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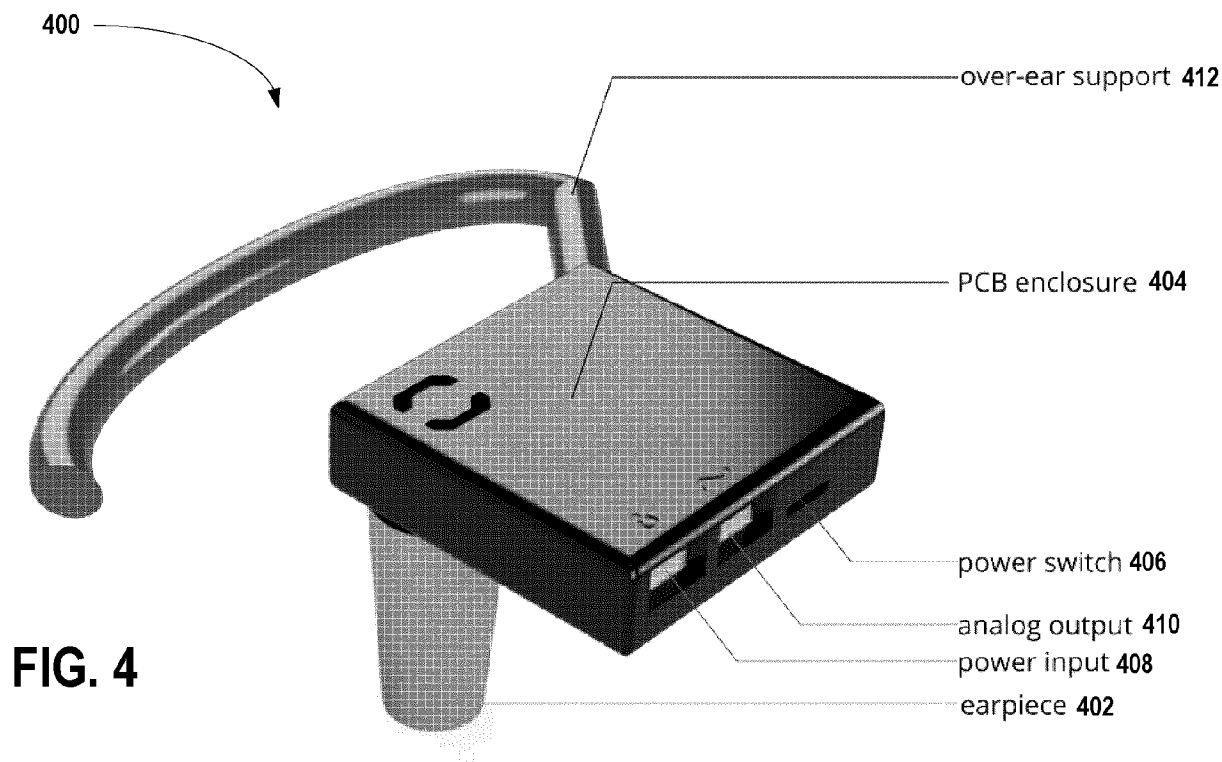


FIG. 4

(57) **Abrégé/Abstract:**

An in-ear EEG device is provided. The in-ear EEG device comprises an over-ear support arm coupled to an enclosure, and an earpiece coupled to the enclosure. The enclosure has a power switch, an analog output, a power input, and a processor. The processor is configured to receive EEG data and generate output data for the analog output. The earpiece collects the EEG data and transmits the EEG data to the processor.

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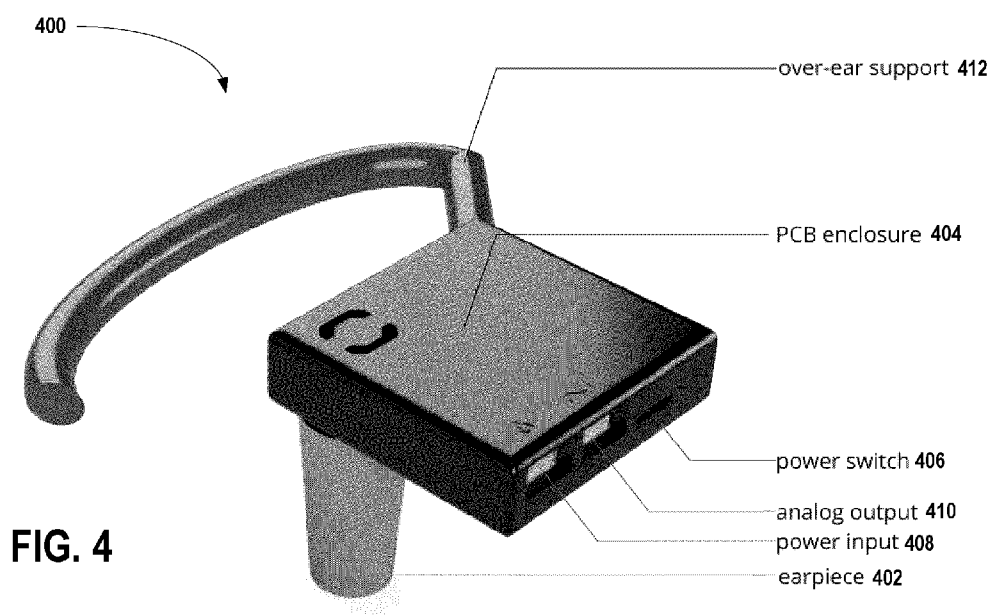


FIG. 4

(57) Abstract: An in-ear EEG device is provided. The in-ear EEG device comprises an over-ear support arm coupled to an enclosure, and an earpiece coupled to the enclosure. The enclosure has a power switch, an analog output, a power input, and a processor. The processor is configured to receive EEG data and generate output data for the analog output. The earpiece collects the EEG data and transmits the EEG data to the processor.

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IN-EAR EEG DEVICE AND BRAIN-COMPUTER INTERFACES

FIELD

[0001] The present disclosure generally relates to the field of brain-computer interfaces and electroencephalogram (EEG) devices.

5 INTRODUCTION

[0002] In-ear electroencephalography (EEG) is a method for measuring electrical signals from the brain. This technology is garnering increased interest in the research community and more broadly due to its advantages over conventional measurement systems. EEG caps, often used in brain-computer interface (BCI) systems and
10 neuroscience research, present a non-invasive means to collect neural activity. However, difficulty reducing electrode impedances, long setup times, patient discomfort, and limited ability for long-term recording continue to plague EEG measurement systems.

SUMMARY

[0003] In accordance with one aspect, there is provided an in-ear
15 electroencephalography (EEG) device. The EEG device comprises an enclosure, an earpiece coupled to the enclosure, and an over-ear support arm coupled to an enclosure. The enclosure has a power switch, an analog output, a power input, and a processor. The processor is configured to receive EEG data and generate output data for the analog output. The earpiece has two electrodes to collect the EEG data. The earpiece transmits
20 the EEG data to the processor. The over-ear support arm has a reference electrode to collect the EEG data. The over-ear support arm transmits the EEG data to the processor.

[0004] In accordance with another aspect, there is provided an in-ear EEG device. The EEG device comprises an over-ear support arm coupled to an enclosure, an analog output, and a power input. The enclosure comprises a printed circuit board (PCB) of the
25 device and includes a processor and a header. The processor is configured to receive EEG data and generate output data. The header is used for connecting an earpiece to the EEG device.

[0005] In accordance with another aspect, there is provided a method of validating an
30 in-ear EEG device for use as a brain-computer interface (BCI). The method comprises performing a set of trial experiments on a plurality of subjects where each subject

wearing the in-ear EEG device and a clinical EEG cap (e.g., EEG system), extracting P300 features from signals received from the in-ear EEG device, extracting P300 features from signals received from the clinical EEG cap, extracting auditory steady-state response (ASSR) features from the signals received from the in-ear EEG device,
5 extracting ASSR features from the signals received from the clinical EEG cap, classifying the P300 features and ASSR features received from the in-ear EEG device signals, classifying the P300 features and ASSR features received from the clinical EEG cap signals, and comparing the in-ear EEG classifications and the clinical EEG cap signal classifications.

10 [0006] In accordance with another aspect, there is provided a non-transitory computer-readable storage medium comprising computer-executable instructions for validating an in-ear EEG device for use as a brain-computer interface (BCI). The computer-executable instructions cause a processor to extract P300 features from signals received from an in-ear EEG device, extract P300 features from signals received from a clinical EEG cap,
15 extract auditory steady-state response (ASSR) features from the signals received from the in-ear EEG device, extract ASSR features from the signals received from the clinical EEG cap, classify the P300 features and ASSR features received from the in-ear EEG device signals, classify the P300 features and ASSR features received from the clinical EEG cap signals, and compare the in-ear EEG classifications and the clinical EEG cap
20 signal classifications.

[0007] In accordance with another aspect, there is provided an in-ear EEG device. The in-ear EEG device comprises an over-ear support arm coupled to an enclosure, and an earpiece coupled to the enclosure. The enclosure has a power switch, an analog output, a power input, and a processor. The processor is configured to receive EEG data and
25 generate output data for the analog output. The earpiece collects the EEG data and transmits the EEG data to the processor.

[0008] In various further aspects, the disclosure provides corresponding systems and devices, and logic structures such as machine-executable coded instruction sets for implementing such systems, devices, and methods.

30 [0009] In this respect, before explaining at least one embodiment in detail, it is to be understood that the embodiments are not limited in application to the details of construction and to the arrangements of the components set forth in the following

description or illustrated in the drawings. Also, it is to be understood that the phraseology and terminology employed herein are for the purpose of description, and should not be regarded as limiting.

5 [0010] Many further features and combinations thereof concerning embodiments described herein will appear to those skilled in the art following a reading of the instant disclosure.

DESCRIPTION OF THE FIGURES

[0011] Embodiments will be described, by way of example only, with reference to the attached figures, wherein in the figures:

10 [0012] **FIG. 1** illustrates an example of an EEG 10-20 system.

[0013] **FIG. 2** illustrates an example of an in-ear EEG system design.

[0014] **FIG. 3** illustrates an example of an alternative in-ear EEG system design.

[0015] **FIG. 4** illustrates, in a three-dimensional rendering, an example of an in-ear EEG mechanical design, in accordance with some embodiments.

15 [0016] **FIG. 5** illustrates different elevation and perspective views of the in-ear EEG system, in accordance with some embodiments.

[0017] **FIG. 6** illustrates, in a signal flow diagram, an example of a signal pathway 600, in accordance with some embodiments.

20 [0018] **FIG. 7** illustrates, in a schematic diagram, an example of the topology of the notch filter, in accordance with some embodiments.

[0019] **FIG. 8** illustrates, in a schematic diagram, an example of a Sallen-Key topology of the high-pass filter, in accordance with some embodiments.

[0020] **FIG. 9** illustrates, in a schematic diagram, an example of a Sallen-Key topology of the low-pass filter, in accordance with some embodiments.

25 [0021] **FIG. 10** illustrates, in a signal flow diagram, an alternative example of a signal pathway, in accordance with some embodiments.

[0022] **FIG. 11A** illustrates, in a computer-aided design (CAD), an example of a printed circuit board of the PCB, in accordance with some embodiments.

[0023] **FIG. 11B** illustrates, in a computer-aided design (CAD), another example of a printed circuit board of the PCB, in accordance with some embodiments.

5 [0024] **FIG. 12** illustrates an example of an experimental setup, in accordance with some embodiments.

[0025] **FIG. 13** illustrates an example of an experimental protocol, in accordance with some embodiments.

10 [0026] **FIG. 14** illustrates an example of a P300 feature extraction process, in accordance with some embodiments.

[0027] **FIG. 15** illustrates an example of an ASSR feature extraction process, in accordance with some embodiments.

[0028] **FIG. 16** is a view of an example brain-computer interface (BCI) system, in accordance with some embodiments.

15 [0029] **FIG. 17** is a view of an example BCI platform and classification device, in accordance with some embodiments.

[0030] **FIG. 18** is a view of an example interface application, in accordance with some embodiments.

20 [0031] **FIG. 19** illustrates, in a flowchart, an example of a method of validating an in-ear EEG device for use as a BCI, in accordance with some embodiments.

[0032] **FIG. 20A** illustrates, in a display, an example of four directional visual cues, in accordance with some embodiments.

25 [0033] **FIG. 20B** illustrates an example of a system environment showing a participant wearing electrode sensors watching an output unit, in accordance with some embodiments.

[0034] FIG. 20C illustrates another example of a system environment showing the participant wearing the electrode sensors watching the display unit, in accordance with some embodiments.

[0035] It is understood that throughout the description and figures, like features are identified by like reference numerals.

DETAILED DESCRIPTION

[0036] The present disclosure relates to in-ear EEG as a measurement system. Its small size provides improved user comfort, especially over long periods of time. The size and location also allows for improved discreetness. The location of the electrodes also provides robustness against eye-blink artifacts (though introduces greater susceptibility to artifacts related to facial muscle movements, i.e., mastication). There may be a limited number of electrodes, which precludes the use of EEG processing techniques such as independent component analysis (ICA). It is desirable to overcome the processing hurdles and relatively limited data.

[0037] Embodiments of methods, systems, and apparatus are described through reference to the drawings.

[0038] Some embodiments herein relate to in-ear electroencephalography (EEG) devices. The following terms are used in this disclosure:

[0039] ASSR : auditory steady-state response.

[0040] BCI : brain-computer interface.

[0041] CAD : computer-aided design.

[0042] CMRR : common-mode rejection ratio.

[0043] EEG : electroencephalography.

[0044] fc : cut-off frequency.

[0045] ISI : inter-stimulus interval.

[0046] ITR : information transfer rate.

[0047] MMN : mismatch negativity.

[0048] PCB : printed-circuit board.

[0049] PSD : power-spectral density.

[0050] SSVEP : steady-state visually evoked potential.

5 [0051] SWLDA : Step-wise Linear Discriminant Analysis.

[0052] Embodiments described herein relate to brain-computer interfaces and electroencephalogram (EEG) devices. Brain-computer interfaces (BCIs) are a communication pathway between an enhanced or wired brain and an external device. An EEG device detects electrical activity in the brain using electrodes attached to portions of
10 the head. Brain cells communicate via electrical impulses and are active all the time. This electrical activity can be detected and measured by an EEG recording. **FIG. 1** illustrates an example of an EEG 10-20 system **100**. The figure shows electrode **102** placement and nomenclature as standardized by the American Electroencephalographic Society.

[0053] To allow persons with severe motor impairments to communicate, brain-
15 computer interfaces can provide a direct pathway between a user's brain and the outside world. Communicative brain-computer interfaces can be largely grouped into two categories: gaze-independent BCIs and gaze-dependent BCIs. The latter consists of BCI systems which involve direct user control of gaze, and have been the focus of the majority of research related to communicative BCIs. Alternately, gaze-independent BCIs
20 do not require user gaze control, and may be better suited for users with severe motor impairments. Amongst gaze-independent BCIs are those using sound to stimulate users and elicit neural responses; a technique which has shown promise.

[0054] Morphologies of in-ear EEG systems vary between research groups. **FIG. 2** illustrates an example of an in-ear EEG system design **200**. As shown in **FIG. 2**, some
25 designs include electrodes implanted into flexible foam ear-plug type substrates **202**, while attaching a separate reference electrode to the outside of the earlobe **204**. Other designs have simply re-purposed in-ear headphones, used for music listening, into electrical measurement devices. **FIG. 3** illustrates an example of an alternative in-ear EEG system design **300** that provides a self-contained earpiece with two electrodes, with
30 the reference extending outside the ear as part of a self-contained package.

[0055] The range of BCI paradigms usable with in-ear EEG has not be explored extensively. Nonetheless, there has been early success demonstrated by various groups. Many have shown a notable auditory steady-state response (ASSR). The ASSR is an auditory-evoked neural response to an amplitude or frequency-modulated pure tone; the
5 ASSR is a consequence of the tonotopic organization of the cochlea. The steady-state visually evoked potential (SSVEP), another neural response elicited by a frequency modulated stimulus, can also be measured through in-ear EEG. One research group assessed a three-class SSVEP system with stimulus presented at frequencies of 10, 15 and 20-Hz. Another research has also demonstrated the viability of alpha-attenuation
10 paradigms by asking users to alternate between a math task with their eyes open and resting with their eyes closed.

