, by building a large
15 user database on the database, server, or cloud structure 20, a data analysis pipeline connected to such database, server, or cloud structure 20 can preprocess data (clean it up), extract all different kinds of features, and then apply an appropriate data model, to overcome this issue. The brain activity of the user 12 may be tracked with additional life/work context to acquire meta data in depth
20 assessment of awareness and behavior modulation patterns of the user 12.

Although, all of the tracked data analysis has been described as being performed by the database, server, or cloud structure 20, it should be appreciated that at least a portion of the tracked data analysis functionality may be incorporated in the peripheral life/work context device 16, with the caveat that it is preferred that the

tracking of the brain activity between a pool of users be performed by the database, server, or cloud structure 20.

[0040] Having described the structure, function, and application of data models of the mental state awareness system 10, one method 100 of operating the mental state awareness system 10 will now be described.

[0041] Initially, the user 12 may have a subconscious mental state (block 102).

Such mental state may be, e.g., anxiety, although the user 12 may have other mental states, e.g., focus, attention, creativity, positive or negative reflections/attitude on experiences or the use of objects, the employment of certain critical cognitive

brain areas, etc., as discussed above. The anxiety of the user 12 may be broken down into a specific experience (block 104), e.g., anxiety about a thing (block 104a), e.g., rent, mortgage, or credit card payment is due, anxiety about a topic (block 104b), e.g., concerned over the well-being of a parent, being interviewed, presenting or acting in front of an audience, or anxiety about fear (block 104c), e.g., fear of

darkness in unfamiliar spaces, fear of aircraft travel, fear of ocean liner travel, fear of heights. The peripheral life/work context device 16 may incorporate additional life/work context into the experience of the user 12 (e.g., GPS tracking, calendar scheduling, means for listening to music, means for listening to a lecture, means for learning a language, means for engaging in video conversations with others located in remote locations, etc.) (block 106). It should be appreciated that, although the additional life/work context is illustrated as being provided to the user 12 after or during the initial experience that results in the mental state, the additional life/work context can be provided to the user 12 at any time during the method 100.

[0042] The brain interface assembly 14 detects the brain activity of the user 12

(block 108). For example, the brain interface assembly 14 may detect energy (e.g.,

optical energy or magnetic energy) from the brain and through the skull of the user 12, and determine the brain activity in response to detecting the energy from the brain of the user 12. The brain interface assembly 14 (or alternatively, the database, server, or cloud structure 20) then determines the mental state of a user 12 (in this case, anxiety) based on the detected brain activity (block 110).

[0043] The biofeedback device 16 then provides biofeedback to the user 12 indicative of the determined mental state of the user 12 caused by any one of the experiences (block 112). For example, the biofeedback device 16 may provide/direct vibrational signals to the user 12 indicative of the determined mental state of the user 12 through peripheral somatosensation, e.g., vibrational signals encoded with one or more messages, or alternatively, may provide/direct audio or visual signals to the user 12 indicative of the determined mental state of the user 12. Thus, input is provided to the brain of the user 12 to make the user 12 aware of his or her mental state, thereby closing the loop on the experience 108 (block 114). As such, the user 12 may regulate, adjust, and/or calibrate his or her emotions or make more objective decisions (block 116). Furthermore, the peripheral life/work context device 16 may automatically regulate, adjust and/or calibrate the experience of the user 12 based on the determined mental state of the user 12 by, e.g., playing soothing music (block 118).

[0044] Referring to **Fig. 3**, one particular embodiment of a mental state awareness system 10a will now be described. The mental state awareness system 10a comprises an optically-based non-invasive brain interface assembly 14a, which may, e.g., incorporate any one or more of the neural activity detection technologies described in U.S. Patent Application Ser. No. 15/844,370, entitled "Pulsed Ultrasound Modulated Optical Tomography Using Lock-In Camera," U.S. Patent

Application Ser. No. 15/844,398, entitled "Pulsed Ultrasound Modulated Optical Tomography With Increased Optical/Ultrasound Pulse Ratio," U.S. Patent Application Ser. No. 15/844,411, entitled "Optical Detection System For Determining Neural Activity in Brain Based on Water Concentration," U.S. Patent Application Ser. No. 15/853,209, entitled "System and Method For Simultaneously Detecting Phase Modulated Optical Signals," U.S. Patent Application Ser. No. 15/853,538, entitled "Systems and Methods For Quasi-Ballistic Photon Optical Coherence Tomography In Diffusive Scattering Media Using a Lock-In Camera" (now U.S. Patent No. 10,219,700), U.S. Patent Application Ser. No. 16/266,818, entitled "Ultrasound Modulating Optical Tomography Using Reduced Laser Pulse Duration," U.S. Provisional Patent Application Ser. No. 62/657,634, entitled "Balanced Holography Technique For Imaging In Highly Scattering Medium," U.S. Provisional Patent Application Ser. No. 62/692,074, entitled "Frequency Domain Optical Spectroscopy For Neural Decoding," U.S. Provisional Patent Application Ser. No. 62/667,770, entitled "Ultrasound-Mediated Optical Detection," U.S. Provisional Patent Application Ser. No. 62/692,124, entitled "Interferometric Frequency-Swept Source And Detector In A Photonic Integrated Circuit," U.S. Provisional Patent Application Ser. No. 62/726,168, entitled "Single-Shot Spectral-Domain Interferometric Near-Infrared Spectroscopy Based On Orthogonal Dispersion, U.S. Provisional Patent Application Ser. No. 62/719,509, entitled "Interferometric Parallel Detection Of Multiple-Scattered Light With Swept Source Illumination," U.S. Provisional Patent Application Ser. No. 62/740,814, entitled "Coherence Gated Diffuse Correlation Spectroscopy Neural Decoding," U.S. Provisional Patent Application Ser. No. 62/722,152, entitled "Time-Of-Flight Optical Measurement And Decoding Of Fast-Optical Signals," U.S. Provisional Patent Application Ser. No. 62/781,098, entitled "Detection Of Fast-

Neural Signal Using Depth-Resolved Spectroscopy,” U.S. Patent Application Ser. No. 16/226,625, entitled “Spatial and Temporal-Based Diffusive Correlation Spectroscopy Systems and Methods,” and U.S. Provisional Patent Application Ser. No. 62/772,584, entitled “Diffuse Correlation Spectroscopy Measurement Systems and Methods,” which are all expressly incorporated herein by reference.

[0045] The brain interface assembly 14a includes a wearable unit 22a configured for being applied to the user 12, and in this case, worn on the head of the user 12; and an auxiliary head-worn or non-head-worn unit 24a (e.g., worn on the neck, shoulders, chest, or arm). Alternatively, the functionality of the unit 24a may be incorporated into the head-worn unit 22a. The auxiliary non-head-worn unit 24a may be coupled to the head-worn unit 22a via a wired connection 26 (e.g., electrical wires). Alternatively, the brain interface assembly 14a may use a non-wired connection (e.g., wireless radio frequency (RF) signals (e.g., Bluetooth, Wifi, cellular, etc.) or optical links (e.g., fiber optic or infrared (IR)) for providing power to or communicating between the respective head-worn unit 22a and the auxiliary unit 24a.

[0046] The head-worn unit 22a comprises electronic or optical components, such as, e.g., one or more optical sources, an interferometer, one or more optical detector(s) (not shown), etc., an output port 28a for emitting sample light 30 generated by the brain interface assembly 14a into the head of the user 12, an input port 28b configured for receiving neural-encoded signal light 32 from the head of the user 12, which signal light is then detected, modulated and/or processed to determine neural activity within the brain of the user 12, and a support housing structure 34 containing the electronic or optical components, and ports 28a, 28b.

[0047] The support housing structure 34 may be shaped, e.g., have a banana, headband, cap, helmet, beanie, other hat shape, or other shape adjustable and conformable to the user's head, such that the ports 28a, 28b are in close contact with the outer skin of the head, and in this case, the scalp of the user 12. The support housing structure 34 may be made out of any suitable cloth, soft polymer, plastic, hard shell, and/or any other suitable material as may serve a particular implementation. In an alternative embodiment, optical fibers (not shown) may be respectively extended from the ports 28a, 28b, thereby freeing up the requirement that the ports 28a, 28b be disposed in close proximity to the surface of the head. In any event, an index matching fluid may be used to reduce reflection of the light generated by the head-worn unit 22a from the outer skin of the scalp. An adhesive, strap, or belt (not shown) can be used to secure the support housing structure 34 to the head of the user 12.

[0048] The auxiliary unit 24a comprises a housing 36 containing a controller 38 and a processor 40. The controller 38 is configured for controlling the operational functions of the head-worn unit 22a, whereas the processor 40 is configured for processing the neural-encoded signal light 32 acquired by the head-worn unit 22a to detect and localize the neural activity within the brain of the user 12. The auxiliary unit 24a may additionally include a power supply (which if head-worn, may take the form of a rechargeable or non-chargeable battery), a control panel with input/output functions, a display, and memory. Alternatively, power may be provided to the auxiliary unit 24a wirelessly (e.g., by induction).

[0049] The functionalities of the peripheral life/work context device 16, biofeedback device 18, and database, server, or cloud structure 20 may be the same as described above with respect to **Fig. 1**.

[0050] The peripheral life/work context device 16 is coupled to the auxiliary unit 24a of the brain interface assembly 14a (and/or the biofeedback device 18) via a wireless connection 42 (e.g., wireless radio frequency (RF) signals (e.g., Bluetooth, Wifi, cellular, etc.) or optical links (e.g., fiber optic or infrared (IR)) for communicating
5 between the peripheral life/work context device 16 and the brain interface assembly 14a (and/or the biofeedback device 18). Alternatively, a wired connection between the peripheral life/work context device 16 and the brain interface assembly 14a (and/or the biofeedback device 18) may be used.