[0056] Groups have also been able to demonstrate the viability of in-ear EEG in detecting other evoked potentials, both auditory and visual. In one study, an auditory odd-ball paradigm was able to elicit a distinct mismatch negativity (MMN) in all 13
15 subjects. Furthermore, across a series of four sessions the correlation coefficient between all 7200 presented auditory stimuli was 0.80, suggesting consistent recording of the EEG signal using the in-ear system. Correlations were also similar between the ear-lobe referenced signal and the Cz referenced signal; a result corroborated by other research groups and supporting the use of a self-contained in-ear EEG system.

[0057] Passive BCIs detect changes in mental-state. Some groups have been able to perform classification between a sub-vocalization task, multiplication task, and rest task with accuracies of up to 70%. As described in US application number 15/865,794 (titled
20 "EEG Brain-Computer Interface Platform and Process for Detection of Changes to Mental State" and filed on January 9, 2018, which is hereby incorporated by reference herein in its entirety) in a mental task involving an anagram task, math task, and rest, mental
25 states such as fatigue, frustration and attention were classified with classification accuracies of 74.8%, 71.6% and 84.8%, respectively, using an LDA classifier.

[0058] Reactive BCIs use external stimuli in order to elicit specific neural activity. This neural activity is then used to control a communication system. One of the most widely
30 used neural activity in reactive BCIs is the P300 response. This phenomenon was first characterized in 1965 and occurs when an external event is different than that expected and elicits a neural response. Most commonly, this response is produced as part of an

odd-ball paradigm, whereby the subject is asked to focus their attention on one of n targets. The targets are presented in a random order. When the desired target is presented, a P300 response is elicited.

5 [0059] Hybrid-BCIs, whereby multiple stimulus modalities are used in conjunction, have boosted information transfer rates (ITRs) when compared to traditional single modality systems. This result has been demonstrated in traditional visual BCI systems. Recently, a group has shown that auditory P300 and ASSR can be combined to improve BCI performance. However, these studies have exclusively used cap-based EEG systems with many electrodes.

10 [0060] The research on relevant BCI protocols for in-ear EEG has been largely concerned with signal quality and whether gross neural signal changes can be detected. There has been limited exploration into the real-world performance of an in-ear EEG BCI in communication applications. In assessing in-ear BCI performance, a reasonable starting point is the confirmation of in-ear automatic detection of well-established P300
15 and ASSR signals.

[0061] Current systems use clinical cap-EEG systems, which, besides being expensive, require long-setup times, and are also impractical for extended periods of use. An EEG system which can be used with existing BCI experimental paradigms while being less expensive, more comfortable, and more discreet, would prove highly useful.
20 To this end, a novel active in-ear EEG system and to test the device using a hybrid P300-ASSR paradigm is desirable.

[0062] Though in-ear EEG systems provide a fewer number of electrodes than existing cap-based EEG systems, they have a smaller size and an ability to be discretely worn over longer periods of time. This small size and focus on long-term usability presents
25 some engineering challenges. Specifically, the electrical and mechanical design should be adequately miniaturized to reduce weight and increase user comfort during use. Existing in-ear EEG systems presently exist in research environments and contain passive electrodes. Though the use of passive electrodes simplifies the design, they also reduce overall signal output quality due to the signal transmission over a longer distance
30 before amplification. This leaves the EEG signal (which itself is on the order of microvolts) highly susceptible to electrical noise. To avoid this, in one embodiment, active filters directly within the earpiece are implemented.

[0063] In some embodiments, an in-ear EEG system includes an active filter system capable of amplifying and filtering the micro-volt amplitude EEG signal. The distance between the electrode and the filter system in an in-ear EEG system is preferably minimized to less than 1 centimetre (cm).

5 [0064] In some embodiments, the in-ear EEG system may include wireless capabilities such as a Bluetooth, Wi-Fi or other radio for transmitting measurements taken from the in-ear EEG device to a server for processing.

[0065] In some embodiments, the in-ear EEG system mechanical design includes a computer-aided design (CAD) of the device enclosure accounting for wearability. The in-ear EEG system electrical design includes active filters and corresponding printed-circuit board (PCB) for eventual miniaturization of the device. In some embodiments, each filter
10 may be on a separate chip. In other embodiments, multiple filters may be on the same chip.

[0066] **FIG. 4** illustrates, in a three-dimensional rendering, an example of an in-ear EEG device **400**, in accordance with some embodiments. The in-ear EEG device **400** comprises an earpiece **402**, a PCB enclosure **404**, a power switch **406**, and connections for both electrical power input **408** and analog output **410**. An over-ear support **412** is placed around the ear-lobe so as to ensure proper placement of the device and enhance comfort over long periods of use. Furthermore, a contiguous hole exists in the earpiece
15 **402**, PCB and enclosure **404**, which should allow for reduced sound attenuation and enable the wearer to hear their environment.
20

[0067] In some embodiments, the over-ear support **412** may be shaped as a hook or other shape to be placed around the earlobe. In other embodiments, the over-ear support **412** may comprise an earlobe clip. In other embodiments, a unit may cover both ears
25 with an earpiece **402** at one or both ears.

[0068] **FIG. 5** illustrates different elevation and perspective views **500** of an example of the in-ear EEG system **500**, in accordance with some embodiments. In this example, two of the dimensions (length and width) of the PCB enclosure **404** are shown as being 34.69 millimetres (mm) by 35 mm in a first plan view **502**. In a second plan view **504**, the third
30 dimension (depth) is shown as 11.29 mm. It is understood that the selection of which dimensions are considered as length, width and depth are arbitrary, and that other

dimension sizes may be used in other examples. The third plan view **506** shows the power port **508** and output signal port **410**. The second **504** and third **506** plan views, and a perspective view **408**, show that the earpiece **402** may be detachable from the device **400** and connected to earpiece attachment **450**. The device may be manufactured using additive manufacturing (i.e., 3D printing).

[0069] The electrical signal produced by neural activity in the brain (the basis of EEG) is on the order of microvolts. Frequencies of interest in the EEG signal include the delta (0.5 to 3.5-Hz), theta (4 to 7-Hz), alpha (8 to 13-Hz), beta (15 to 28-Hz) and gamma (30 to 70-Hz) bands. The small magnitude of the EEG signal necessitates amplification so that its magnitude is adequate to be discretized by an analog-to-digital converter (ADC). Furthermore, environmental noise (namely, 60-Hz electrical power line noise) and aliasing present the need to filter the raw EEG signal prior to digital conversion.

[0070] Any time wiring is involved, electrical noise in the environment could inject false signals into the wires before they reach the processor. Buffers (i.e., common buffer amplifiers in analog circuit design) may be added near the electrodes inside the ear allowing for shorter wires between the electrodes and the first piece of circuitry. A buffer amplifier is a circuit that separates the input signal from the downstream electronics (including the length of wiring). It is possible for downstream electronics, and specifically relatively long wires, to affect and change the input signal, and a buffer amplifier separates the two parts of the circuit, by adjusting the effective impedances seen by the input signal and the downstream electronics, so that the effects are minimized.

[0071] The buffers may also help minimize the impact of environmental noise. Thus, downstream electronic components (e.g., amplifier, filters, processor, etc.) may be positioned further away from the electrode pads than they otherwise could without the buffers. This, in turn, provides more freedom to the physical design of the system. A design where the downstream components are next to the ear would not need buffers. Buffers could be used when the physical design of the system has those components further away.

[0072] An amplifier is a signal stage that increases the signal strength before the signal reaches the processor. Since the processor has a set resolution, a small signal may be too weak to be picked up by the processor, even if it contained valuable information. The amplifier would allow the signal to be stronger, so that the processor can

pick up the variations in the signal. Whether or not an amplifier is to be used may depend on the resolution of the processor and the types of signals that are to be recorded from the electrodes.

[0073] **FIG. 6** illustrates, in a signal flow diagram, an example of a signal pathway **600**,
 5 in accordance with some embodiments. The signal pathway **600** is shown from input **602** to output **614** along with the LTSpice© simulations **616**, **618**, **620** of the filter magnitude characteristics. This example includes a 60-Hz notch-filter **606** used after a first gain stage **604**, a high-pass filter **608** ($f_c = 1\text{-Hz}$) used prior to a second gain stage **610**, and a low-pass filter **612** ($f_c = 100\text{-Hz}$). The simulations **616**, **618**, **620** plot magnitude vs.
 10 frequency of the signals passing through the filters **606**, **608**, **612**.

[0074] In some embodiments, the input **602** may comprise two electrodes **102** placed inside the ear-canal (on the earpiece **402**), along with a reference electrode placed either on the earlobe or the mastoid. In the case of the latter design choice, the reference electrode will follow the curve of the ear-lobe support. These electrodes may serve as the
 15 positive and negative inputs of the first-stage operational-amplifier, and may be placed approximately 180 degrees apart on the earpiece to maximize the differential signal.

[0075] Electrical power-line noise (60-Hz in North-America, and 50-Hz in Europe) can cause undesirable noise in the collected signal even when attempts to mitigate this through the use of differential amplifiers with a high common-mode rejection ratio (CMRR). A notch-filter **606** (otherwise known as a band-reject filter) centered at 60-Hz
 20 may be implemented in the signal pathway **600** to reduce the effect of the 60-Hz on the resulting output signal. **FIG. 7** illustrates, in a schematic diagram, an example of the topology **700** of the notch filter **606**, in accordance with some embodiments.

[0076] A high-pass filter **608** may be used prior to the second gain stage **610** in order
 25 to remove 0-Hz (DC) offset in the signal. This provides that there is minimal to no saturation of the output signal, and provides that information from the signal is not lost. **FIG. 8** illustrates, in a schematic diagram, an example of a Sallen-Key topology **800** of the high-pass filter **608**, in accordance with some embodiments.

[0077] Aliasing, the process whereby digital sampling causes shifts in frequencies
 30 above the Nyquist frequency is prevented by low-pass filtering the signal so that there is sufficient attenuation of frequencies above half the sampling frequency. In order to

ensure adequate attenuation and to enable the use of lower sampling frequencies, a low-pass Butterworth filter of order 4 was used with a cut-off of ($f_c = 100\text{-Hz}$). This assumes a sampling frequency of 1000-Hz and will suppress signals above 500-Hz (i.e., $f_s/2$) by approximately -56 dB. **FIG. 9** illustrates, in a schematic diagram, an example of a Sallen-Key topology **900** of the low-pass filter **612**, in accordance with some embodiments. This topology **900** may be used to realize this analog filter, and the associated component values are shown in **FIG. 9**.

[0078] **FIG. 10** illustrates, in a signal flow diagram, an alternative example of a signal pathway **1000**, in accordance with some embodiments. The signal pathway **1000** is shown from input **1002** to output **1014**. The signal pathway **1000** does not include a notch filter. The signal is passed through a high-pass filter **1006** after a first gain stage **1004** and prior to a second gain stage **1008**. After the second gain stage **1008**, the signal is passed through a high-pass filter **1010** and then to a low-pass filter **1012** with a cut-off frequency of 40-Hz (rather than 100-Hz). An advantage of this alternative design is that it precludes the need for a 60-Hz notch filter. However, the lower cut-off frequency of the low-pass filter **1012** will remove some information-containing EEG components above 40-Hz (specifically in the gamma band). Simulations **1016**, **1018**, **1020** show filter magnitude characteristics of the high-pass filters **1006**, **1010** and low-pass filter **1012**. Other combinations of filters and gains are possible in other examples. For example, the signal pathway **1000** may be modified such that the low-pass filter is 100-Hz and an additional gain stage is added.

[0079] In some embodiments, the PCB will be designed to miniaturize the design and ensure the reliability of the electrical components. **FIG. 11A** illustrates, in a computer-aided design (CAD), an example of a PCB **1100A**, in accordance with some embodiments. To enable customizable gains during the development phase, two variable resistors (potentiometers) may be added to the board **1100A**. The 2-pin header **450** to connect to the earpiece **402** is visible in the top-left corner of the board **1100A** along with the holes in the PCB **1100A** to allow for sound to pass through the device **400**. **FIG. 11B** illustrates, in a CAD, the top layer **1100B** of the PCB **1100A**. The 2-pin header **450** is also shown in **FIG. 11B**.

[0080] A study may be performed to assess using the in-ear EEG device **400** for a P300-ASSR BCI. For example, a study may determine the level of classification accuracy

that can be achieved when deploying an in-ear EEG device **400** measurement system in a P300-ASSR BCI paradigm with typically developed adults. The in-ear EEG device **400** may be used to collect data from patients (or subjects in studies). For example, 15 consenting typically developed adults may be the patients (or subjects). A subject may wear the in-ear EEG device **400**.

[0081] In one study embodiment, an ASSR task may be used to determine if a signal originates from neurons in the brain, and will be used to assess the fidelity of recording using the in-ear EEG electrode. White noise amplitude-modulated at 37-Hz and 43-Hz may be presented to the user for one minute, and the resulting signal from the in-ear EEG device **400** may be collected. The user may be instructed to focus on the sound, after which the user will rest for 20-seconds and then repeat this process for a total of 20 trials.

[0082] The in-ear EEG device **400** may be worn in both ears of patients to collect activity in both hemispheres of the brain. For validation purposes, measurements may also be made simultaneously via a clinical cap-based EEG system. Validating signals may be acquired from electrodes **102** placed at 32 electrode locations of the international 10-20 system **100**. The FT7 **152** and FT8 **154** are added as they are prime candidates for reference electrodes **102** using an in-ear EEG device **400**. An illustration of the 10-20 system **100** is shown in FIG. 1. In some study embodiments, subjects may also wear the in-ear EEG device **400** and data may be simultaneously recorded from both the cap and in-ear device. The signal processing, and classification methods which follow will be performed identically on both the gross cap-EEG data as well as the in-ear EEG data.

[0083] FIG. 12 illustrates an example of an experimental setup **1200**, in accordance with some embodiments. Preferably, research subjects will be seated comfortably in-front of a computer monitor. A fixation cross may be presented on the screen for the duration of the experiment to mitigate eye-blink artifacts. Surrounding the subject may be four speakers (**1202**, **1204**, **1206**, **1208**) each corresponding to a different target (1,2, 3 and 4) as shown in FIG. 12. Each target may, for the duration of the stimulus period, play Gaussian white noise AM-modulated at 37-Hz, 43-Hz, 46-Hz and 49-Hz respectively.

[0084] At the start of the experiment, subjects are asked to focus on one of the four speakers **1202**, **1204**, **1206**, **1208**. In some embodiments, this prompt may be a computerized voice asking the subject to "Please focus on speaker X" and may come

from the corresponding speaker X. This prompt may last for a duration of approximately 1.5 seconds. After this, the stimulus period may begin and the four speakers **1202**, **1204**, **1206**, **1208** may produce the previously described AM-modulated noise. In a pseudo-random order, the volume of the AM-modulated noise from one of the targets (1, 2, 3 or 4) may increase for a duration of 200-ms (milliseconds) followed by 200-ms of equal volume (denoted as the inter-stimulus interval (ISI)), and then another random target may increase in volume relatively sharply for a duration of 200-ms. This process may continue until each target has increased in volume (i.e., a single repetition of each speaker **1202**, **1204**, **1206**, **1208** increasing in volume). **FIG. 13** illustrates an example of an overview of an experimental protocol **1300**, in accordance with some embodiments. One example trial sequence, 3-2-1-4 is shown. These sequences may be randomly generated for each trial to avoid user adaptation. This single repetition of stimuli may be presented to the subject as part of a single trial block and forms the basic P300 eliciting odd-ball paradigm.

[0085] Each experiment may be divided into two phases: a training phase, and an online-spelling phase. During the training phase, the subject may be prompted with a speaker to focus on one of the speakers, and each selection will consist of 10 trial blocks. In some embodiments, no feedback is provided to the user after each selection during the training phase. Each run may comprise 10 selections, and the training phase may comprise 10 runs, totaling 100 selections.

[0086] During the online phase, the number of trial blocks may dynamically change based on the confidence of the machine learning algorithm. Each trial is followed by a feedback period whereby a voice prompt is used to convey the target the computer believes the user was focusing on. The online phase may last for a duration of 5 runs (50 selections).

[0087] In one study embodiment, 15 participants will be recruited that are 18 years of age or older, have no history of stroke or other neurological conditions, have normal or corrected-to-normal vision, and have normal hearing.

[0088] Both P300 and ASSR features may be extracted from the EEG signal. These complimentary features may then be used together in the machine learning algorithm to classify user selections.

[0089] Some groups have used simple decimation to down-sample (i.e., taking every nth sample to reduce the number of data points) to extract P300 features from the EEG signal. However, this method is susceptible to collecting random noise in the data. The P300 features may be extracted by using a moving average filter and taking the average of every 40 samples resulting in a sample rate of 1000-Hz / 40 = 25-Hz. **FIG. 14** illustrates an example of a P300 feature extraction process **1400**, in accordance with some embodiments. This is equivalent to first low-pass filtering the signal and then retaining every nth sample; a process known as decimation.

[0090] **FIG. 15** illustrates an example of an ASSR feature extraction process **1500**, in accordance with some embodiments. A fast-fourier transform may be performed on the EEG data and the resulting frequency domain data used to calculate the power-spectral density (PSD) with bins centered at the target frequencies +/- 1-Hz. A feature vector including the PSD in each bin for each trial may be used in the machine learning algorithm.

[0091] BLDA classifiers, or other machine learning (i.e., neural networks, deep learning, etc.) classifiers, may be used to train both the P300 and ASSR classifiers. Each trial may produce a P300 feature vector along with an ASSR feature vector for both targets and non-targets. These labelled vectors may be used to train two separate Stepwise Linear Discriminant Analysis (SWLDA) classifiers, one for the P300 and one for the ASSR. This will produce an ASSR and P300 score. SWLDA, like other linear-discriminant analysis algorithms, assumes a normal data distribution with equal covariance between class one and two. Its aim is to find a class-separating hyperplane that maximizes the separation of the class means while minimizing inner class variance.

$$Score^{p300} = \frac{1}{K} \sum_{i=1}^K Y_{ij}^{p300}$$

Here i represents the trial number, j is the target number, K is the total number of trials and Y is the P300 response score calculated using the down-sampled raw EEG data multiplied by the weights determined using the SWLDA classifier.

[0092] Similarly, for the ASSR classification, the feature vector may be tagged with either a target or a non-target label using the subject training data. These labeled vectors

may then be used to train a SWLDA classifier that will be used to classify new data in the online section of the experiment.

[0093] This will produce a $Score_c^{fusion}$ for each target (i.e., class). The ASSR and P300 scores may be fused as:

$$Score_c^{fusion} = wc1 * Score_c^{ASSR} + wc2 * Score_c^{P300}$$

- 5 The SWLDA class with the highest fusion score may be classified as the target class.

[0094] FIG. 16 is a view of an example brain-computer interface (BCI) system 1600, in accordance with some embodiments. BCI system 1600 includes BCI platform 1610, which includes classification device 1620. BCI platform 1610 connects to interface application 1630, for example, to gather EEG data or other data from a user engaged with interface application 1630. The data gathered or a modification of the data gathered may encode communication or input (such as EEG signals or other readings denoting brain activity) from individuals who are performing mental tasks. The interface application 1630 can include electrodes to generate EEG signals. Interface application 1630 can include other sensors, for example. Interface application 1630 and BCI platform 1610 can receive other types of data, including imaging data, for example. Interface application 1630 can include one or more clocks to synchronize data collected from different sensors and modalities.

[0095] BCI platform 1610 can connect to interface application 1630 to cause one or more questions to be presented to a user engaged at interface application 1630, and to receive one or more responses to questions or other data input from the user. The questions can be presented on a display device using an interface generated by interface application 1630. The questions can be presented by way of an audio signal and speaker, as another example. BCI platform 1610 can organize the received data or aggregate the data with other data. For example, data from a question and answer exchange with a user can be used by BCI platform 1610 to verify collected EEG data encoding the user's mental state. BCI platform 1610 can organize the received data or aggregate the data with other data using time stamps and clock data for synchronization.

[0096] Interface application 1630 can engage a user, for example, via electrodes 102 strategically placed on the user's scalp corresponding to brain regions providing

discriminative information or showing task-based activation, such as data corresponding to mental state. In some embodiments, the electrodes **102** may form part of a headset that is engaged with a BCI platform **1610**, or houses a BCI platform **1610**. The headset can additionally process data. Interface application **1630** can also engage a user via a display, interactive display, keyboard, mouse, or other sensory apparatus. Interface application **130** can transmit and receive signals or data from such devices and cause data to be sent to BCI platform **1610**. In some embodiments, the headset may comprise the in-ear EEG device **400** monitoring a subset of the electrodes **52**.

[0097] In some embodiments, interface application **1630** can process data before sending the data via network **1640** and/or to BCI platform **1610**. A user can be engaged with interface application **1630** via electrodes **102**, or a headset or in-ear EEG device **400**. In some embodiments, BCI platform **1610** and/or classification device **1620** can be housed in the headset or other means of engagement with interface application **1630**. In some embodiments, BCI platform **1610** and/or classification device **1620** can connect to interface application **1630** over a network **1640** (or multiple networks).

[0098] Classification device **1620** associated with BCI platform **1610** can receive sensor data, for example, EEG data from a single user via interface application **1630**. Classification device **1620** can receive stored data from one or more external systems **1650** or interface applications **1630**, such as data corresponding to other sessions of data collection, for example. Classification device **1620** can build or train a classification model using this data, for example, EEG data from a single user. Classification device **1620** can use the classifier to classify mental states of the user and cause a result to be sent to an entity (such as external system **1650**) or interface application **1630**. The result can cause an entity to actuate a response, which can be an alert to a caregiver, or data for a researcher.

[0099] The classifier can be re-trained on additional EEG data, for example, data collected from the user at a more contemporaneous time. This may improve the accuracy of the classifier, for example, if same session data are more relevant than data collected from previous days. Further, additional data may improve the accuracy of the classifier so it can be continuously updated and trained as more data and feedback is provided to the BCI platform **1610**.

[0100] BCI platform **1610** can connect to interface application **1630** via a network **1640** (or multiple networks). Network **1640** (or multiple networks) is capable of carrying data and can involve wired connections, wireless connections, or a combination thereof. Network **1640** may involve different network communication technologies, standards and protocols, for example.

[0101] In some embodiments, external systems **1650** can connect to BCI platform **1610** and/or classification device **1620**, for example, via network **1640** (or multiple networks). External systems **1650** can be one or more databases or data sources or one or more entities that aggregate or process data. For example, an external system **1650** can be a second BCI platform **1610** that collects EEG data (or other data), performs feature extraction on the data, and builds a classification model. The external system **1650** can then process the data and/or build one or more classification models based on a selection of features. The one or more classification models can be used by one or more other BCI platforms **1610**, stored in a database, and/or transmitted to an external system **1650**, for example, that is accessible by researchers or developers.

[0102] External systems **1650** can receive data from an interface application **1630**, BCI platform **1610**, and/or classification device **1620**. This data can include raw data collected by interface application **1630**, such as EEG data from electrodes **102** placed on a user's scalp, data processed by interface application **1630**, BCI platform **1610**, and/or classification device **1620** (including a classification device **1620** housed in a headset associated with electrodes **102** placed on a user's scalp or in-ear device **400**), and/or data from one or more other external systems **1650**. This connectivity can facilitate the viewing, manipulation, and/or analysis of the data by a researcher, developer, and/or healthcare provider engaged with an external system **1650**.

[0103] FIG. 17 is a view of an example BCI platform **1610** and classification device **1620**, in accordance with some embodiments. A BCI platform **1610** can include an I/O unit **1711**, processing device **1712**, communication interface **1723**, and classification device **1620**.

[0104] A BCI platform **1610** can connect with one or more interface applications **1630**, entities **1750**, data sources **1760**, and/or databases **1770**. This connection may be over a network **1640** (or multiple networks). BCI platform **1610** receives and transmits data from

one or more of these via I/O unit **1711**. When data is received, I/O unit **1711** transmits the data to processing device **1712**.

[0105] Each I/O unit **1711** can enable the BCI platform **1610** to interconnect with one or more input devices, such as a keyboard, mouse, camera, touch screen and a microphone, and/or with one or more output devices such as a display screen and a speaker.

[0106] A processing device **1712** can execute instructions in memory **1721** to configure classification device **1620**, and more particularly, data collection unit **1722**, signal processing and feature extraction unit **1723**, oversampling unit **1724**, feature selection unit **1725**, and classification unit **1726**. A processing device **1712** can be, for example, any type of general-purpose microprocessor or microcontroller, a digital signal processing (DSP) processor, an integrated circuit, a field programmable gate array (FPGA), a reconfigurable processor, or any combination thereof. The oversampling is optional and in some embodiments there may not be an oversampling unit.

[0107] Memory **1721** may include a suitable combination of any type of computer memory that is located either internally or externally such as, for example, random-access memory (RAM), read-only memory (ROM), compact disc read-only memory (CDROM), electro-optical memory, magneto-optical memory, erasable programmable read-only memory (EPROM), and electrically-erasable programmable read-only memory (EEPROM), Ferroelectric RAM (FRAM) or the like. Classification device **1620** can include memory **1721**, databases **1727**, and persistent storage **1728**.

[0108] Each communication interface **1723** can enable the BCI platform **1610** to communicate with other components, to exchange data with other components, to access and connect to network resources, to serve applications, and perform other computing applications by connecting to a network (or multiple networks) capable of carrying data including the Internet, Ethernet, plain old telephone service (POTS) line, public switch telephone network (PSTN), integrated services digital network (ISDN), digital subscriber line (DSL), coaxial cable, fiber optics, satellite, mobile, wireless (e.g. Wi-Fi, WiMAX), SS7 signaling network, fixed line, local area network, wide area network, and others, including any combination of these.

[0109] The BCI platform **1610** can be operable to register and authenticate users (using a login, unique identifier, and password for example) prior to providing access to applications, a local network, network resources, other networks and network security devices. The platform **1610** may serve one user or multiple users.

5 [0110] The database(s) **1727** may be configured to store information associated with or created by the classification device **1620**. Database(s) **1727** and/or persistent storage **1728** may be provided using various types of storage technologies, such as solid state drives, hard disk drives, flash memory, and may be stored in various formats, such as relational databases, non-relational databases, flat files, spreadsheets, extended markup
10 files, etc.

[0111] Classification device **1620** can be used to build a classification model by training on data received from interface application **1630** or other entities **1750**, for example, EEG data collected during a change in mental state of a user. Data collection unit **1722** associated with a classification device **1620** and BCI platform **1610** can receive
15 data, for example, EEG data from a single user via interface application **1630**. Data collection unit **1722** can receive stored data from one or more external systems (or entities **1750**) or interface applications **1630**, for example, corresponding to other sessions of data collection.

[0112] Signal processing and feature extraction unit **1723** associated with a
20 classification device **1620** can process the data or EEG signals, for example, to remove linear trends, electrical noise, and EEG artifacts, and can reconstruct the EEG signal from the remaining components.

[0113] Signal processing and feature extraction unit **1723** can extract features from the data or EEG data using one or more feature extraction methods, such as common spatial
25 pattern, matched-filtering, spectral power estimates, or auto-regressive (Yule-Walker) model of order of magnitude, e.g., three, or wavelet transform. This can produce a vector of features. The order of magnitude can vary.

[0114] Oversampling unit **1724** can sample the data or EEG data, for example, to oversample data collected at a more contemporaneous time. In some embodiments,
30 cost-sensitive classification can be used to give the more contemporaneous data larger coefficients in the cost function compared to data collected on, for example, a previous

day. Oversampling unit **1724** can thus facilitate higher classification accuracies, for example, by oversampling data collected from the same session that the classification model, once built, will be used to classify EEG data. The oversampling is optional, and in some embodiments there may not be an oversampling step.

5 [0115] Feature selection unit **1725** can select features from the features extracted from the data or EEG data. This may help reduce or avoid overfitting the data, facilitate the generalizability of the data, or facilitate the applicability of a classifier modelled on the data or features extracted from the data. In some embodiments, a classification model is trained on data or features selected from a single user, for example, the ten best features
 10 extracted from a set of features extracted from the data collected from the user. The features may be selected based on how they relate to accuracy of the resulting classification model or lowest error.

[0116] Classification unit **1726** associated with the classification device **1620** can use the selected features to train an algorithm, such as a linear support vector machine. The
 15 algorithm can be used for machine learning classification of data to facilitate classification of mental state given EEG data as input. For example, BCI platform **1610** can use EEG data to build a support vector machine classification model for a particular user who was or is engaged with interface application **1630**. The classifier can be re-trained on additional EEG data, for example, data collected from the user at a more
 20 contemporaneous time. This may improve the accuracy of the classifier, for example, if same session data are more valuable than data collected from previous days.

[0117] At a later time or at a time immediately following re-training of the classifier, interface application **1630** can receive EEG data from the user, for example, corresponding to the user's mental state. Interface application **1630** can transmit the data
 25 to BCI platform **1610**. As described above, data collection unit **1722** can collect the EEG data, signal processing and feature extraction unit **1723** can process the data and extract features, feature selection unit **1725** can select the relevant subset of features, and classification unit **1726** can use the personalized classification model for that user to help determine the user's mental state. An example classification model can be a support
 30 vector machine classification model. Another example classification model can be a shrinkage linear discriminant analysis model. The determination can be processed and/or

presented to a user via interface application **1630** or transmitted to an external system (or entities **1750**), for example, a device or system accessible by a caregiver or researcher.

[0118] **FIG. 18** is a view of an example interface application **1630**, in accordance with some embodiments. In some embodiments, interface application **1630** includes a classification device **1620**. In some embodiments, interface application **1630** is connected to a headset associated with or housing a BCI platform **1610** and classification device **1620**. The headset may include multiple electrodes **102** to collect EEG data when connected to a user's scalp. In some embodiments, the headset may comprise the in-ear EEG device **400**. The signals may be collected by signal collection unit **1834**, which may connect to BCI platform **1610** optionally housed within the headset. The BCI platform **1610** can create and/or use one or more classifiers as described above. For example, the BCI platform **1610** within a headset or in-ear EEG device **400** can train and retrain a classifier using EEG data from one or more sessions from a single user engaged with interface application **1630** or headset or in-ear EEG device **400**. BCI platform **1610** can use the classifier to classify mental states of the user using further EEG signals. BCI platform **1610** may be operable as described above.

[0119] In some embodiments, signal collection unit **1834** may be associated with an interface application **1630** that does not include a headset or in-ear EEG device **400**. Signal collection unit **1834** can gather data, for example EEG data, from a user engaged with interface application **1630**. Interface application **1630** can then cause transmission of data, the EEG signals, processed data or processed EEG signals, or other information to a BCI platform **1610** and/or classification device **1620** over a network **1640** (or multiple networks). The BCI platform **1610** can train and retrain a classifier using EEG data from one or more sessions from a single user engaged with interface application **1630** or headset or in-ear EEG device **400**. BCI platform **1610** can use the classifier to classify mental states of the user using further EEG signals. BCI platform **1610** may be operable as described above.

[0120] In some embodiments, interface application **1630** connects to a BCI platform **1610** and classification device **1620** over a network **1640** (or multiple networks).

[0121] Each I/O unit **1837** enables the interface application **1630** (including headset or in-ear device **400**) to interconnect with one or more input devices, such as a keyboard, mouse, camera, touch screen, microphone, electrodes, headset, or other sensory

collection devices, for example, that can detect brain activity or mental state. Each I/O unit **1837** also enables the interface application **1630** (including headset or in-ear EEG device **400**) to interconnect with one or more output devices such as a display screen, speaker, or other devices presenting visuals, haptics, or audio.

5 [0122] A processing device **1838** can execute instructions in memory **1832** to configure user interface unit **1833** and signal collection unit **1834**. A processing device **1838** can be, for example, any type of general-purpose microprocessor or microcontroller, a digital signal processing (DSP) processor, an integrated circuit, a field programmable gate array (FPGA), a reconfigurable processor, or any combination
10 thereof.

[0123] Memory **1832** may include a suitable combination of any type of computer memory that is located either internally or externally such as, for example, random-access memory (RAM), read-only memory (ROM), compact disc read-only memory (CDROM), electro-optical memory, magneto-optical memory, erasable programmable
15 read-only memory (EPROM), and electrically-erasable programmable read-only memory (EEPROM), Ferroelectric RAM (FRAM) or the like. Storage devices **1831** can include memory **1832**, databases **1835**, and persistent storage **1836**.