[0051] The biofeedback device 18 is coupled to the brain interface assembly 14a
10 (and in this case, to the auxiliary unit 24a) via a wired connection 44 (e.g., electrical wires). Alternatively, a non-wired connection (e.g., wireless radio frequency (RF) signals (e.g., Bluetooth, Wifi, cellular, etc.) or optical links (e.g., fiber optic or infrared (IR)) for providing power to or communicating between the respective the auxiliary unit 24a of the brain interface assembly 14a and the biofeedback device 18 may be
15 used.

[0052] The database, server, or cloud structure 20 may be coupled to the auxiliary unit 24a of the brain interface assembly 14a (and/or the peripheral life/work context device 16 and biofeedback device 18) via a wireless connection 46 (e.g., wireless radio frequency (RF) signals (e.g., Bluetooth, Wifi, cellular, etc.) or optical links (e.g.,
20 fiber optic or infrared (IR)) for providing power to or communicating between the biofeedback device 18 and the database, server or cloud structure 20. Alternatively, a wired connection between the database, server, or cloud structure 20 and the auxiliary unit 24a of the brain interface assembly 14a (and/or the peripheral life/work context device 16 and biofeedback device 18) may be used.

[0053] Referring to **Fig. 4**, another particular embodiment of a mental state awareness system 10b will now be described. The mental state awareness system 10b comprises an optically-based non-invasive brain interface assembly 14b, which may, e.g., incorporate any one or more of the neural activity detection technologies described in U.S. Non-Provisional Patent Application Ser. No. 16/051,462, entitled
5 “Fast-Gated Photodetector Architecture Comprising Dual Voltage Sources with a Switch Configuration” (now U.S. Patent No. 10,158,038), U.S. Patent Application Ser. No. 16/202,771, entitled “Non-Invasive Wearable Brain Interface Systems Including a Headgear and a Plurality of Self-Contained Photodetector Units
10 Configured to Removably Attach to the Headgear,” and U.S. Patent Application Ser. No. 16/283,730, entitled “Stacked Photodetector Assemblies,” which are all expressly incorporated herein by reference.

[0054] The brain interface assembly 14b includes a head-worn unit 22b that is configured for being applied to the user 12, and in this case, worn on the head of the
15 user 12; and an auxiliary non-head-worn unit 24b (e.g., worn on the neck, shoulders, chest, or arm). Alternatively, the functionality of the unit 24b may be incorporated into the head-worn unit 22b, as described below. The auxiliary non-head-worn unit 24b may be coupled to the head-worn unit 22b via a wired connection 26 (e.g., electrical wires). Alternatively, the brain interface assembly 14b may use a non-
20 wired connection (e.g., wireless radio frequency (RF) signals (e.g., Bluetooth, Wifi, cellular, etc.) or optical links (e.g., fiber optic or infrared (IR)) for providing power to or communicating between the respective head-worn unit 22b and the auxiliary unit 24b.

[0055] The head-worn unit 22b includes one or more light sources 48 configured for
25 generating light pulses. The light source(s) 48 may be configured for generating one

or more light pulses at one or more wavelengths that may be applied to a desired target (e.g., a target within the brain). The light source(s) 48 may be implemented by any suitable combination of components. For example, light source(s) 48 described herein may be implemented by any suitable device. For example, a light source as
5 used herein may be, for example, a distributed feedback (DFB) laser, a super luminescent diode (SLD), a light emitting diode (LED), a diode-pumped solid-state (DPSS) laser, a laser diode (LD), a super luminescent light emitting diode (sLED), a vertical-cavity surface-emitting laser (VCSEL), a titanium sapphire laser, a micro light emitting diode (mLED), and/or any other suitable laser or light source.

10 **[0056]** The head-worn unit 22b includes a plurality of photodetector units 50, e.g., comprising single-photon avalanche diodes (SPADs) configured for detecting a single photon (i.e., a single particle of optical energy) in each of the light pulses. For example, an array of these sensitive photodetector units can record photons that reflect off of tissue within the brain in response to application of one or more of the
15 light pulses generated by the light sources 48. Based on the time it takes for the photons to be detected by the photodetector units, neural activity and other attributes of the brain can be determined or inferred.

[0057] Photodetector units that employ the properties of a SPAD are capable of capturing individual photons with very high time-of-arrival resolution (a few tens of
20 picoseconds). When photons are absorbed by a SPAD, their energy frees bound charge carriers (electrons and holes) that then become free-carrier pairs. In the presence of an electric field created by a reverse bias voltage applied to the diode, these free-carriers are accelerated through a region of the SPAD, referred to as the multiplication region. As the free carriers travel through the multiplication region,
25 they collide with other carriers bound in the atomic lattice of the semiconductor,

thereby generating more free carriers through a process called impact ionization.

These new free-carriers also become accelerated by the applied electric field and generate yet more free-carriers. This avalanche event can be detected and used to determine an arrival time of the photon. In order to enable detection of a single

5 photon, a SPAD is biased with a reverse bias voltage having a magnitude greater than the magnitude of its breakdown voltage, which is the bias level above which free-carrier generation can become self-sustaining and result in a runaway avalanche. This biasing of the SPAD is referred to as arming the device. When the SPAD is armed, a single free carrier pair created by the absorption of a single
10 photon can create a runaway avalanche resulting in an easily detectable macroscopic current.

[0058] It will be recognized that in some alternative embodiments, the head-worn unit 22b may include a single light source 48 and/or single photodetector unit 50.

For example, brain interface system 14b may be used for controlling a single optical
15 path and for transforming photodetector pixel measurements into an intensity value that represents an optical property of a brain tissue region. In some alternative embodiments, the head-worn unit 22b does not include individual light sources. Instead, a light source configured to generate the light that is detected by the photodetector may be included elsewhere in the brain interface system 14b. For
20 example, a light source may be included in the auxiliary unit 24b.

[0059] The head-worn unit 22b further comprises a support housing structure 52 containing the light source(s) 48, photodetector units 50, and other electronic or optical components. As will be described in further detail below, the support housing structure 52 may be shaped, e.g., have a banana, headband, cap, helmet, beanie,
25 other hat shape, or other shape adjustable and conformable to the user's head, such

that the photodetector units 50 are in close contact with the outer skin of the head, and in this case, the scalp of the user 12. The support housing structure 52 may be made out of any suitable cloth, soft polymer, plastic, hard shell, and/or any other suitable material as may serve a particular implementation.

5 **[0060]** The auxiliary unit 24b comprises the housing 36 containing the controller 38 and the processor 40. The controller 38 is configured for controlling the operational functions of the head-worn unit 22b, whereas the processor 40 is configured for processing the photons acquired by the head-worn unit 22b to detect and localize the neural activity within the brain of the user 12. The auxiliary unit 24b may

10 additionally include a power supply (which if head-worn, may take the form of a rechargeable or non-chargeable battery), a control panel with input/output functions, a display, and memory. Alternatively, power may be provided to the auxiliary unit 24b wirelessly (e.g., by induction).

[0061] The functionalities of the peripheral life/work context device 16, biofeedback
15 device 18, and database, server, or cloud structure 20 may be the same as described above with respect to **Fig. 1**.

[0062] The peripheral life/work context device 16 is coupled to the auxiliary unit 24b of the brain interface assembly 14b (and/or the biofeedback device 18) via a wireless connection 42 (e.g., wireless radio frequency (RF) signals (e.g., Bluetooth, Wifi,
20 cellular, etc.) or optical links (e.g., fiber optic or infrared (IR)) for communicating between the peripheral life/work context device 16 and the brain interface assembly 14b (and/or the biofeedback device 18). Alternatively, a wired connection between the peripheral life/work context device 16 and the brain interface assembly 14c (and/or the biofeedback device 18) may be used.

[0063] The biofeedback device 18 is coupled to the brain interface assembly 14b (and in this case, to the auxiliary unit 24b) via a wired connection 44 (e.g., electrical wires). Alternatively, a non-wired connection (e.g., wireless radio frequency (RF) signals (e.g., Bluetooth, Wifi, cellular, etc.) or optical links (e.g., fiber optic or infrared (IR)) for providing power to or communicating between the respective the auxiliary unit 24b of the brain interface assembly 14c and the biofeedback device 18 may be used.

[0064] The database, server, or cloud structure 20 may be coupled to the auxiliary unit 24b of the brain interface assembly 14b (and/or the peripheral life/work context device 16 and biofeedback device 18) via a wireless connection 46 (e.g., wireless radio frequency (RF) signals (e.g., Bluetooth, Wifi, cellular, etc.) or optical links (e.g., fiber optic or infrared (IR)) for providing power to or communicating between the biofeedback device 18 and the database, server or cloud structure 20. Alternatively, a wired connection between the database, server, or cloud structure 20 and the auxiliary unit 24b of the brain interface assembly 14b (and/or the peripheral life/work context device 16 and biofeedback device 18) may be used.

[0065] Referring now to **Figs. 5A-5D**, different embodiments of the brain interface assembly 14b will be described. Such brain interface assemblies 14b may communicate wirelessly or via wire with the peripheral life/work context device 16, biofeedback device 18, and database, server, cloud structure 20, as described above. Each of the brain interface assemblies 14b described below comprises a head-worn unit 22b having a plurality of photodetector units 50 and a support housing structure 52 in which the photodetector units 50 are embedded. Each of the photodetector units 50 may comprise, e.g., a SPAD, voltage sources, capacitors, switches, and any other circuit components (not shown) required to detect photons.

Each of the brain interface assemblies 14b may also comprise one or more light sources (not shown) for generating light pulses, although the source of such light may be derived from ambient light in some cases. Each of brain interface assemblies 14b may also comprise a control/processing unit 54, such as, e.g., a control circuit, time-to-digital (TDC) converter, and signal processing circuit for controlling the operational functions of the photodetector units 50 and any light source(s), and processing the photons acquired by photodetector units 50 to detect and localize the neural activity within the brain of the user 12. As will be described in further detail below, the control/processing unit 54 may be contained in the head-worn unit 22b or may be incorporated into a self-contained auxiliary unit. As will be set forth below, the support housing structure 52 may be shaped, e.g., have a banana, headband, cap, helmet, beanie, other hat shape, or other shape adjustable and conformable to the user's head, such that the photodetector units 50 are in close contact with the outer skin of the head, and in this case, the scalp of the user 12.

[0066] As shown in **Fig. 5A**, a brain interface assembly 14b(1) comprises a head-worn unit 22b(1) and a power source 56 coupled to the head-worn unit 22b(1) via a power cord 58. The head-worn unit 22b(1) includes the photodetector units 50 (shown as 50-1 through 50-12) and a control/processing unit 54a. The head-worn unit 22b(1) further includes a support housing structure 52a that takes a form of a cap that contains the photodetector units 50 and control/processing unit 54a. The material for the cap 52a may be selected out of any suitable cloth, soft polymer, plastic, hard shell, and/or any other suitable material as may serve a particular implementation. The power source 56 may be implemented by a battery and/or any other type of power source configured to provide operating power to the photodetector units 50, control/processing unit 54a, and any other component

included within the brain interface assembly 22b(1) via the power cord 58. The head-worn unit 22b(1) optionally includes a crest or other protrusion 60 formed in the cap 52a for providing means of carrying a control/processing unit 54a.

[0067] As shown in **Fig. 5B**, a brain interface assembly 14b(2) comprises a head-

worn unit 22b(2) and a control/processing unit 54b coupled to the head-worn unit

22b(2) via a wired connection 62. The head-worn unit 22b(2) includes the

photodetector units 50 (shown as 50-1 through 50-4), and a support housing

structure 52b that takes a form of a helmet containing the photodetector units 50.

The material for the helmet 52b may be selected out of any suitable polymer, plastic,

hard shell, and/or any other suitable material as may serve a particular

implementation. Unlike the control/processing unit 54a of the brain interface

assembly 14b(1) illustrated in **Fig. 5A**, which is contained in the head-worn unit

22b(1), the control/processing unit 54b is self-contained, and may take the form of a

garment (e.g., a vest, partial vest, or harness) for being worn on the shoulders of the

user 12. The self-contained control/processing unit 54b may additionally include a

power supply (which if head-worn, may take the form of a rechargeable or non-

chargeable battery), a control panel with input/output functions, a display, and

memory. Alternatively, power may be provided to the self-contained

control/processing unit 54b wirelessly (e.g., by induction).

[0068] As shown in **Fig. 5C**, a brain interface assembly 14b(3) comprises a head-

worn unit 22b(3) and a power source 56 coupled to the head-worn unit 22b(3) via a

power cord 74. The head-worn unit 22b(3) includes the photodetector units 50

(shown as 50-1 through 50-12) and a control/processing unit 54c. The head-worn

unit 22b(3) further includes a support housing structure 52c that takes a form of a

beanie that contains the photodetector units 50 and control/processing unit 54c. The

material for the beanie 68c may be selected out of any suitable cloth, soft polymer, plastic, and/or any other suitable material as may serve a particular implementation.

The power source 56 may be implemented by a battery and/or any other type of power source configured to provide operating power to the photodetector units 50, control/processing unit 54c, and any other component included within the brain interface assembly 22b(3) via a wired connection 58.

[0069] As shown in **Fig. 5D**, a brain interface assembly 14b(4) comprises a head-worn unit 22b(4) and a control/processing unit 54d coupled to the head-worn unit 22b(4) via a wired connection 62. The head-worn unit 22b(4) includes the

photodetector units 50 (shown as 50-1 through 50-4), and a support housing structure 52d that takes a form of a headband containing the photodetector units 50.

The material for the headband 52d may be selected out of any suitable cloth, soft polymer, plastic, hard shell, and/or any other suitable material as may serve a particular implementation. The control/processing unit 54d is self-contained, and

may take the form of a garment (e.g., a vest, partial vest, or harness) for being worn on the shoulders of the user 12. The self-contained control/processing unit 54d may additionally include a power supply (which if head-worn, may take the form of a rechargeable or non-chargeable battery), a control panel with input/output functions, a display, and memory. Alternatively, power may be provided to the self-contained control/processing unit 54d wirelessly (e.g., by induction).

[0070] Referring to **Fig. 6**, still another particular embodiment of a mental state awareness system 10c will now be described. The mental state awareness system 10c comprises a magnetically-based non-invasive brain interface assembly 14c, which may, e.g., incorporate any one or more of the neural activity detection

technologies described in U.S. Provisional Patent Application Ser. No. 62/689,696,

entitled "Magnetic Field Measurement Systems and Methods of Making and Using," U.S. Provisional Patent Application Ser. No. 62/732,327, entitled "Variable Dynamic Range Optical Magnetometer and Methods of Making and Using", U.S. Provisional Patent Application Ser. No. 62/741,777, entitled, "Integrated Gas Cell and Optical Components for Atomic Magnetometry and Methods for Making and Using," U.S. Provisional Patent Application Ser. No. 62/752,067, entitled "Magnetic Field Shaping Components for Magnetic Field Measurement Systems and Methods for Making and Using," U.S. Patent Application Ser. No. 16/213,980, entitled "Systems and Methods Including Multi-Mode Operation of Optically Pumped Magnetometer(S)," U.S. Provisional Patent Application Ser. No. 62/732,791, entitled "Dynamic Magnetic Shielding and Beamforming Using Ferrofluid for Compact Magnetoencephalography (MEG)," U.S. Provisional Patent Application Ser. No. 62/796,958, entitled "Optically Pumped Magnetometer with Amplitude-Selective Magnetic Shield," and U.S. Provisional Patent Application Ser. No. 62/804,539, entitled "Neural Bandpass Filters for Enhanced Dynamic Range Magnetoencephalography (MEG) Systems and Methods," which are all expressly incorporated herein by reference.

[0071] The brain interface assembly 14c includes a magnetoencephalography (MEG) head-worn unit 22c that is configured for being applied to the user 12, and in this case, worn on the head of the user 12; and an auxiliary non-head-worn unit 24c (e.g., worn on the neck, shoulders, chest, or arm). Alternatively, the functionality of the unit 24c may be incorporated into the head-worn unit 22c, as described below. The auxiliary non-head-worn unit 24c may be coupled to the head-worn unit 22c via a wired connection 26 (e.g., electrical wires). Alternatively, the brain interface assembly 14c may use a non-wired connection (e.g., wireless radio frequency (RF) signals (e.g., Bluetooth, Wifi, cellular, etc.) or optical links (e.g., fiber optic or infrared

(IR)) for providing power to or communicating between the respective head-worn unit 22c and the auxiliary unit 24c.

[0072] The head-worn unit 22c includes a plurality of optically pumped magnetometers (OPMs) 64 or other suitable magnetometers to measure biologically generated magnetic fields from the brain of the user 12 and a passive shield 66 (and/or flux concentrators). By placing the passive shield 66 over the head of the user 12, the ambient background magnetic field arising from areas outside the passive shield 66 is greatly decreased and the magnetometers 64 can measure or detect magnetic fields from activity occurring in the brain of the user 12 due to the reduction in the ambient background magnetic field.

[0073] An OPM is an optical magnetometry system used to detect a magnetic field that propagates through the human head. Optical magnetometry can include the use of optical methods to measure a magnetic field with very high accuracy—on the order of 1×10^{-15} Tesla. Of particular interest for their high-sensitivity, an OPM can be used in optical magnetometry to measure weak magnetic fields. (The Earth's magnetic field is typically around 50 micro Tesla). In at least some systems, the OPM has an alkali vapor gas cell that contains alkali metal atoms in a combination of gas, liquid, or solid states (depending on temperature). The gas cell may contain a quenching gas, buffer gas, or specialized anti-relaxation coatings or any combination thereof. The size of the gas cells can vary from a fraction of a millimeter up to several centimeters, allowing the practicality of OPMs to be used with wearable non-invasive brain interface devices.

[0074] The head-worn unit 22c further comprises a support housing structure 68 containing the OPMs 64, passive shield 66, and other electronic or magnetic components. As will be described in further detail below, the support housing

structure 84 may be shaped, e.g., have a banana, headband, cap, helmet, beanie, other hat shape, or other shape adjustable and conformable to the user's head, such that the OPMs 64 are in close contact with the outer skin of the head, and in this case, the scalp of the user 12. The support housing structure 68 may be made out
5 of any suitable cloth, soft polymer, plastic, hard shell, and/or any other suitable material as may serve a particular implementation.

[0075] The auxiliary unit 24c comprises the housing 36 containing the controller 38 and the processor 40. The controller 38 is configured for controlling the operational functions of the head-worn unit 22c, whereas the processor 40 is configured for
10 processing the magnetic fields detected by the head-worn unit 22c to detect and localize the neural activity within the brain of the user 12. The auxiliary unit 24c may additionally include a power supply (which if head-worn, may take the form of a rechargeable or non-chargeable battery), a control panel with input/output functions, a display, and memory. Alternatively, power may be provided to the auxiliary unit
15 24c wirelessly (e.g., by induction).

[0076] The functionalities of the peripheral life/work context device 16, biofeedback device 18, and database, server, or cloud structure 20 may be the same as described above with respect to **Fig. 1**.

[0077] The peripheral life/work context device 16 is coupled to the auxiliary unit 24c
20 of the brain interface assembly 14c (and/or the biofeedback device 18) via a wireless connection 42 (e.g., wireless radio frequency (RF) signals (e.g., Bluetooth, Wifi, cellular, etc.) or optical links (e.g., fiber optic or infrared (IR)) for communicating between the peripheral life/work context device 16 and the brain interface assembly 14c (and/or the biofeedback device 18). Alternatively, a wired connection between

the peripheral life/work context device 16 and the brain interface assembly 14c (and/or the biofeedback device 18) may be used.

[0078] The biofeedback device 18 is coupled to the brain interface assembly 14c (and in this case, to the auxiliary unit 24c) via a wired connection 44 (e.g., electrical wires). Alternatively, a non-wired connection (e.g., wireless radio frequency (RF) signals (e.g., Bluetooth, Wifi, cellular, etc.) or optical links (e.g., fiber optic or infrared (IR)) for providing power to or communicating between the respective the auxiliary unit 24c of the brain interface assembly 14c and the biofeedback device 18 may be used.