[0124] Each communication interface **1839** can enable the interface application **1630** to communicate with other components, to exchange data with other components, to
20 access and connect to network resources, to serve applications, and perform other computing applications by connecting to a network (or multiple networks) capable of carrying data including the Internet, Ethernet, plain old telephone service (POTS) line, public switch telephone network (PSTN), integrated services digital network (ISDN), digital subscriber line (DSL), coaxial cable, fiber optics, satellite, mobile, wireless (e.g.,
25 Wi-Fi, WiMAX), SS7 signaling network, fixed line, local area network, wide area network, and others, including any combination of these.

[0125] The interface application **1630** can be operable to register and authenticate users (using a login, unique identifier, and password for example) prior to providing access to applications, a local network, network resources, other networks and network
30 security devices. The BCI platform **1610** may serve one user or multiple users.

[0126] The database **1835** may be configured to store information associated with or created by the classification device **1620**. Database **1835** and/or persistent storage **1836** may be provided using various types of storage technologies, such as solid state drives, hard disk drives, flash memory, and may be stored in various formats, such as relational
 5 databases, non-relational databases, flat files, spreadsheets, extended markup files, and so on.

[0127] User interface unit **1833** can manage the dynamic presentation, receipt, and manipulation of data, such as for example, input received from interface application **1630**. User interface unit **1833** can associate the mental state of the user, for example,
 10 gathered by a signal collection unit **1834** and classified by a BCI platform **1610**, as a mental state and cause storage of same in storage devices **1831** or transmission of same over network **1640** (or multiple networks). As another example, user interface unit **1833** can facilitate validation of a user mental state with the result determined by a BCI platform **1610** or classifier. The interface application **1630** can gather the mental state via
 15 I/O unit **1837** connected to a keyboard, touchscreen, mouse, microphone, or other sensory device. User interface unit **1833** can associate the mental state with the result determined by a BCI platform **1610** or classifier to verify the accuracy of the BCI platform **1610** or classifier. In some embodiments, interface application **1630** can transmit the response to a BCI platform **1610**.

[0128] **FIG. 19** illustrates, in a flowchart, an example of a method **1900** of validating an in-ear EEG device **400** for use as a BCI, in accordance with some embodiments. The method begins with performing **1902** a set of trial experiments on a plurality of subjects, where each subject is wearing the in-ear EEG device **400** and a clinical EEG cap. Next, P300 features are extracted **1904** from signals received from the in-ear EEG device **400**.
 25 Next, P300 features are extracted **1906** from signals received from the clinical EEG cap. It is understood that step **1906** may be performed before step **1904**. Next, auditory steady-state response (ASSR) features are extracted **1908** from the in-ear EEG device **400**. Next, AASR features are extracted **1910** from the clinical EEG cap. It is understood that step **1910** may be performed before step **1908**. Next, the P300 features and ASSR features received from the in-ear EEG device **400** signals are classified **1912**. Next, the
 30 P300 features and ASSR features received from the clinical EEG cap signals are classified **1914**. It is understood that step **1914** may be performed before step **1912**.

Next, the in-ear EEG classifications are compared **1916** with the clinical EEG cap signal classifications. Other steps may be added to the method **1900**.

[0129] An EEG device and BCI system may be used for visual spatial imagery tasks. For example, visual cues may be displayed on an output unit to a participant. **FIG. 20A**
 5 illustrates, in a display, an example of four directional visual cues **2000A**, in accordance with some embodiments. The visual cues comprise an upper-left arrow **2002**, an upper right arrow **2004**, a lower left arrow **2006** and a lower right arrow **2008**. The participant is instructed to choose a direction. A visual cue is presented to the participant. If the visual cue does not match the direction they chose, then the participant is to rest which causes
 10 the presentation of another visual cue. If the visual cue does match the direction they chose, then the participant is to visualize the movement of a character in a game.

[0130] **FIG. 20B** illustrates an example of a system environment **2000B** showing a participant wearing electrode sensors **102** (i.e., electrodes **102**) watching a display unit **2010**, in accordance with some embodiments. The output (i.e., display unit **2010**) is
 15 displaying a visual cue for the direction lower-left **2006**. The participant is to visualize a movement of a character in that direction. In some embodiments, the electrode sensors **102** may comprise electrodes **102** on an earpiece **402** of an in-ear EEG device **400**.

[0131] **FIG. 20C** illustrates another example of a system environment **2000C** showing the participant wearing the electrode sensors **102** watching the display unit **2010**, in
 20 accordance with some embodiments. Here, the character **2022** is correctly moving in the lower-left direction in response to the participant's visualization. In this example, the brain-state that the participant would experience during visualization would be detected by one or more sensors **102** (e.g., electrodes **102**). In some embodiments, the electrode sensors **102** may comprise electrodes **102** on an earpiece **402** of an in-ear EEG device
 25 **400**.

[0132] The EEG signals received by the electrodes **102** may be pre-processed by a collector device and sent to an acquisition unit in a server. The EEG data may then be sent to a processor to determine the visual imagery of the participant. A presentation unit may receive the brain-state and generate the visual elements of the character **2022**
 30 moving along the lower-left direction. The display controller issues control commands to the display device **2010** to update the interface with the visual elements (e.g., have the character **2022** move along the lower-left direction).

[0133] The example described in **FIGs. 20A to 20C** involved the use of active BCI monitoring. However, passive BCI monitoring can be applied in parallel to detect the brain-state that the participant would experience during performance of the mental task. For example, the participant may experience frustration if the task is not successful. Such mental state or brain activity would be detected by one or more sensors **102** (e.g., electrodes **102**).

[0134] The foregoing discussion provides many example embodiments of the inventive subject matter. Although each embodiment represents a single combination of inventive elements, the inventive subject matter is considered to include all possible combinations of the disclosed elements. Thus, if one embodiment comprises elements A, B, and C, and a second embodiment comprises elements B and D, then the inventive subject matter is also considered to include other remaining combinations of A, B, C, or D, even if not explicitly disclosed.

[0135] The embodiments of the devices, systems and methods described herein may be implemented in a combination of both hardware and software. These embodiments may be implemented on programmable computers, each computer including at least one processor, a data storage system (including volatile memory or non-volatile memory or other data storage elements or a combination thereof), and at least one communication interface.

[0136] Program code is applied to input data to perform the functions described herein and to generate output information. The output information is applied to one or more output devices. In some embodiments, the communication interface may be a network communication interface. In embodiments in which elements may be combined, the communication interface may be a software communication interface, such as those for inter-process communication. In still other embodiments, there may be a combination of communication interfaces implemented as hardware, software, and combination thereof.

[0137] Throughout the foregoing discussion, numerous references will be made regarding servers, services, interfaces, portals, platforms, or other systems formed from computing devices. It should be appreciated that the use of such terms is deemed to represent one or more computing devices having at least one processor configured to execute software instructions stored on a computer readable tangible, non-transitory medium. For example, a server can include one or more computers operating as a web

server, database server, or other type of computer server in a manner to fulfill described roles, responsibilities, or functions.

5 [0138] The technical solution of embodiments may be in the form of a software product. The software product may be stored in a non-volatile or non-transitory storage medium, which can be a compact disk read-only memory (CD-ROM), a USB flash disk, or a removable hard disk. The software product includes a number of instructions that enable a computer device (personal computer, server, or network device) to execute the methods provided by the embodiments.

10 [0139] The embodiments described herein are implemented by physical computer hardware, including computing devices, servers, receivers, transmitters, processors, memory, displays, and networks. The embodiments described herein provide useful physical machines and particularly configured computer hardware arrangements.

[0140] Although the embodiments have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein.

15 [0141] Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means, methods and steps described in the specification.

[0142] As can be understood, the examples described above and illustrated are intended to be exemplary only.

WHAT IS CLAIMED IS:

1. An in-ear electroencephalography (EEG) device comprising:

an enclosure having a power switch, analog output, power input, and processor, the processor configured to receive EEG data and generate output data for the analog output;

an earpiece having two electrodes to collect the EEG data, the earpiece coupled to the enclosure to transmit the EEG data to the processor; and

an over-ear support arm having a reference electrode to collect the EEG data, the over-ear support arm coupled to an enclosure to transmit the EEG data to the processor.
2. An in-ear electroencephalography (EEG) device comprising:

an over-ear support arm coupled to an enclosure, the enclosure comprising a printed circuit board (PCB) of the device and including:

an analog output;

a power input;

a processor configured to receive EEG data and generate output data;
and

a header for connecting an earpiece to the EEG device.
3. The in-ear EEG device as claimed in claim 2, further comprising the earpiece connected to the header.
4. The in-ear EEG device as claimed in claim 3, wherein the header is a two-pin header on the PCB.

5. The in-ear EEG device as claimed in claim 3, further comprising two electrodes on the earpiece and a reference electrode on the over-ear support arm.
6. The in-ear EEG device as claimed in claim 5, wherein:

the reference electrode follows a curve of the over-ear support arm; and

the two electrodes on the earpiece serve as positive and negative inputs.
7. The in-ear EEG device as claimed in claim 2, further comprising a power switch.
8. The in-ear EEG device as claimed in claim 2, further comprising a notch filter on the PCB.
9. The in-ear EEG device as claimed in claim 8, wherein the notch filter is centered at 60-Hz.
10. The in-ear EEG device as claimed in claim 2, further comprising a high-pass filter on the PCB.
11. The in-ear EEG device as claimed in claim 10, wherein the high-pass filter is a 1-Hz high-pass filter for removing 0-Hz (DC) offset in a signal.
12. The in-ear EEG device as claimed in claim 2, further comprising a low-pass filter on the PCB.
13. The in-ear EEG device as claimed in claim 12, wherein the low-pass filter is a 100-Hz low-pass filter.

14. The in-ear EEG device as claimed in claim 2, further comprising:
- a 60-Hz notch filter;
 - a 1-Hz high-pass filter; and
 - a 100-Hz low-pass filter;
- wherein a signal input is passed by a first gain stage, the notch-filter, the high-pass filter, a second gain stage and the low-pass filter.
15. The in-ear EEG device as claimed in claim 2, further comprising:
- a first 1-Hz high-pass filter;
 - a second 1-Hz high-pass filter; and
 - a 40-Hz low-pass filter;
- wherein a signal input is passed by a first gain stage, the first high-pass filter, a second gain stage, the second high-pass filter and the low-pass filter.
16. The in-ear EEG device as claimed in claim 2, further comprising:
- a buffer for storing EEG signals; and
 - an amplifier for increasing the signal amplitude.
17. A method of validating an in-ear electroencephalography (EEG) device for use as a brain-computer interface (BCI), the method comprising:
- performing a set of trial experiments on a plurality of subjects, each subject wearing the in-ear EEG device and a clinical EEG cap;
 - extracting P300 features from signals received from the in-ear EEG device;
 - extracting P300 features from signals received from the clinical EEG cap;

extracting auditory steady-state response (ASSR) features from the signals received from the in-ear EEG device;

extracting ASSR features from the signals received from the clinical EEG cap;

classifying the P300 features and ASSR features received from the in-ear EEG device signals;

classifying the P300 features and ASSR features received from the clinical EEG cap signals; and

comparing the in-ear EEG classifications and the clinical EEG cap signal classifications.

18. A non-transitory computer-readable storage medium comprising computer-executable instructions for validating an in-ear electroencephalography (EEG) device for use as a brain-computer interface (BCI), the computer-executable instructions causing a processor to:

extract P300 features from signals received from an in-ear EEG device;

extract P300 features from signals received from a clinical EEG cap;

extract auditory steady-state response (ASSR) features from the signals received from the in-ear EEG device;

extract ASSR features from the signals received from the clinical EEG cap;

classify the P300 features and ASSR features received from the in-ear EEG device signals;

classify the P300 features and ASSR features received from the clinical EEG cap signals; and

compare the in-ear EEG classifications and the clinical EEG cap signal classifications.

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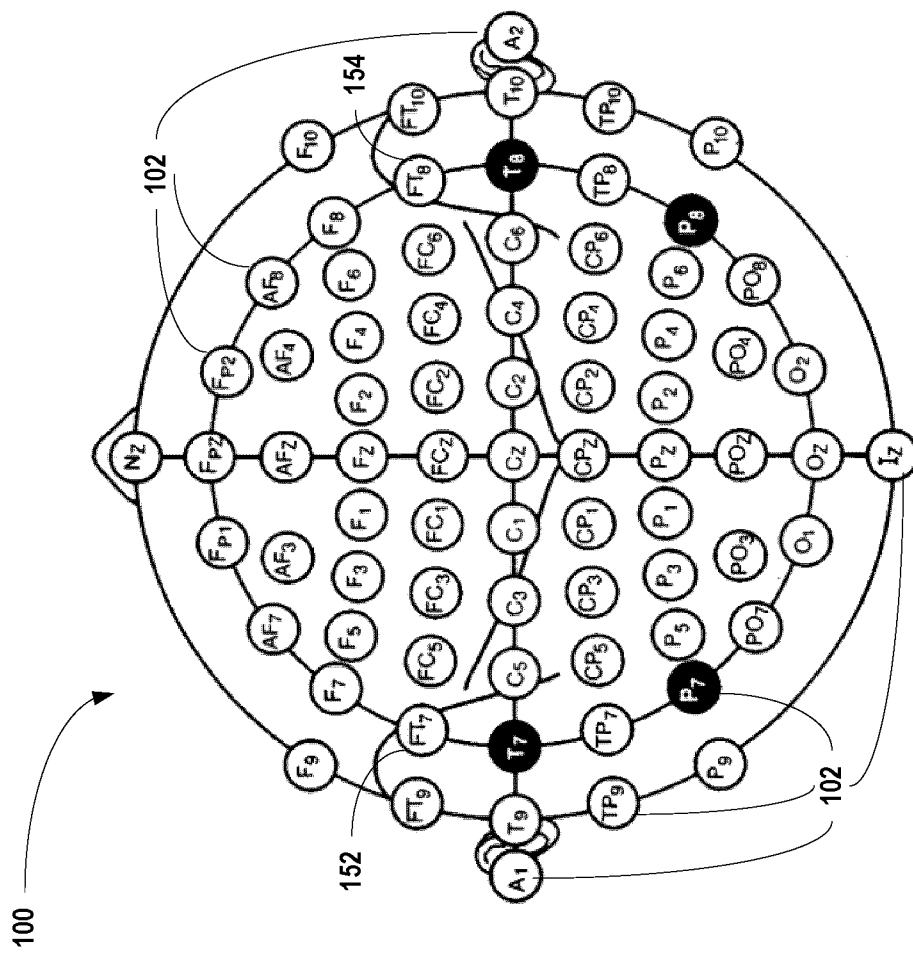


FIG. 1

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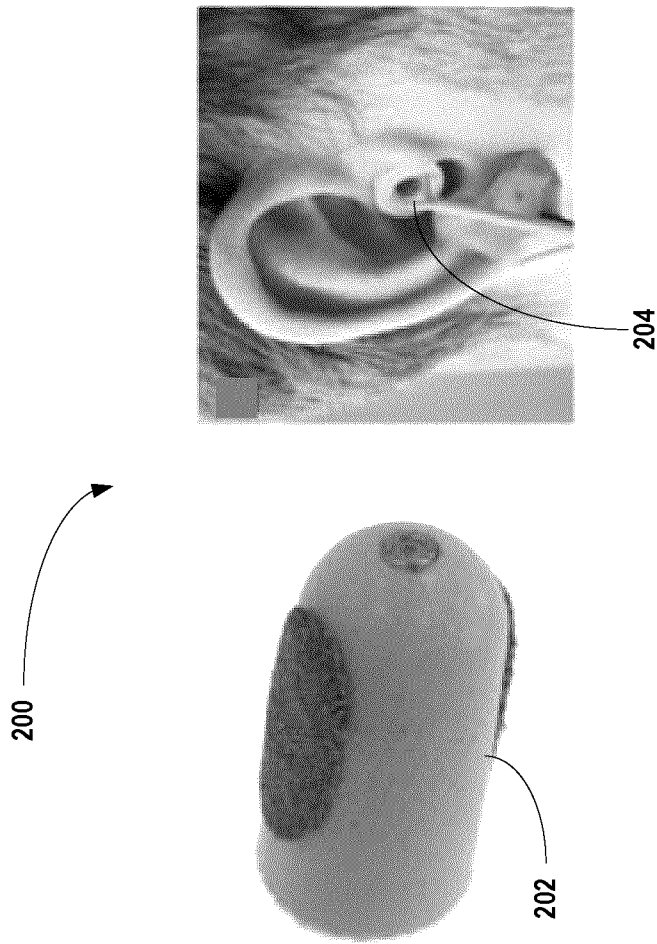