[0079] The database, server, or cloud structure 20 may be coupled to the auxiliary unit 24b of the brain interface assembly 14c (and/or the peripheral life/work context device 16 and biofeedback device 18) via a wireless connection 46 (e.g., wireless radio frequency (RF) signals (e.g., Bluetooth, Wifi, cellular, etc.) or optical links (e.g., fiber optic or infrared (IR)) for providing power to or communicating between the biofeedback device 18 and the database, server or cloud structure 20. Alternatively, a wired connection between the database, server, or cloud structure 20 and the auxiliary unit 24c of the brain interface assembly 14c (and/or the peripheral life/work context device 16 and biofeedback device 18) may be used.

[0080] Referring now to **Figs. 7A-7C**, different embodiments of the brain interface assembly 14c will be described. Such brain interface assemblies 14c may communicate wirelessly or via wire with the peripheral life/work context device 16, biofeedback device 18, and database, server, cloud structure 20, as described above. Each of the brain interface assemblies 14c described below comprises a head-worn unit 22c having a plurality of OPMs 64, a passive shield 66, and a support housing structure 68 in which the OPMs 64 and passive shield 66 are embedded.

Each of brain interface assemblies 14c may also comprise a control/processing unit 70 for controlling the operational functions of the OPMs 64, and processing the magnetic fields detected by the OPMs 64 to detect and localize the neural activity within the brain of the user 12. As will be described in further detail below, the control/processing unit 70 may be contained in the head-worn unit 22c or may be incorporated into a self-contained auxiliary unit. As will be set forth below, the support housing structure 68 may be shaped, e.g., have a banana, headband, cap, helmet, beanie, other hat shape, or other shape adjustable and conformable to the user's head, such that the magnetometers 64 are in close contact with the outer skin of the head, and in this case, the scalp of the user 12.

[0081] As shown in **Fig. 7A**, a brain interface assembly 14c(1) comprises a head-worn unit 22c(1) and a power source 72 coupled to the head-worn unit 22c(1) via a wired connection 74. The head-worn unit 22c(1) includes the OPMs 64 (shown as 64-1 through 64-12) and a control/processing unit 70a. The head-worn unit 22c(1) further includes a support housing structure 68a that takes a form of a helmet that contains the OPMs 64, passive shield 66, and control/processing unit 70a. The material for the helmet 68a may be selected out of any suitable cloth, soft polymer, plastic, hard shell, and/or any other suitable material as may serve a particular implementation. The power source 72 may be implemented by a battery and/or any other type of power source configured to provide operating power to the magnetometers 64, control/processing unit 70a, and any other component included within the brain interface assembly 22c(1) via the wired connection 74. The head-worn unit 22c(1) optionally includes a handle 76 affixed to the helmet 68a for providing a convenient means of carrying the head-worn unit 22c(1).

[0082] As shown in **Fig. 7B**, a brain interface assembly 14c(2) comprises a head-worn unit 22c(2) and a control/processing unit 70b coupled to the head-worn unit 22b(2) via a wired connection 78. The head-worn unit 22c(2) includes the OPMs 64 (shown as 64-1 through 64-12), and a support housing structure 68b that takes a form of a helmet that contains the OPMs 64 and passive shield 66. The material for the helmet 68b may be selected out of any suitable cloth, soft polymer, plastic, hard shell, and/or any other suitable material as may serve a particular implementation. Unlike the control/processing unit 70a of the brain interface assembly 14c(1) illustrated in **Fig. 6A**, which is contained in the head-worn unit 22c(1), the control/processing unit 70b is self-contained, and may take the form of a garment (e.g., a vest, partial vest, or harness) for being worn on the shoulders of the user. The self-contained control/processing unit 70b may additionally include a power supply (which if head-worn, may take the form of a rechargeable or non-chargeable battery), a control panel with input/output functions, a display, and memory. Alternatively, power may be provided to the self-contained control/processing unit 70b wirelessly (e.g., by induction). The head-worn unit 22c(1) optionally includes a crest or other protrusion 80 formed in the helmet 68b for providing means of carrying a control/processing unit 70b'.

[0083] As shown in **Fig. 7C**, a brain interface assembly 14c(3) comprises a head-worn unit 22c(3) and a control/processing unit 70c. The head-worn unit 22c(3) includes the OPMs 64 (shown as 64-1 through 64-12), and a support housing structure 68c that takes a form of a baseball cap that contains the OPMs 64 and passive shield 66. The material for baseball cap 68c may be selected out of any suitable cloth, soft polymer, plastic, hard shell, and/or any other suitable material as may serve a particular implementation. The control/processing unit 70c is self-

contained, and may take the form of a garment (e.g., scarf) for being worn around the neck of the user 12. The self-contained control/processing unit 70c may additionally include a power supply (which if head-worn, may take the form of a rechargeable or non-chargeable battery), a control panel with input/output functions, a display, and memory. Alternatively, power may be provided to the self-contained control/processing unit 70c wirelessly (e.g., by induction).

[0084] Although particular embodiments of the present inventions have been shown and described, it will be understood that it is not intended to limit the present inventions to the preferred embodiments, and it will be obvious to those skilled in the art that various changes and modifications may be made without departing from the spirit and scope of the present inventions. Thus, the present inventions are intended to cover alternatives, modifications, and equivalents, which may be included within the spirit and scope of the present inventions as defined by the claims.

CLAIMS

What is claimed is:

1. A mental state awareness system, comprising:

5 a non-invasive brain interface assembly configured for detecting brain activity of a user;

a processor configured for determining a mental state of a user based on the detected brain activity; and

10 a biofeedback device configured for automatically providing biofeedback to the user indicative of the determined mental state of the user.

2. The mental state awareness system of claim 1, wherein the mental state is one of anxiety, focus, attention, creativity, positive or negative reflections/attitude on experiences or the use of objects, and the employment of certain critical cognitive brain areas.

15 3. The mental state awareness system of claim 1, wherein the non-invasive brain interface assembly is an optical measurement assembly.

4. The mental state awareness system of claim 1, wherein the non-invasive brain interface assembly is a magnetic measurement assembly.

20 5. The mental state awareness system of claim 1, wherein the non-invasive brain interface assembly comprises at least one detector configured for detecting energy from a brain of the user, and processing circuitry configured for identifying the brain activity in response to detecting the energy from the brain of the user.

6. The mental state awareness system of claim 5, wherein the non-invasive brain interface assembly comprises a head-worn unit carrying the at least one energy source.

7. The mental state awareness system of claim 6, wherein the non-invasive
5 brain interface assembly comprises an auxiliary non-head-worn unit carrying the processing circuitry.

8. The mental state awareness system of claim 1, wherein the biofeedback device is configured for providing/directing vibrational signals to the user indicative of the determined mental state of the user through peripheral somatosensation.

10 9. The mental state awareness system of claim 8, wherein the vibrational signals are encoded with one or more messages.

10. The mental state awareness system of claim 1, wherein the biofeedback device is configured for providing/directing audio or visual signals to the user indicative of the determined mental state of the user.

15 11. The mental state awareness system of claim 1, further comprising a peripheral device configured for providing additional life/work context to the user.

12. The mental state awareness system of claim 11, wherein the peripheral device is configured for being programmed with one of a plurality of user experiences corresponding to the additional life/work context.

20 13. The mental state awareness system of claim 11, wherein the peripheral device is configured for automatically providing the additional life/work context to the user in response to the determined mental state of the user, such that the mental state of the user is modified.

14. The mental state awareness system of claim 1, further comprising a database, sever, or cloud structure configured for tracking the detected brain activity of the user.

15. The mental state awareness system of claim 14, wherein the processor is
5 configured for determining the mental state of the user further based on the tracked brain activity of the user.

16. The mental state awareness system of claim 15, wherein the processor is configured for determining the mental state of the user further based on the tracked brain activity of a pool of users.

10 17. The mental state awareness system of claim 15, wherein the processor is configured for tracking life/work context of the user, and acquiring meta data in depth assessment of awareness and behavior modulation patterns of the user.

18. A method of making user aware of a mental state, comprising:
detecting brain activity of a user using a non-invasive brain interface;
15 determining a mental state of a user based on the detected brain activity; and
automatically providing biofeedback to the user indicative of the determined mental state of the user.

19. The method of claim 18, wherein the mental state is one of anxiety, focus, attention, creativity, positive or negative reflections/attitude on experiences or the use of
20 objects, and the employment of certain critical cognitive brain areas.

20. The method of claim 18, wherein the brain activity is optically detected.

21. The method of claim 18, wherein the brain activity is magnetically detected.

22. The method of claim 18, further comprising:

detecting energy from a brain of the user; and
identifying the brain activity in response to detecting the energy from the brain of the user.

23. The method of claim 18, wherein automatically providing biofeedback to the
5 user comprises providing/directing vibrational signals to the user indicative of the
determined mental state of the user through peripheral somatosensation.

24. The method of claim 23, wherein the vibrational signals are encoded with
one or more messages.

25. The method of claim 18, wherein automatically providing biofeedback to the
10 user comprises providing/directing audio or visual signals to the user indicative of the
determined mental state of the user.

26. The method of claim 18, further comprising automatically providing additional
life/work context to the user via a peripheral device.