FIG. 2

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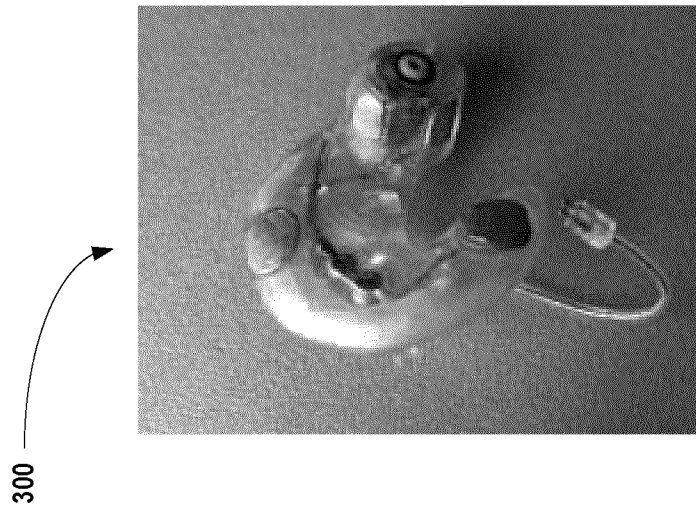


FIG. 3

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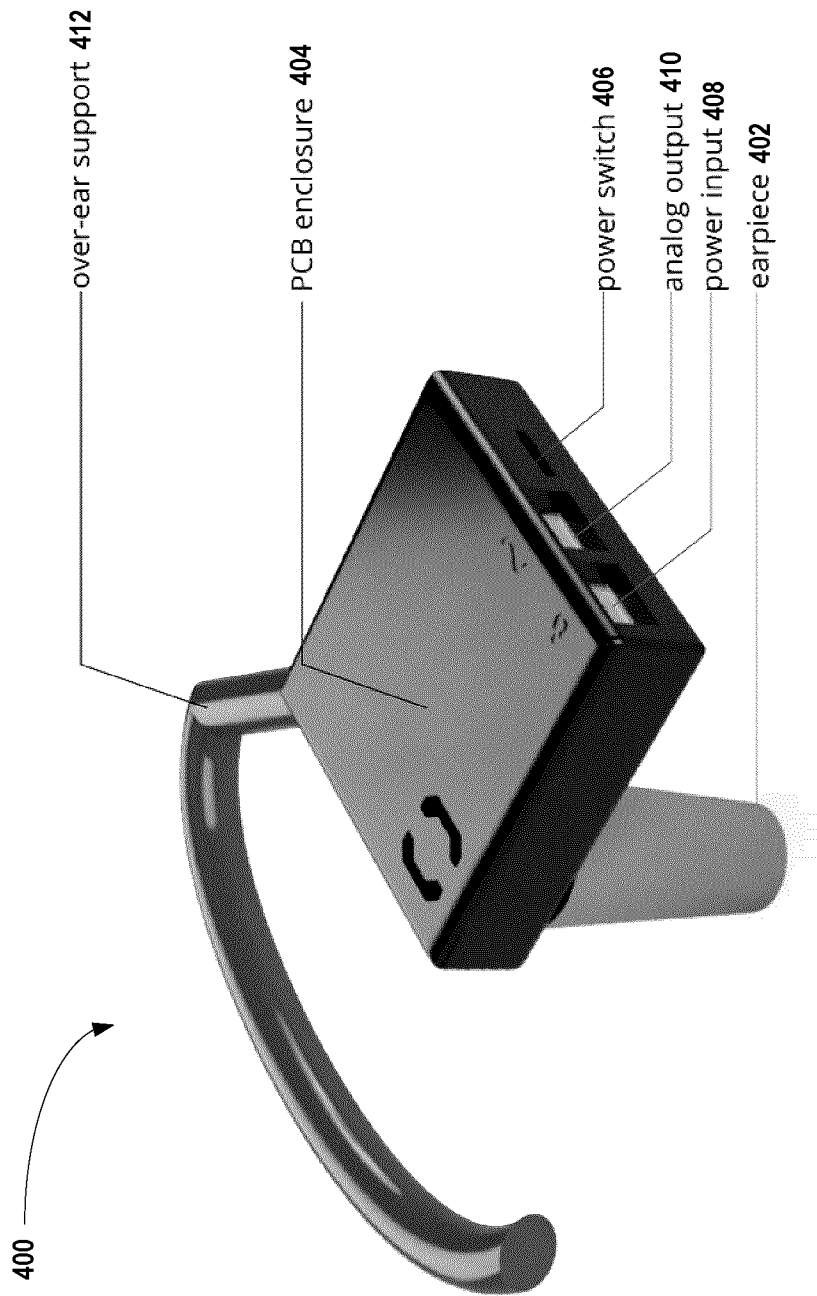


FIG. 4

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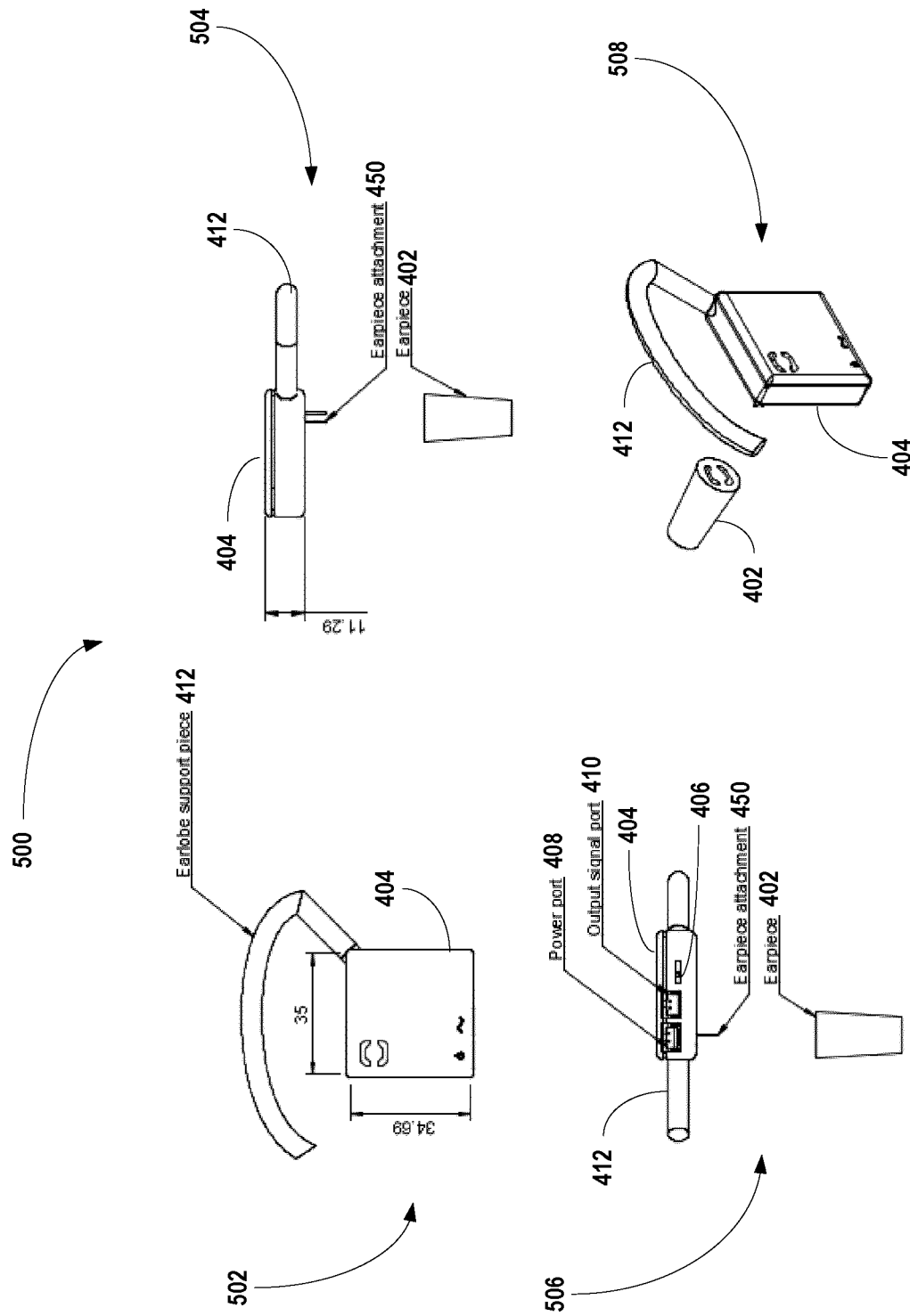


FIG. 5

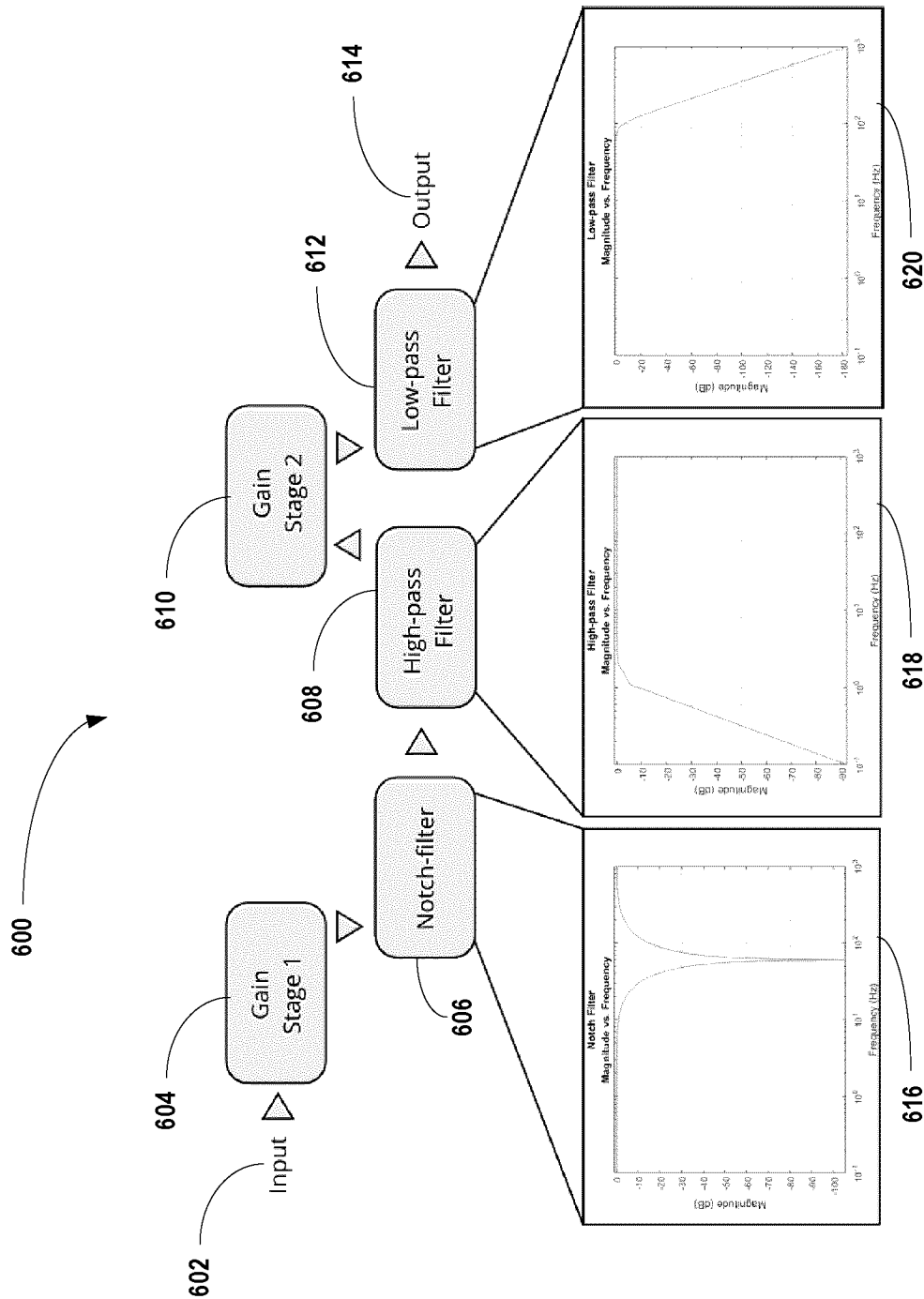


FIG. 6

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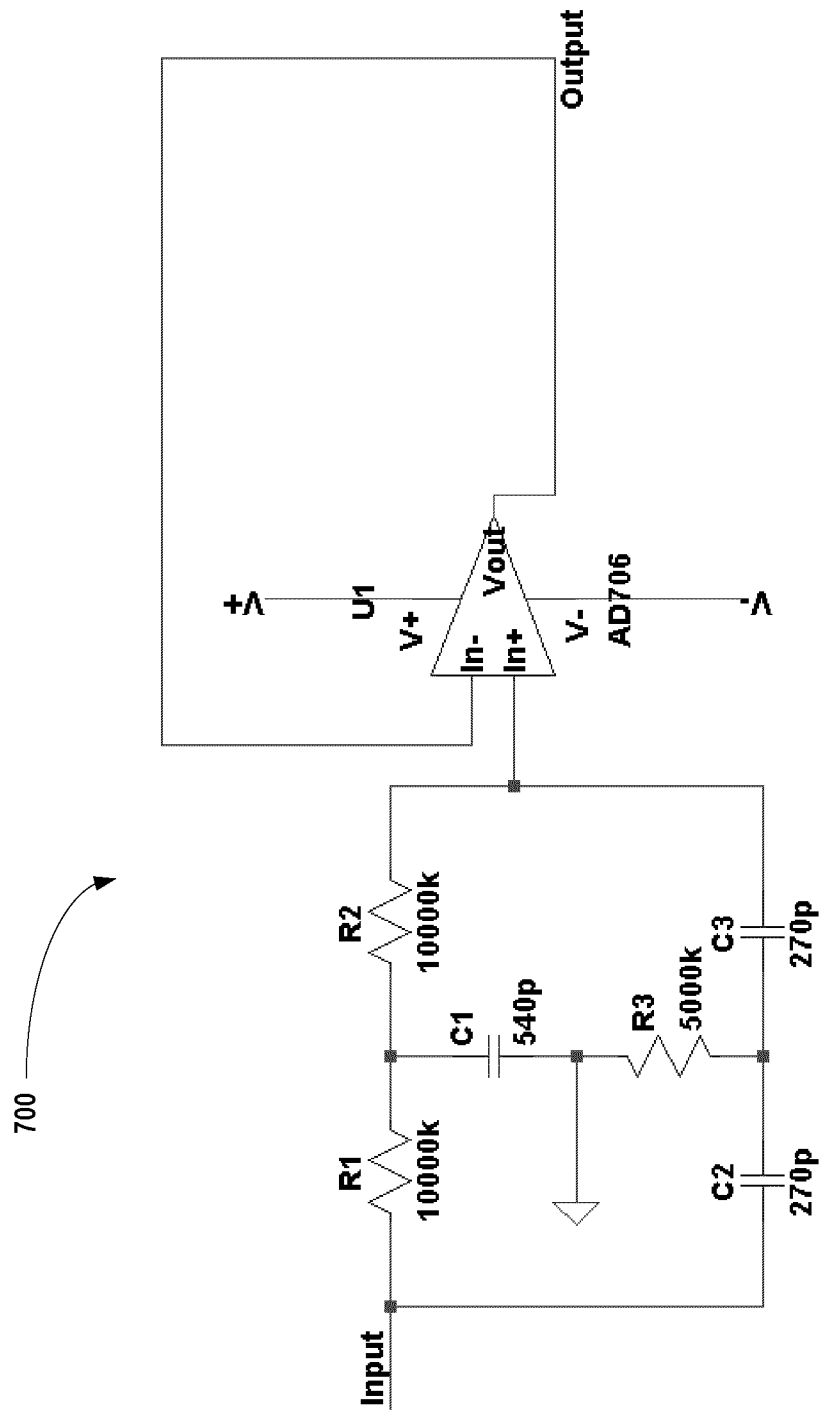


FIG. 7

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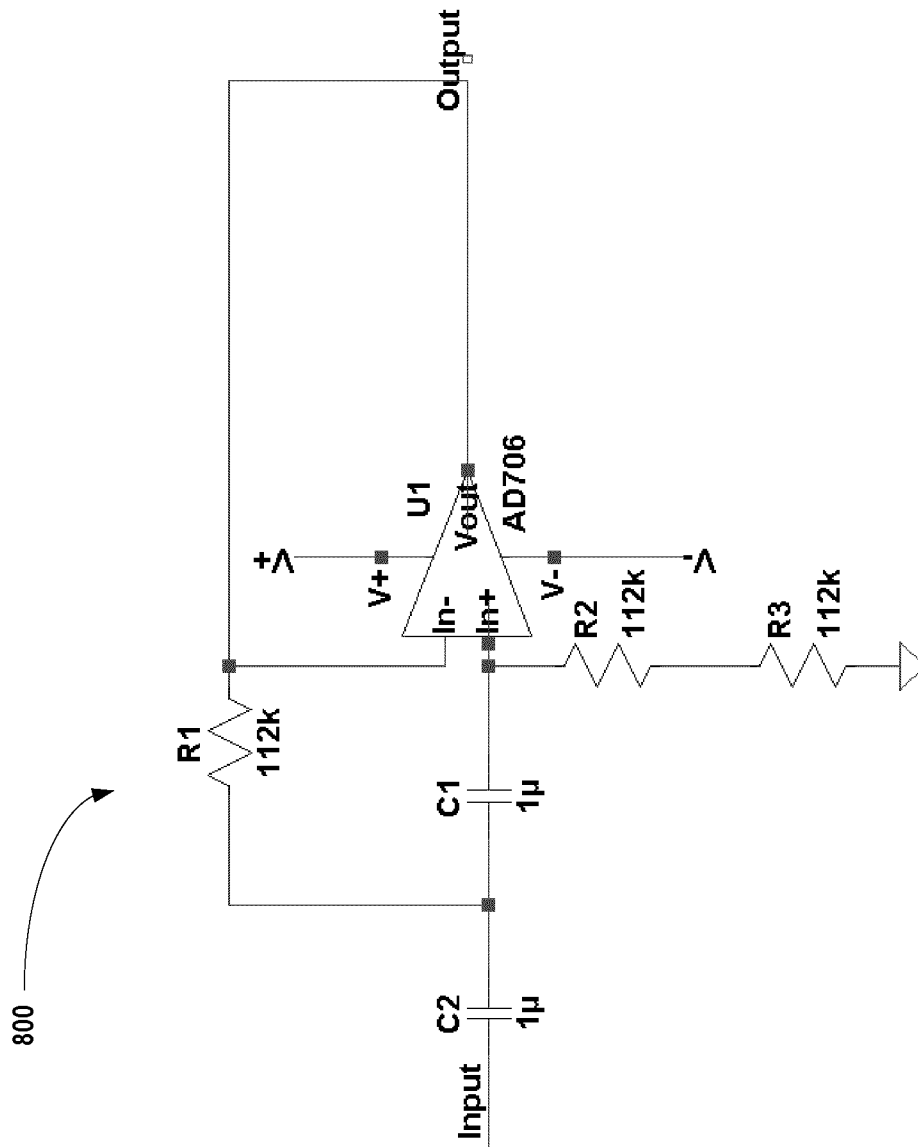


FIG. 8

900

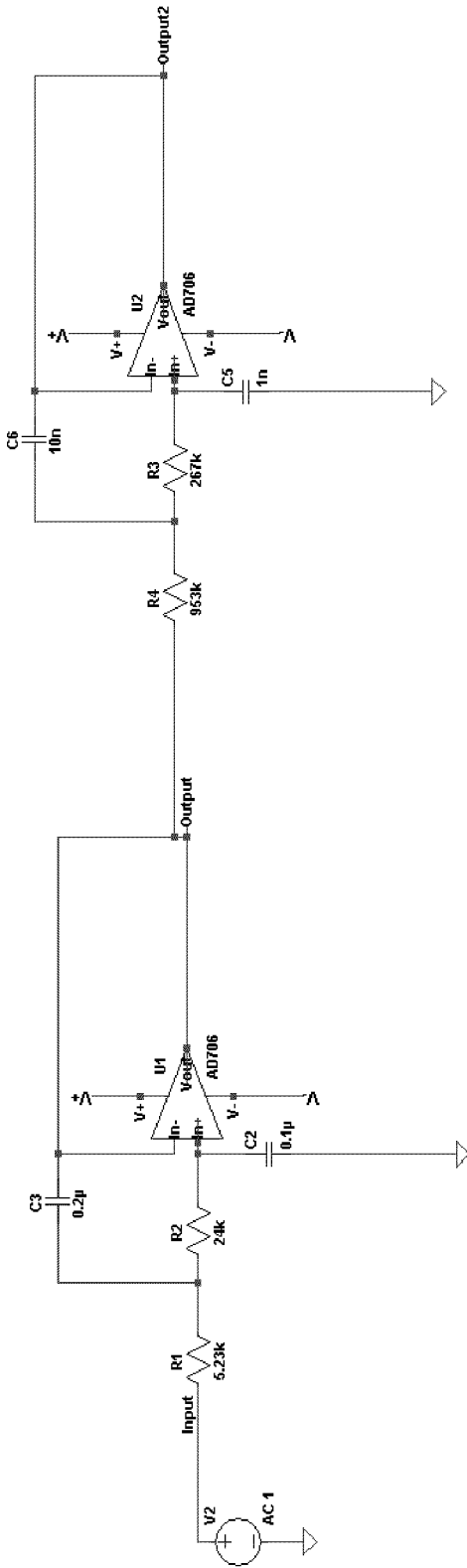


FIG. 9

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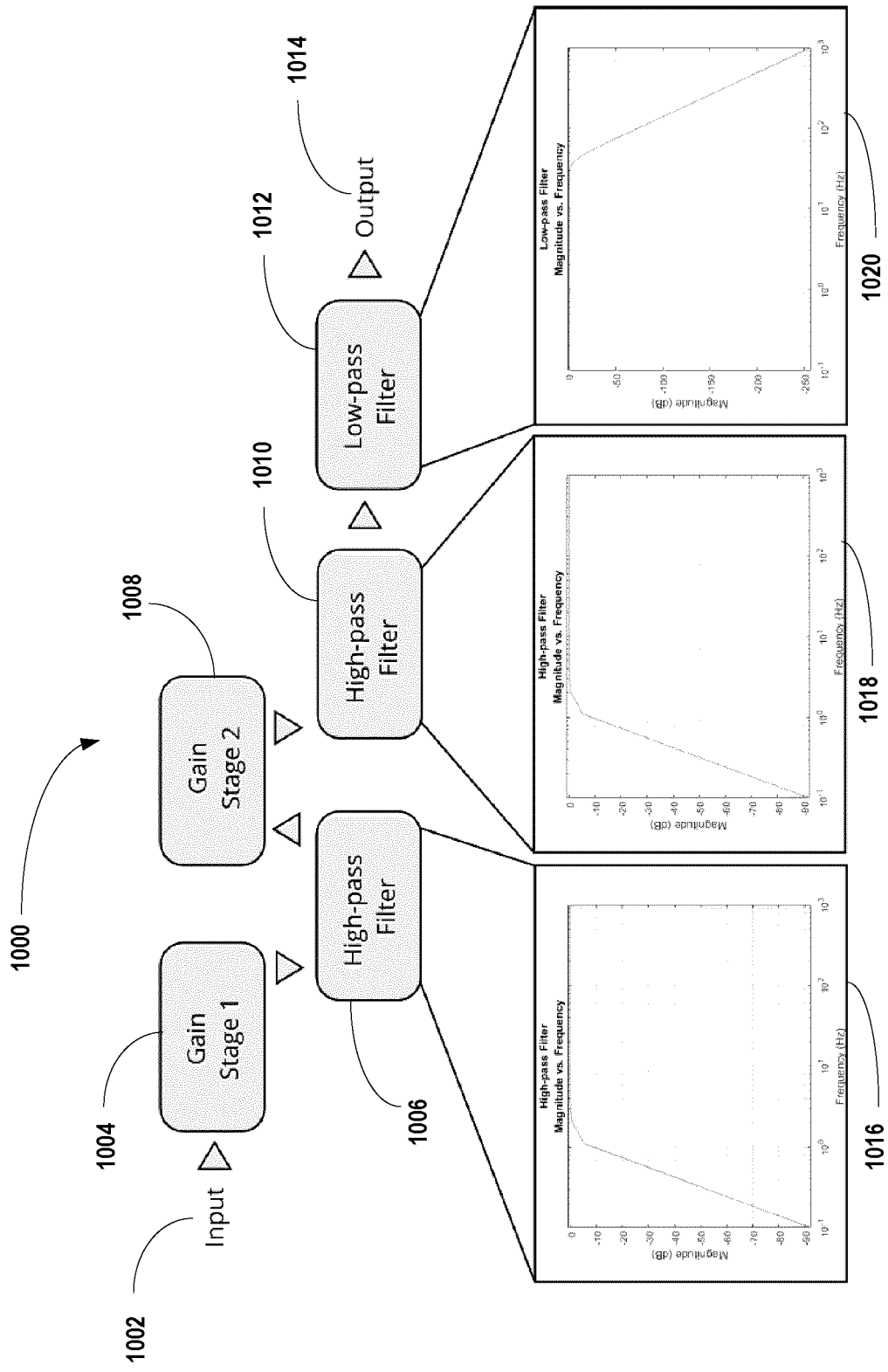


FIG. 10

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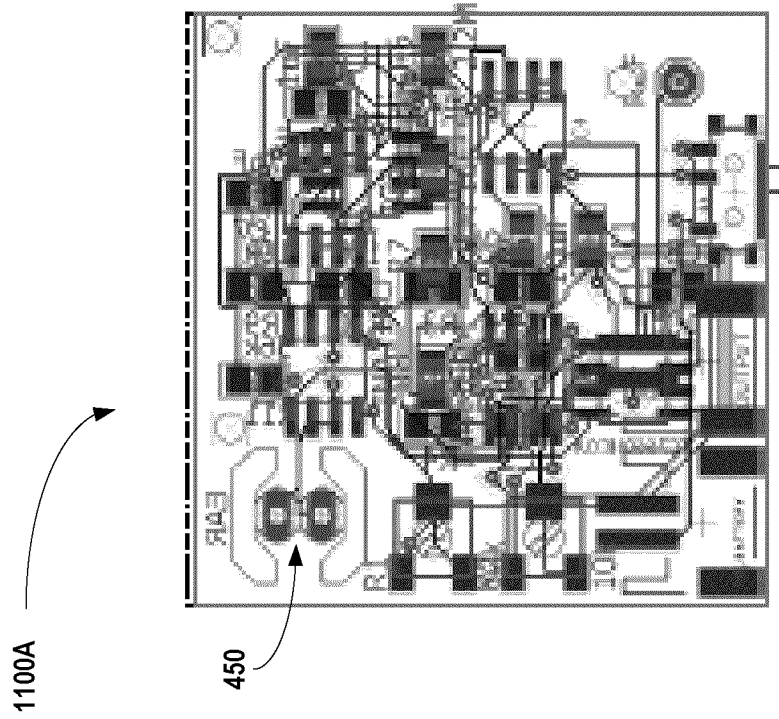


FIG. 11A

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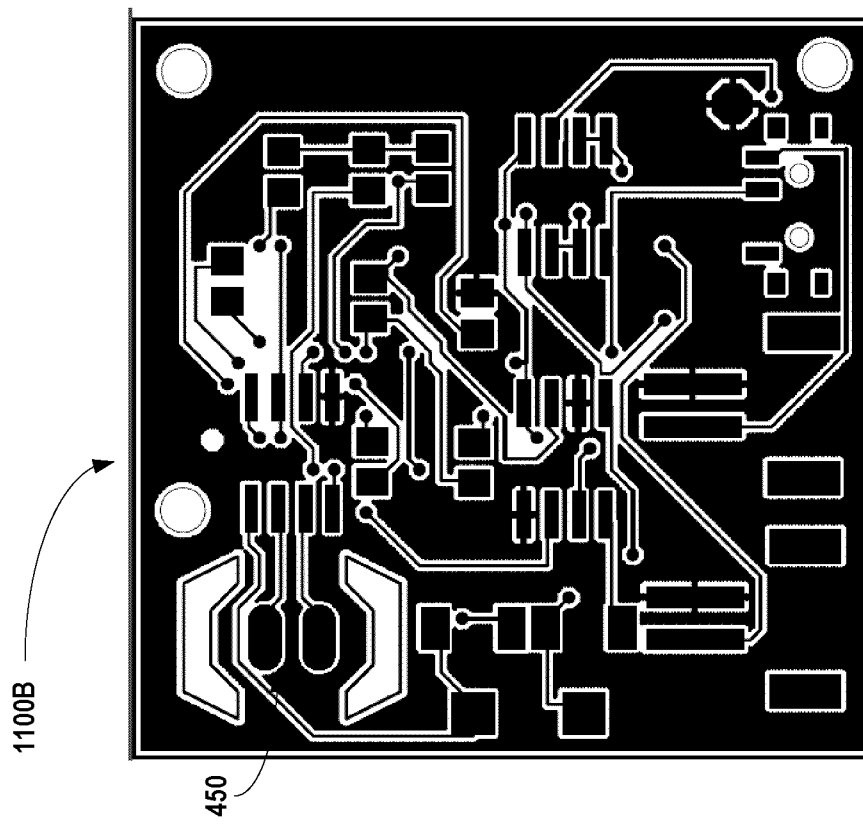


FIG. 11B

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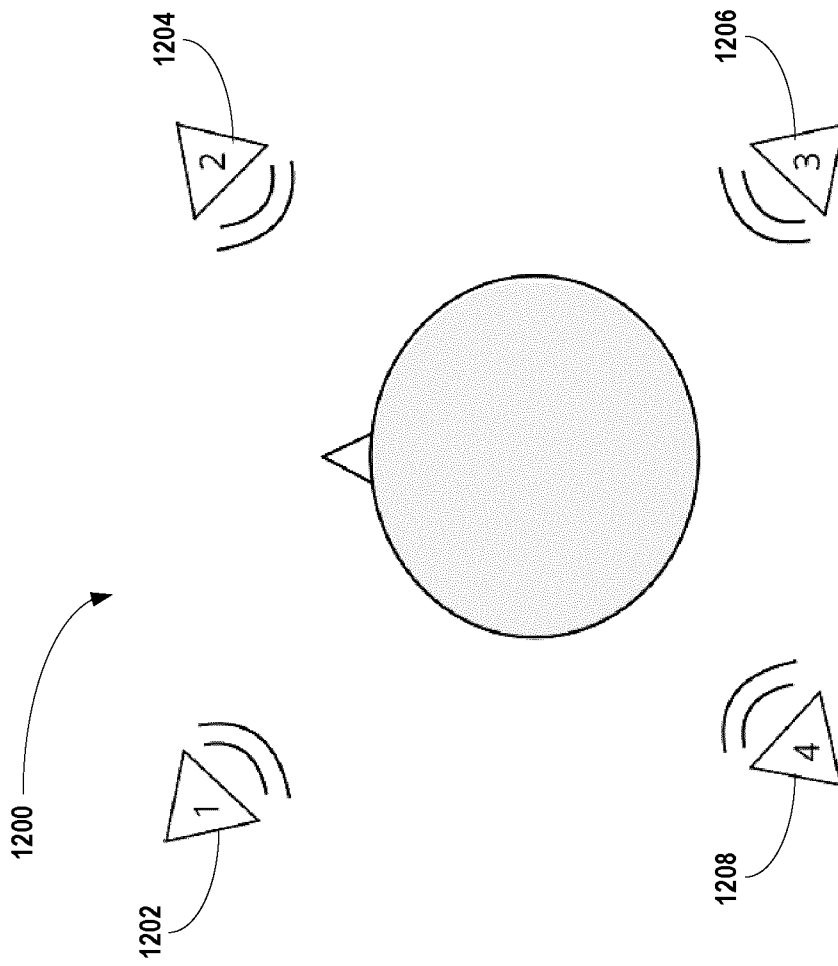