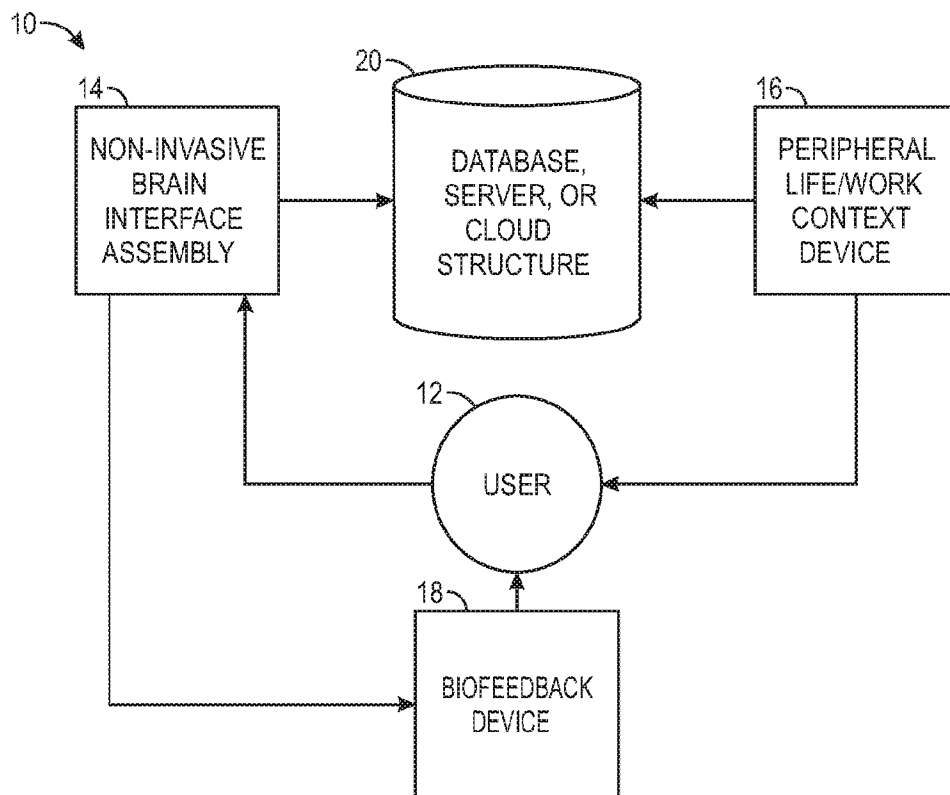
27. The method of claim 26, further comprising programming the peripheral
15 device with one of a plurality of user experiences corresponding to the additional
life/work context.

28. The method of claim 26, further comprising automatically providing the
additional life/work context to the user in response to the determined mental state of the
user, such that the mental state of the user is modified.

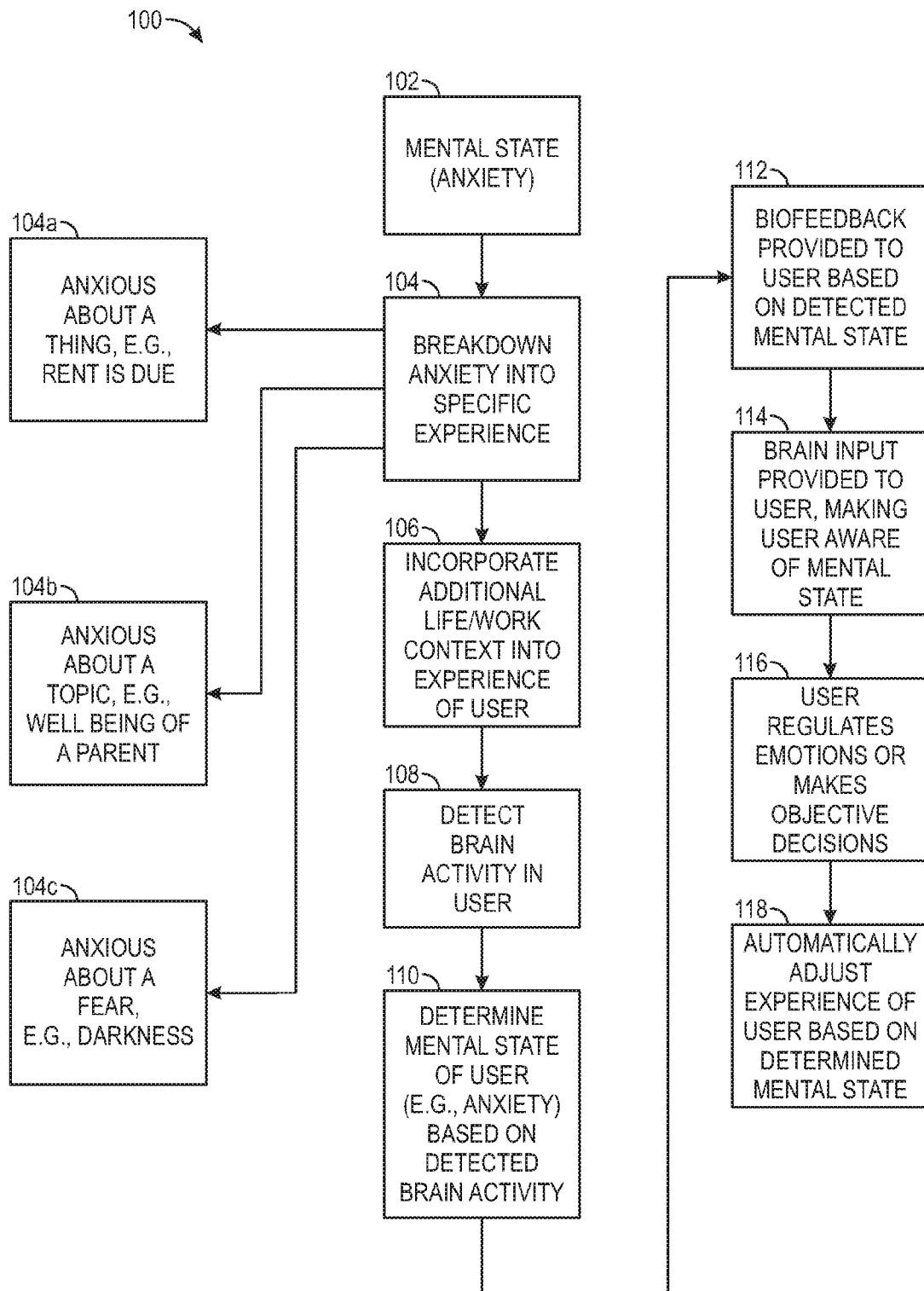
29. The method of claim 18, further comprising tracking a brain activity history of
20 the user.

30. The method of claim 29, wherein the mental state of the user is determined
further based on the tracked brain activity history of the user.

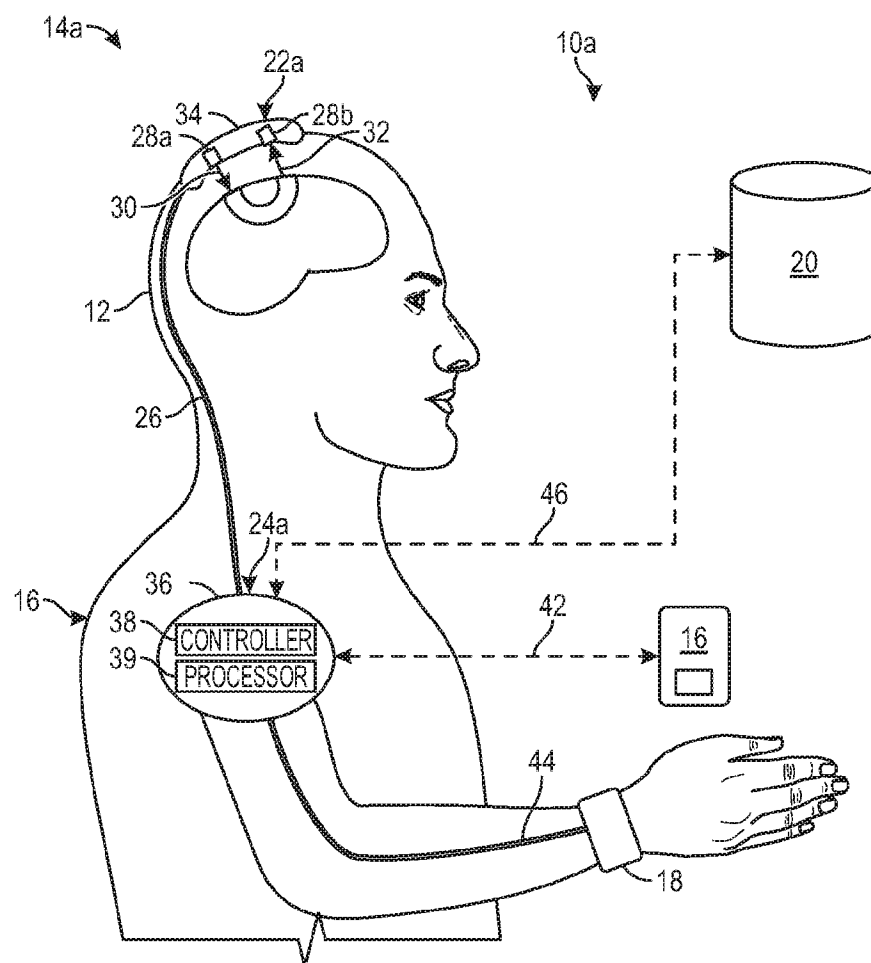
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**FIG. 1**