FIG. 12

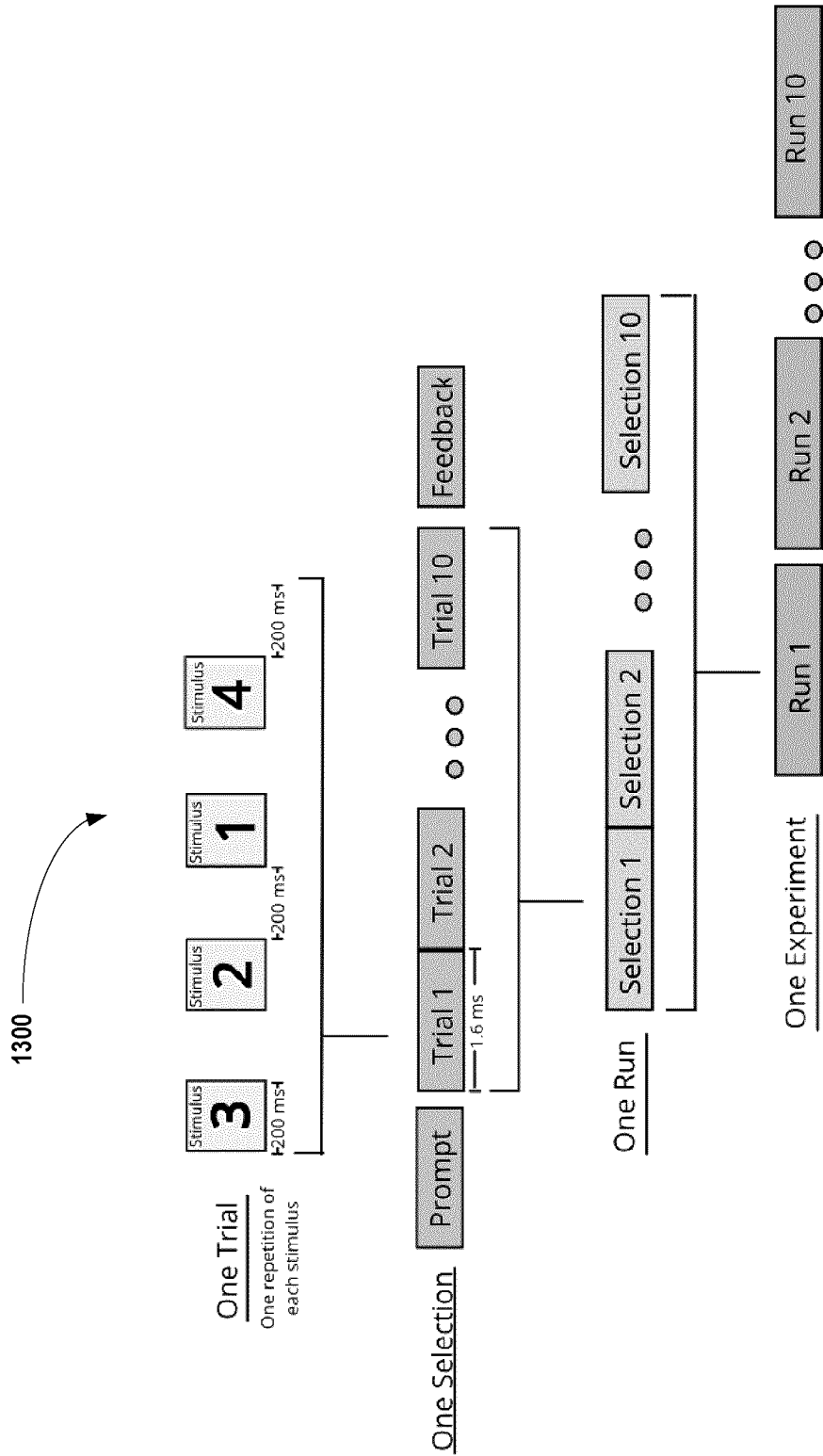


FIG. 13

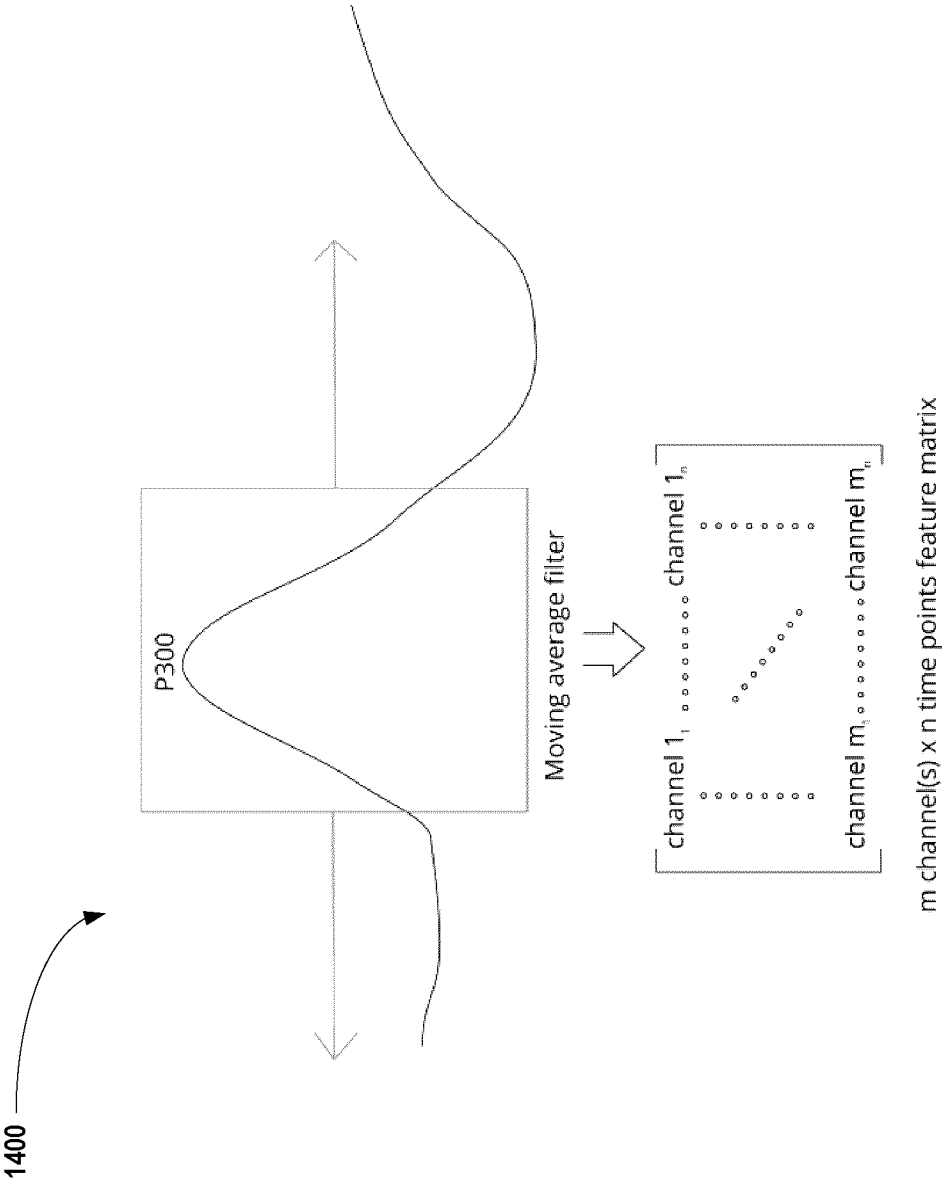


FIG. 14

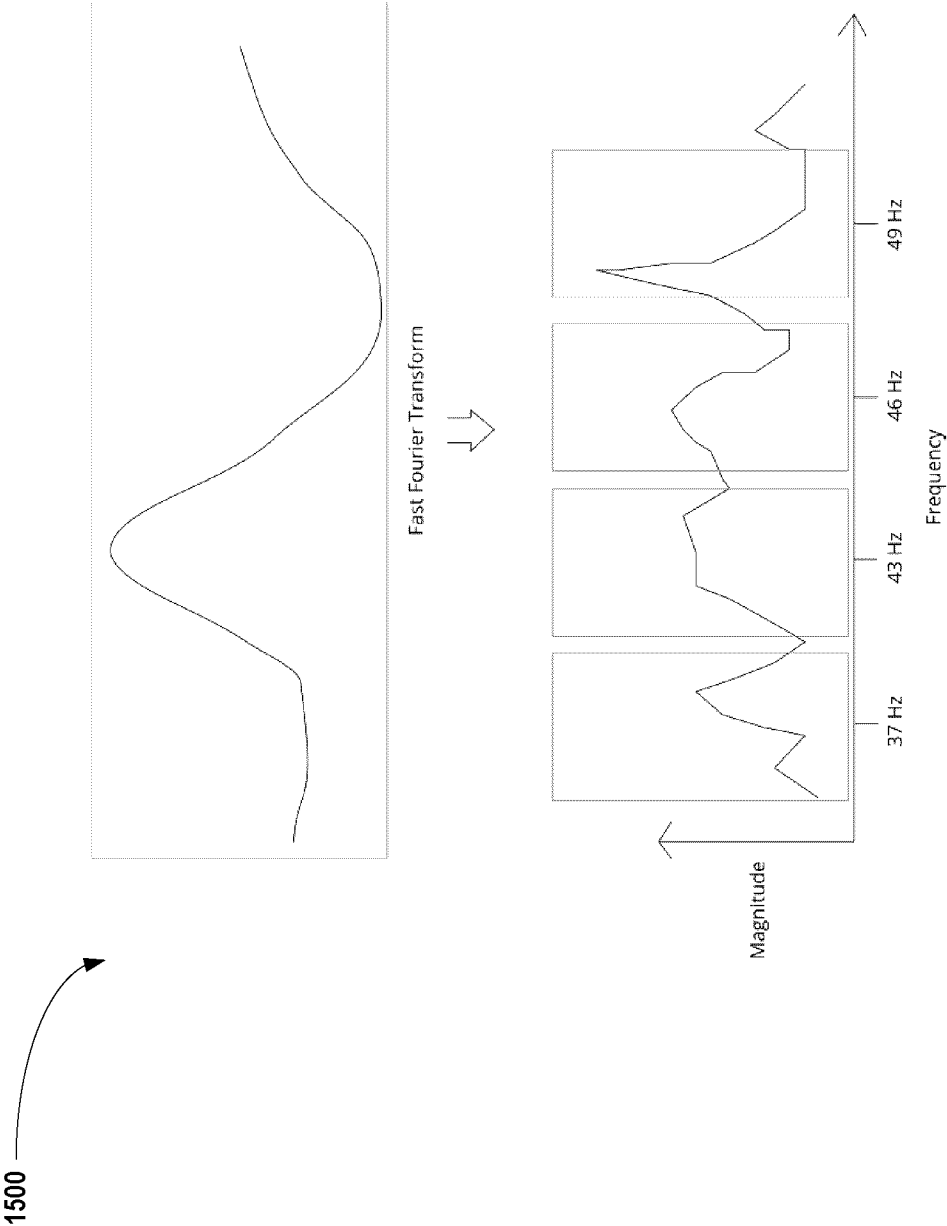


FIG. 15

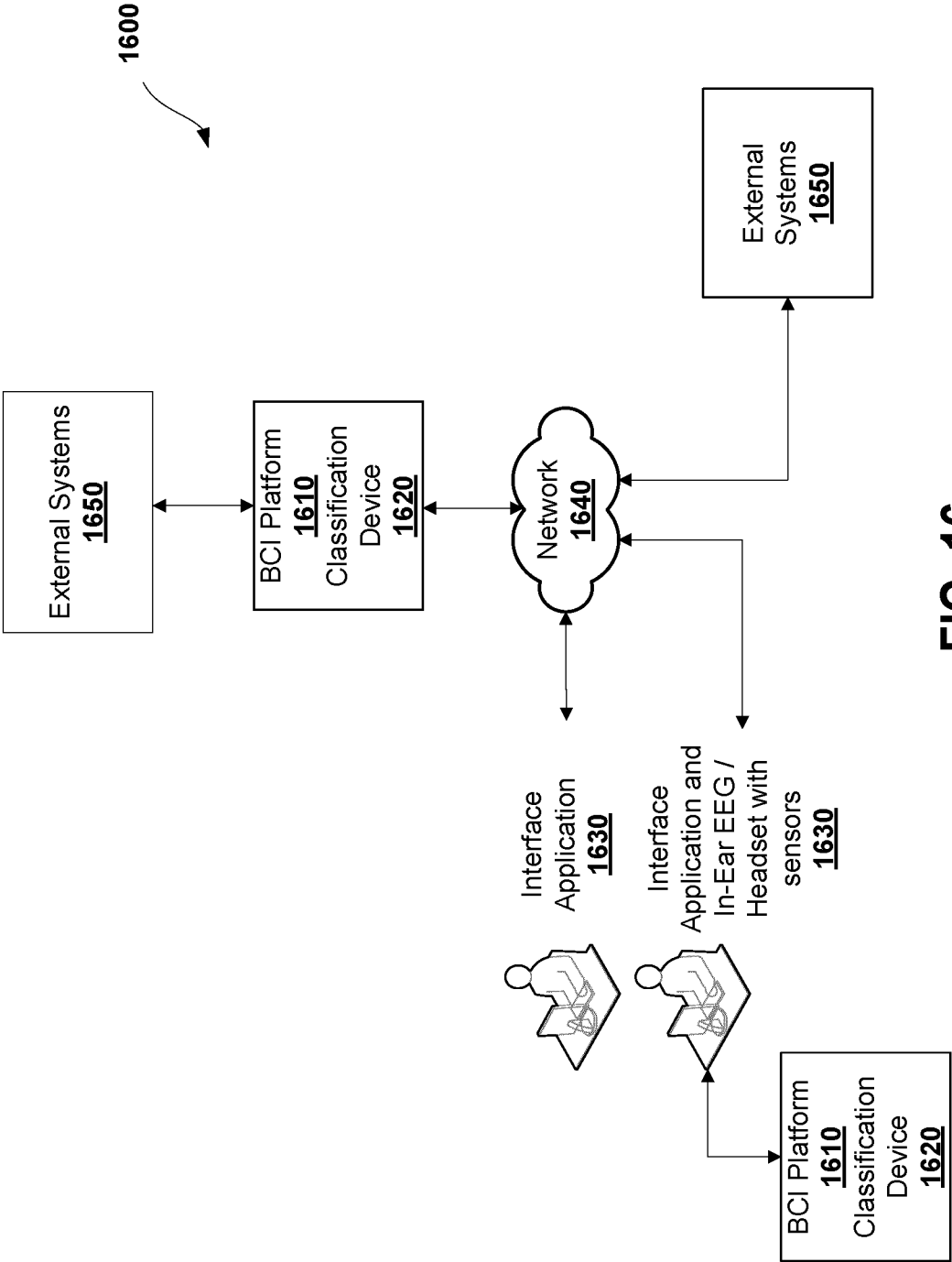
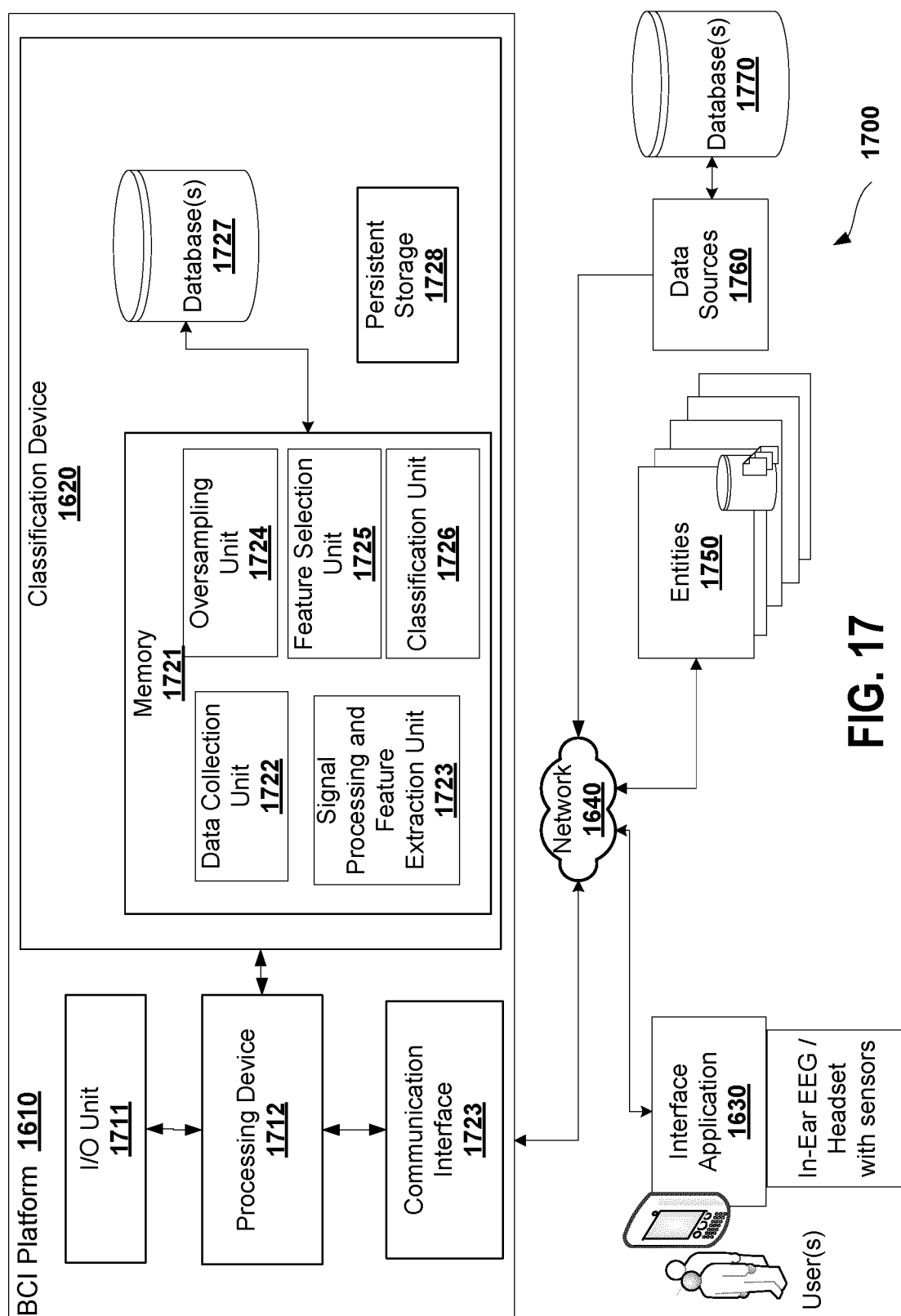