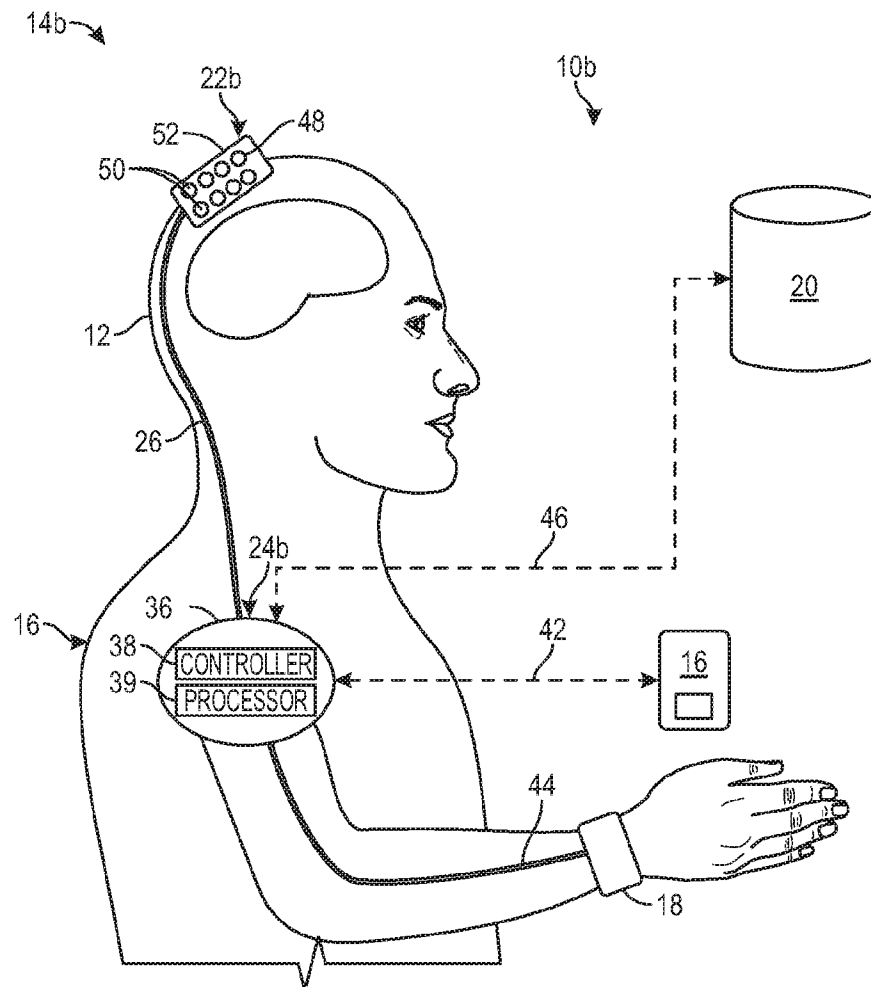
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**FIG. 2**

3/12

**FIG. 3**

4/12

**FIG. 4**

5/12

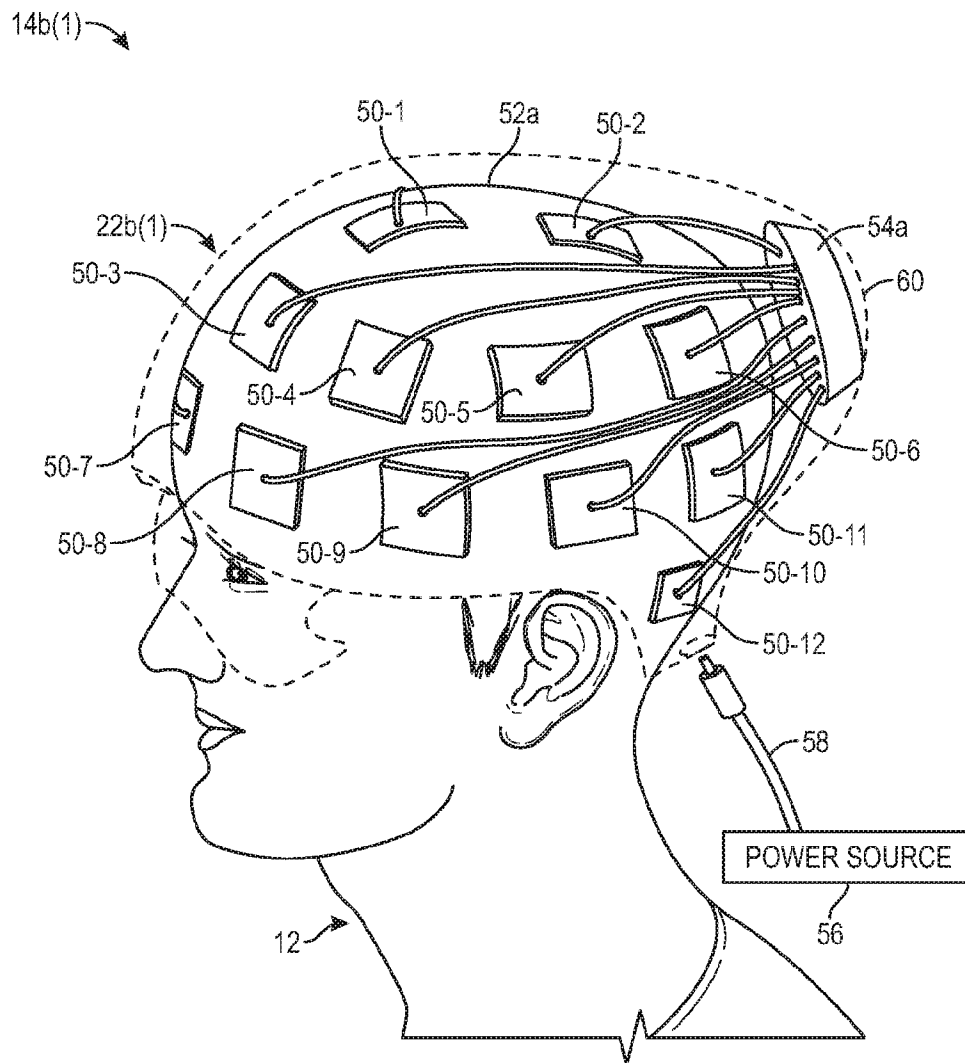


FIG. 5A

6/12

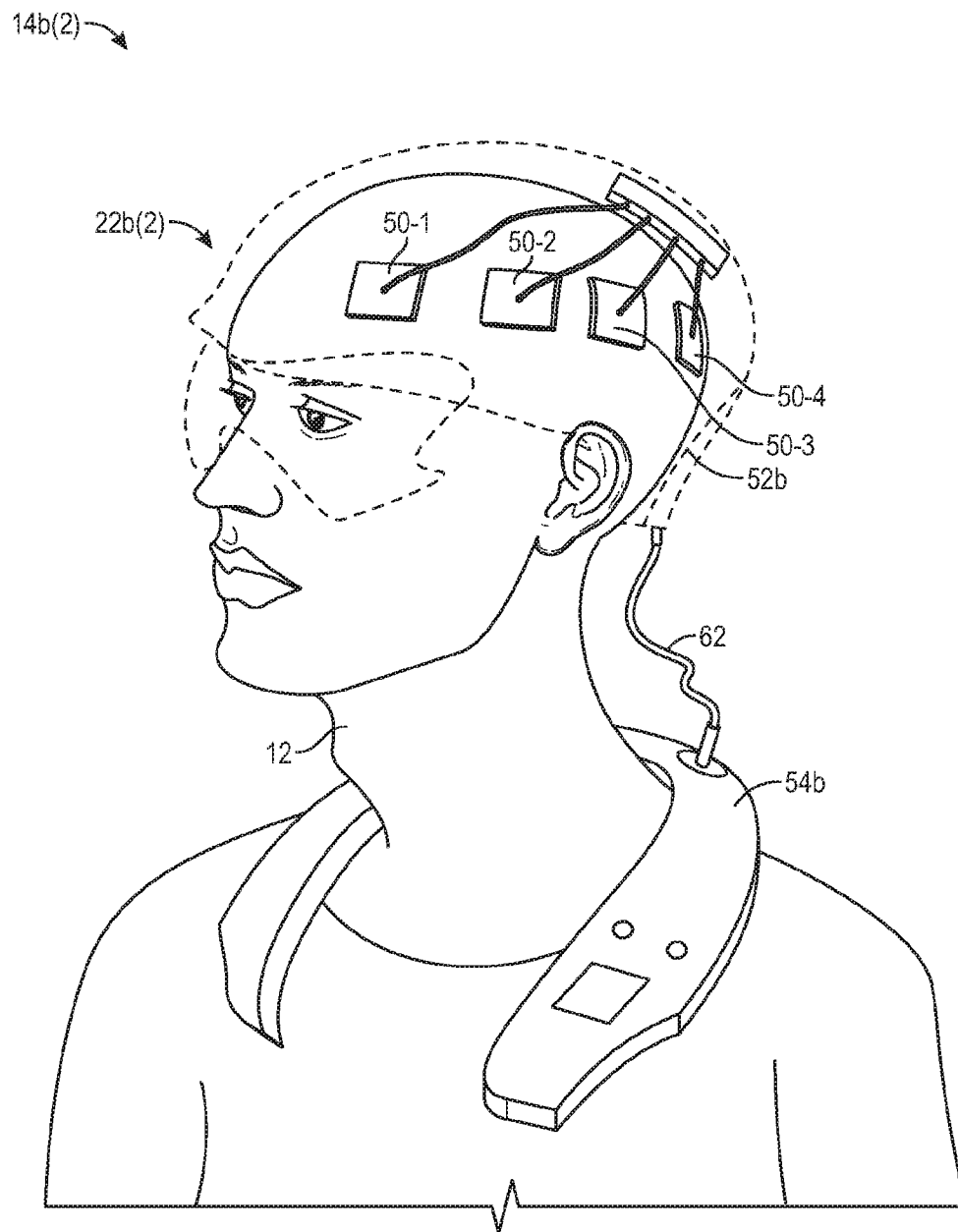


FIG. 5B

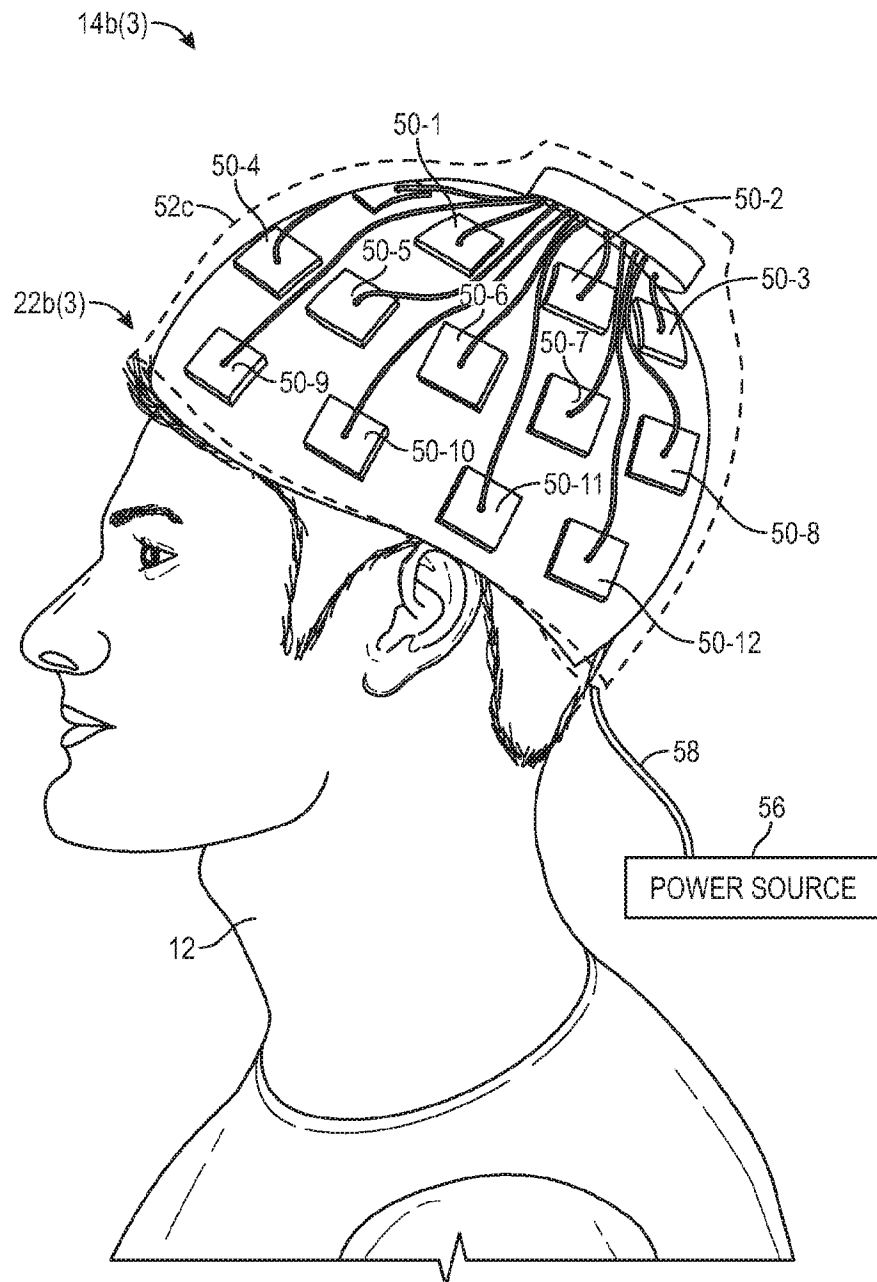


FIG. 5C

8/12

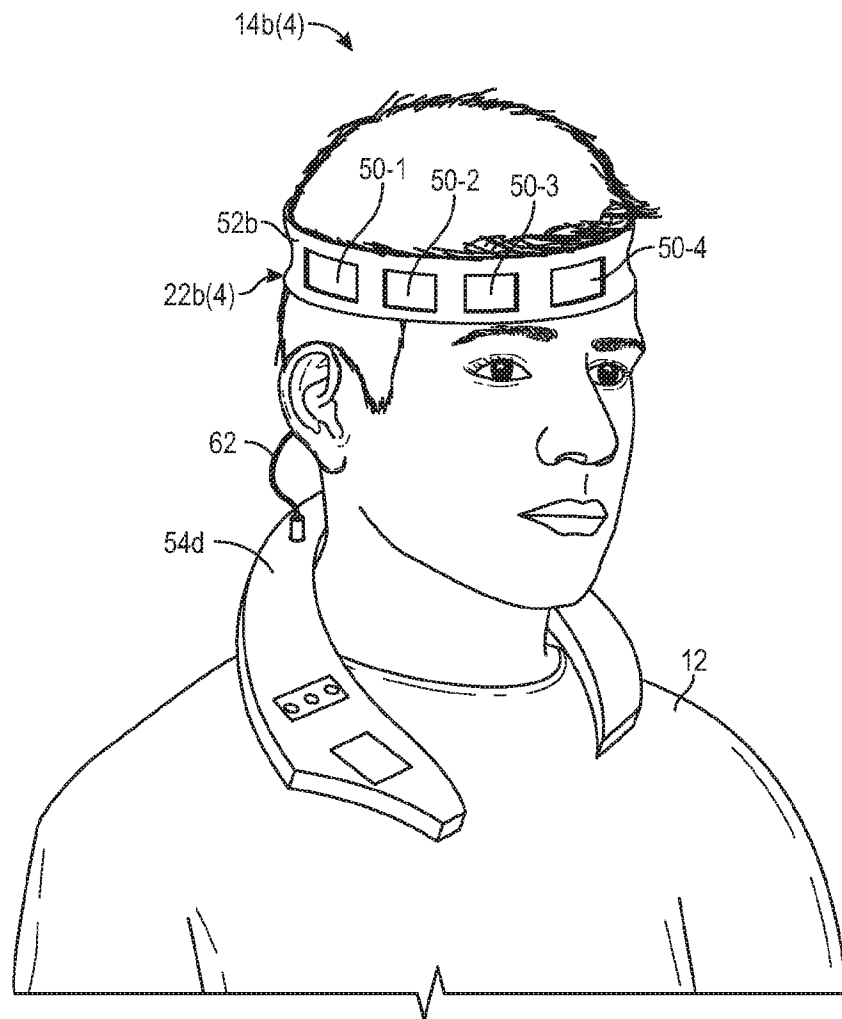
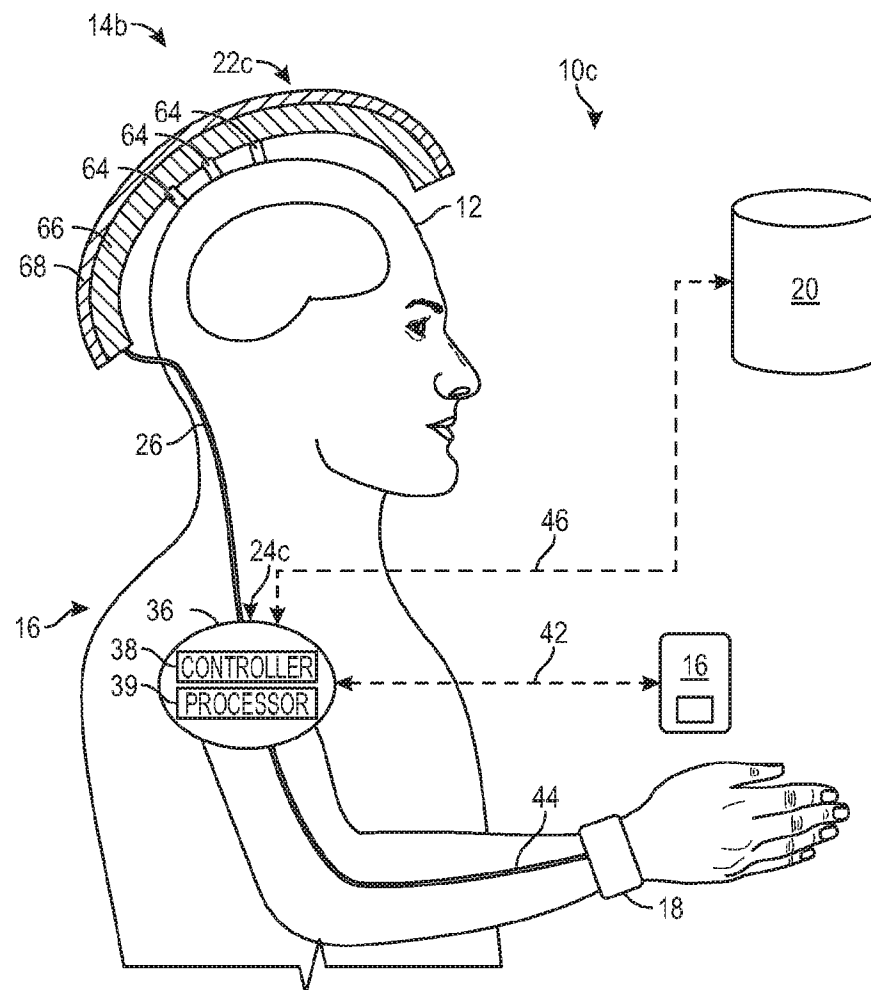
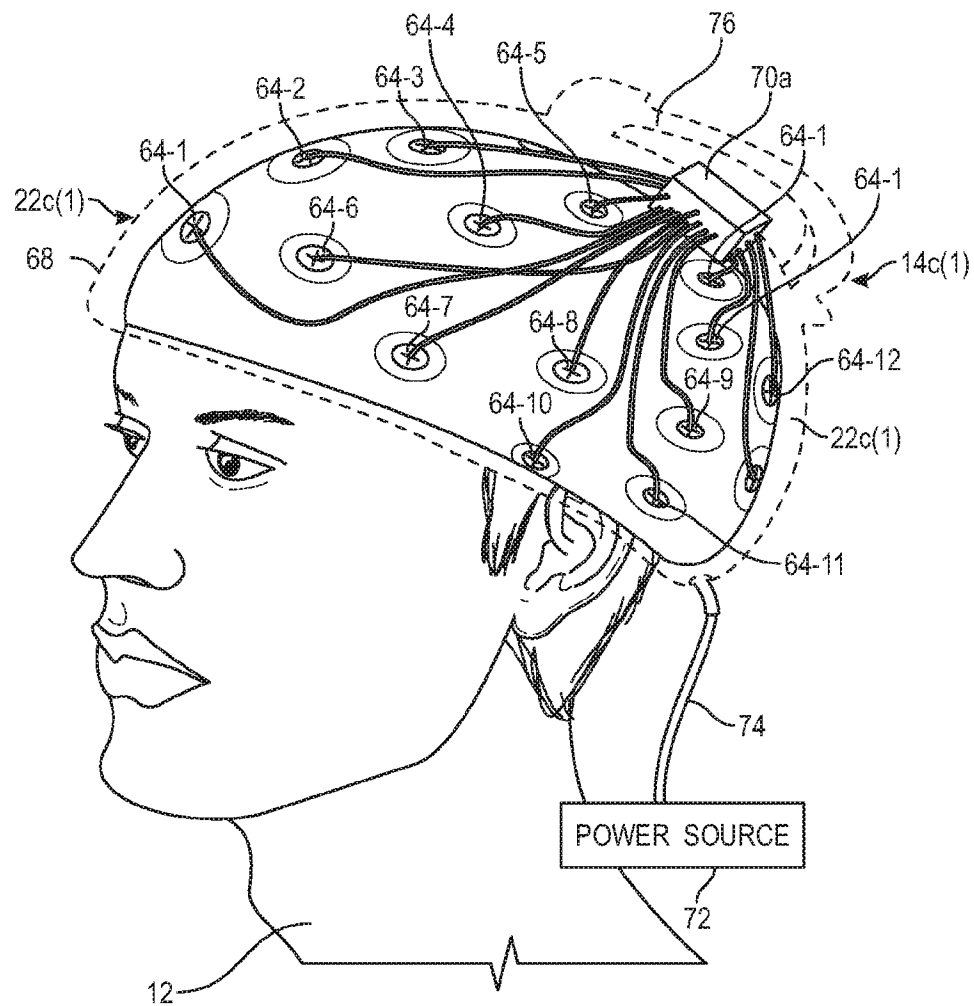


FIG. 5D

9/12

**FIG. 6**

10/12

**FIG. 7A**

11/12

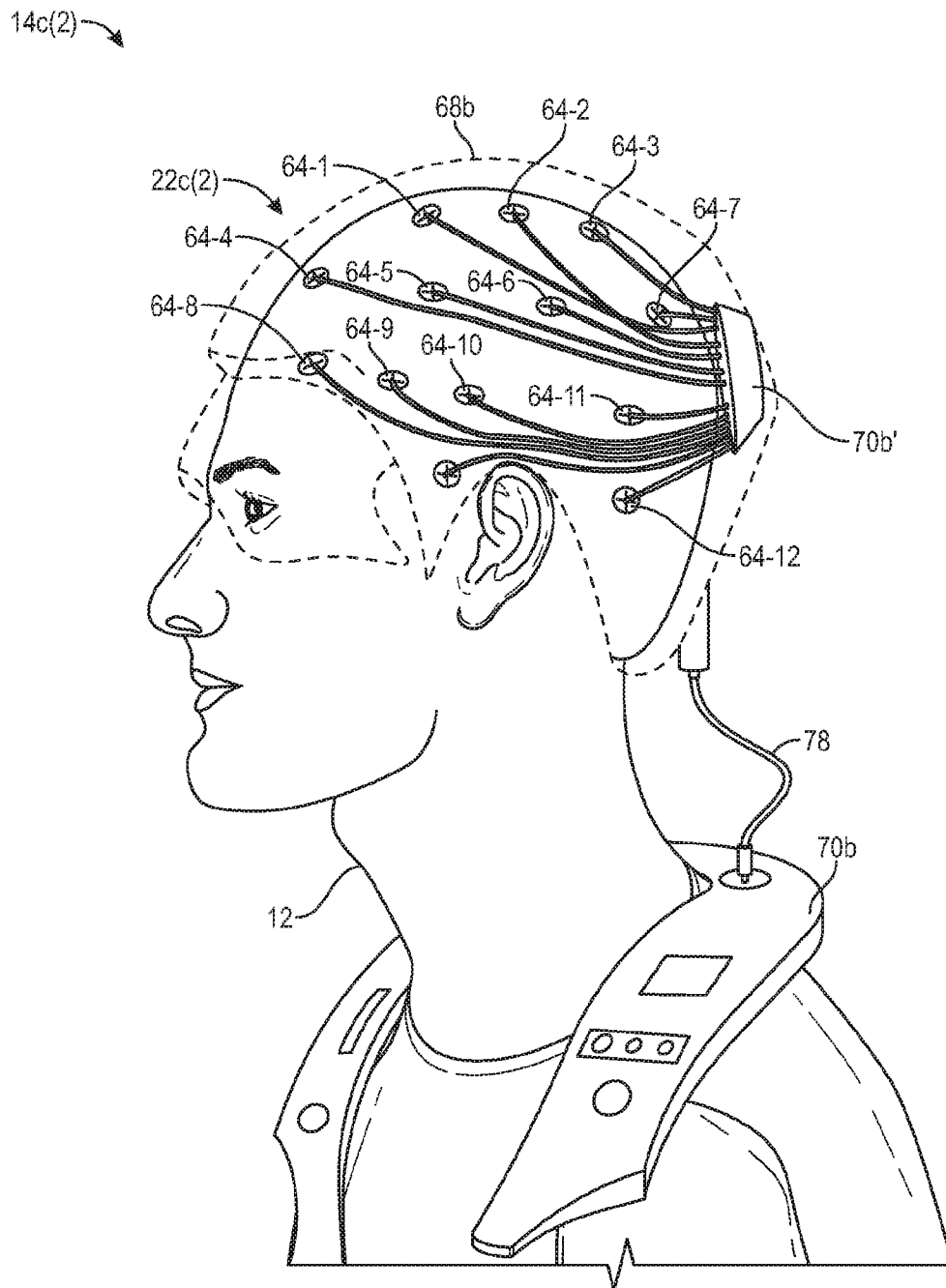


FIG. 7B

12/12

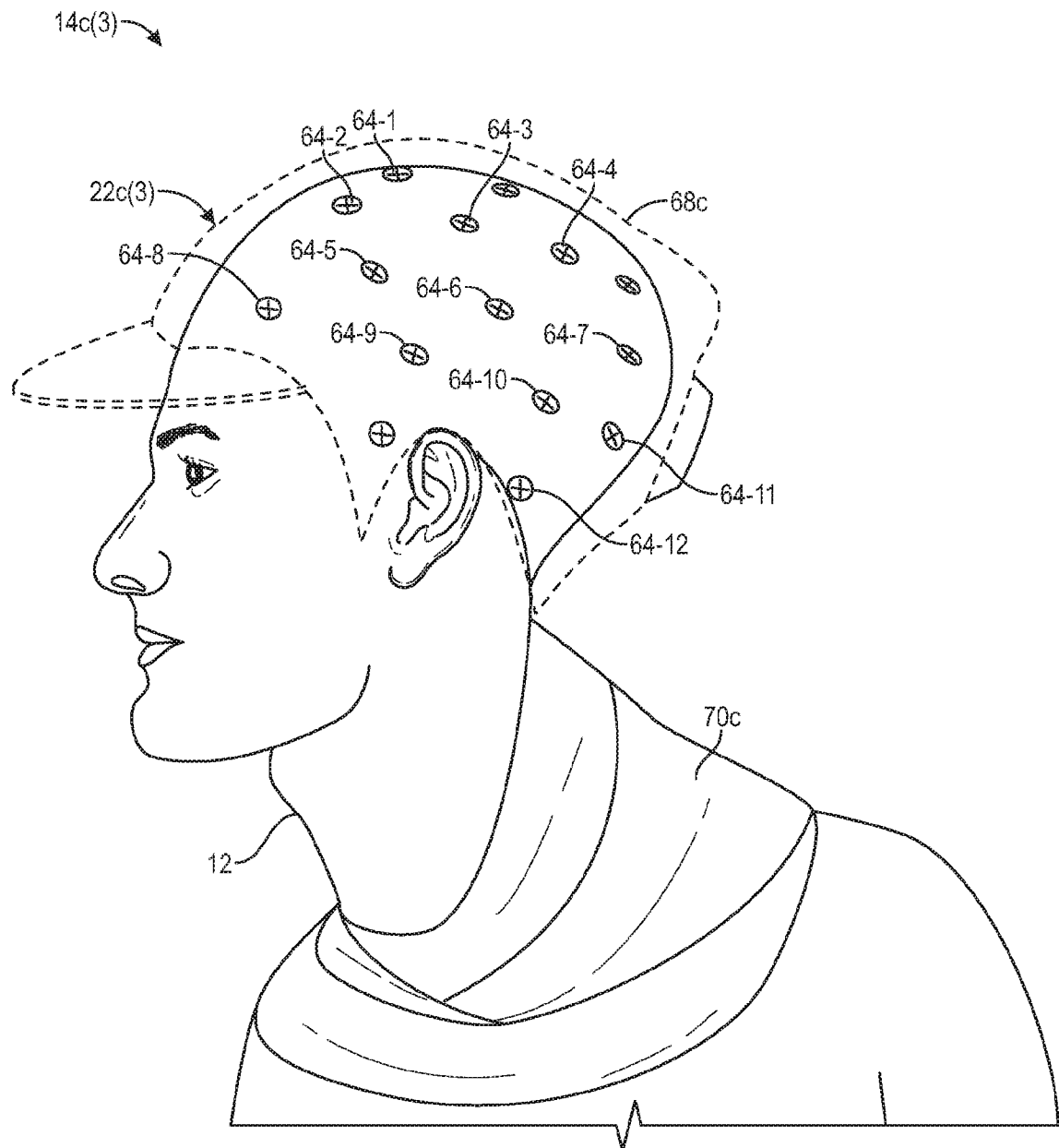


FIG. 7C

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2019/024027

A. CLASSIFICATION OF SUBJECT MATTER
INV. A61B5/00 A61B5/04 A61B5/16
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2014/023999 A1 (GREDER ROD [US]) 23 January 2014 (2014-01-23) paragraphs [0031] - [0059] -----	1-30
X	US 2018/092557 A1 (BICKFORD JAMES A [US] ET AL) 5 April 2018 (2018-04-05) paragraphs [0062] - [0092] -----	1-30
X	US 2014/200432 A1 (BANERJI SUBHASIS [SG] ET AL) 17 July 2014 (2014-07-17) paragraphs [0078] - [0098] -----	1-30
X	US 2017/352283 A1 (LAU MICHAEL P H [US]) 7 December 2017 (2017-12-07) paragraphs [0044] - [0049], [0074] - [0079] -----	1-30



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

19 August 2019

Date of mailing of the international search report

28/08/2019

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Authorized officer

Trachterna, Morten

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2019/024027

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