FIG. 16



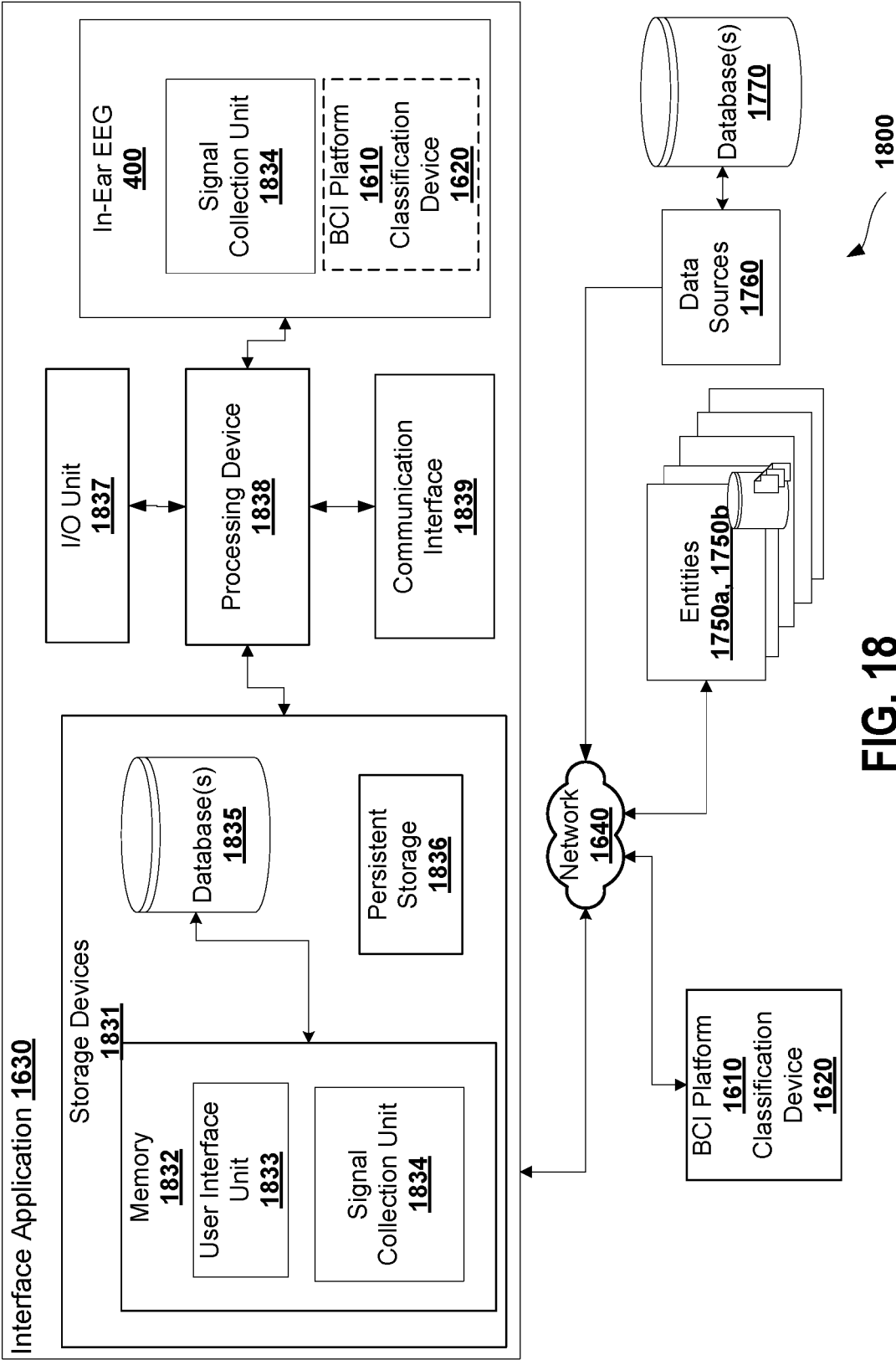
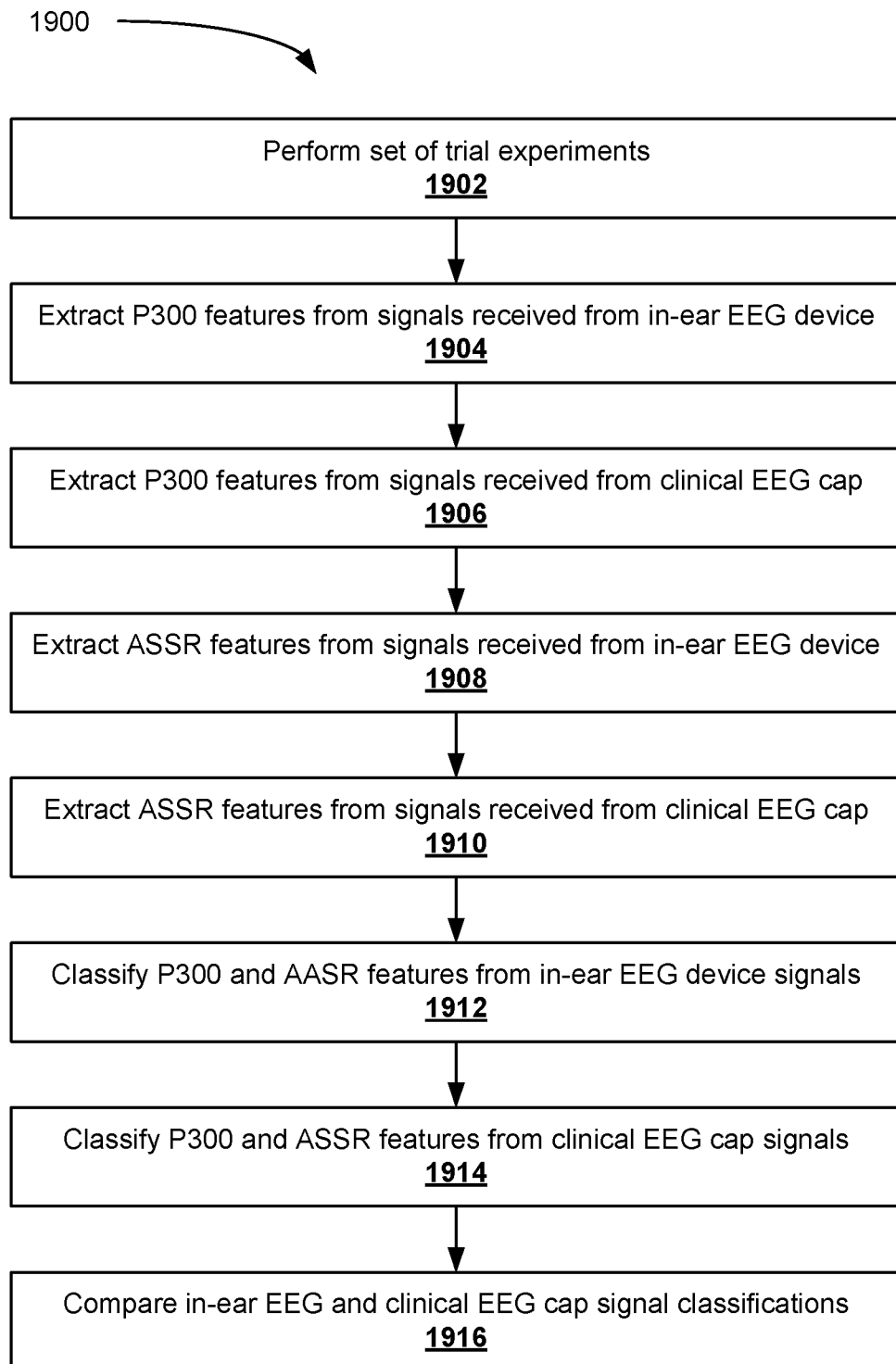


FIG. 18

20/23**FIG. 19**

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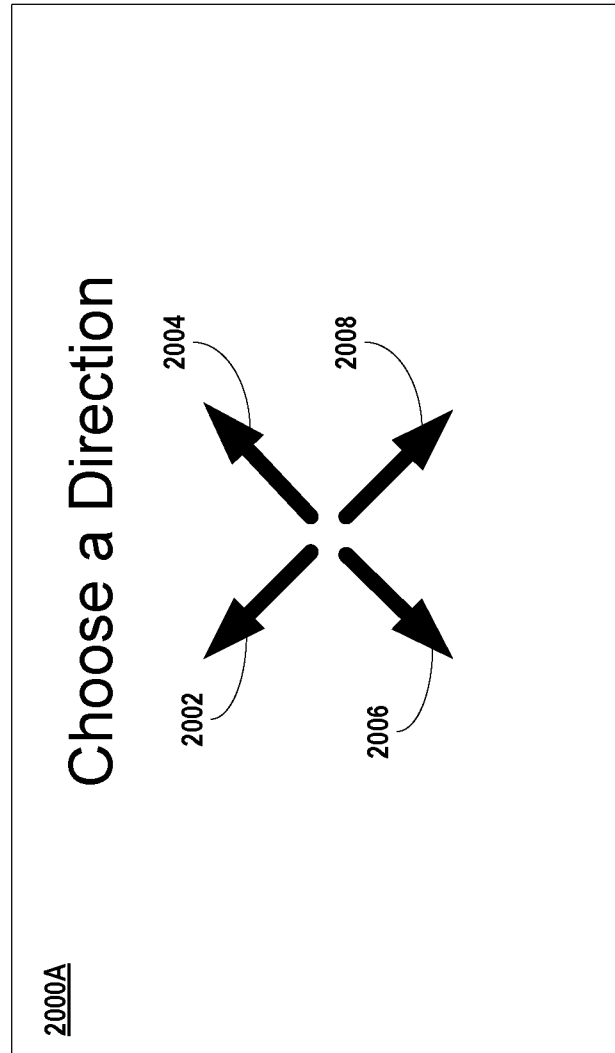


FIG. 20A

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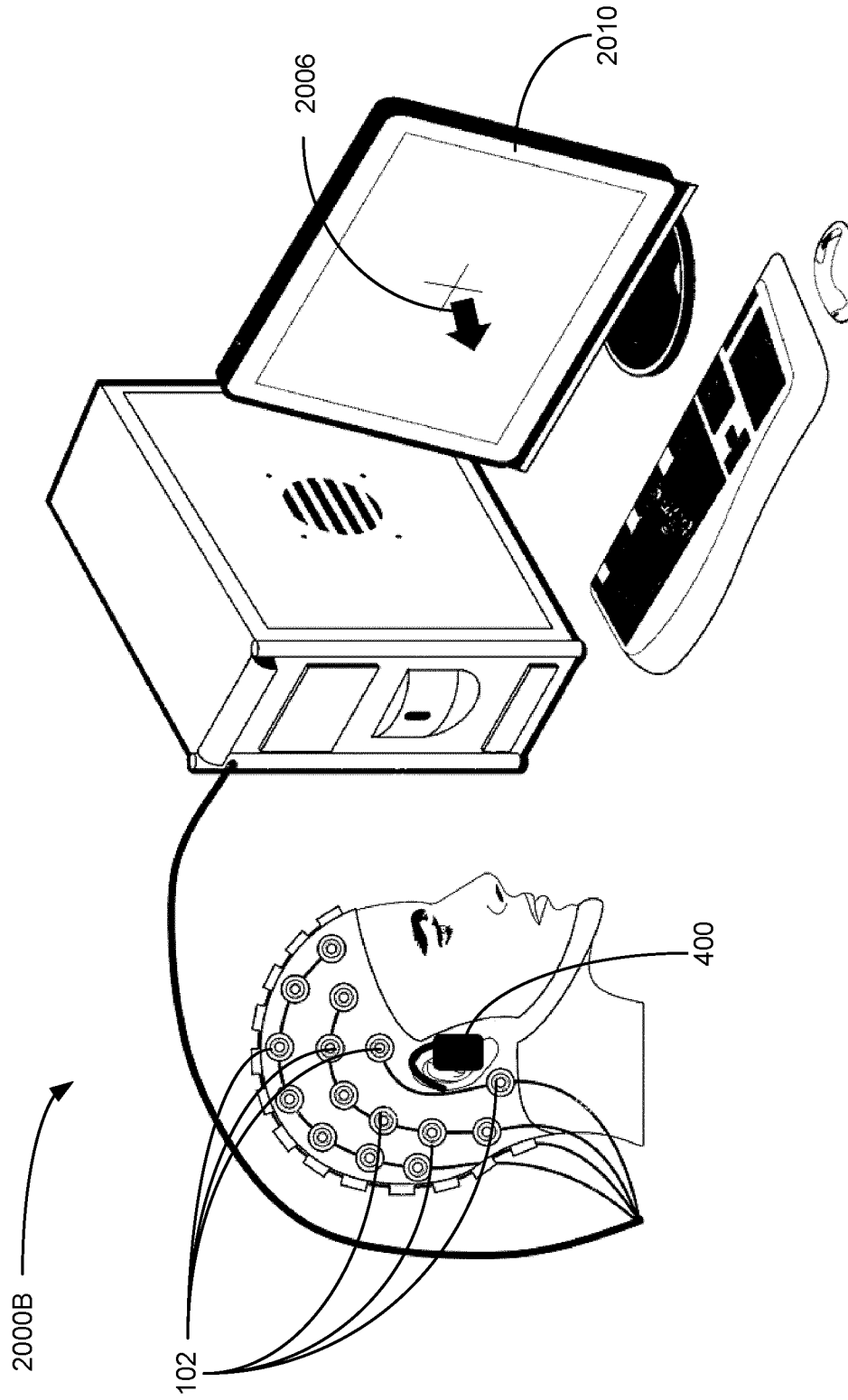


FIG. 20B

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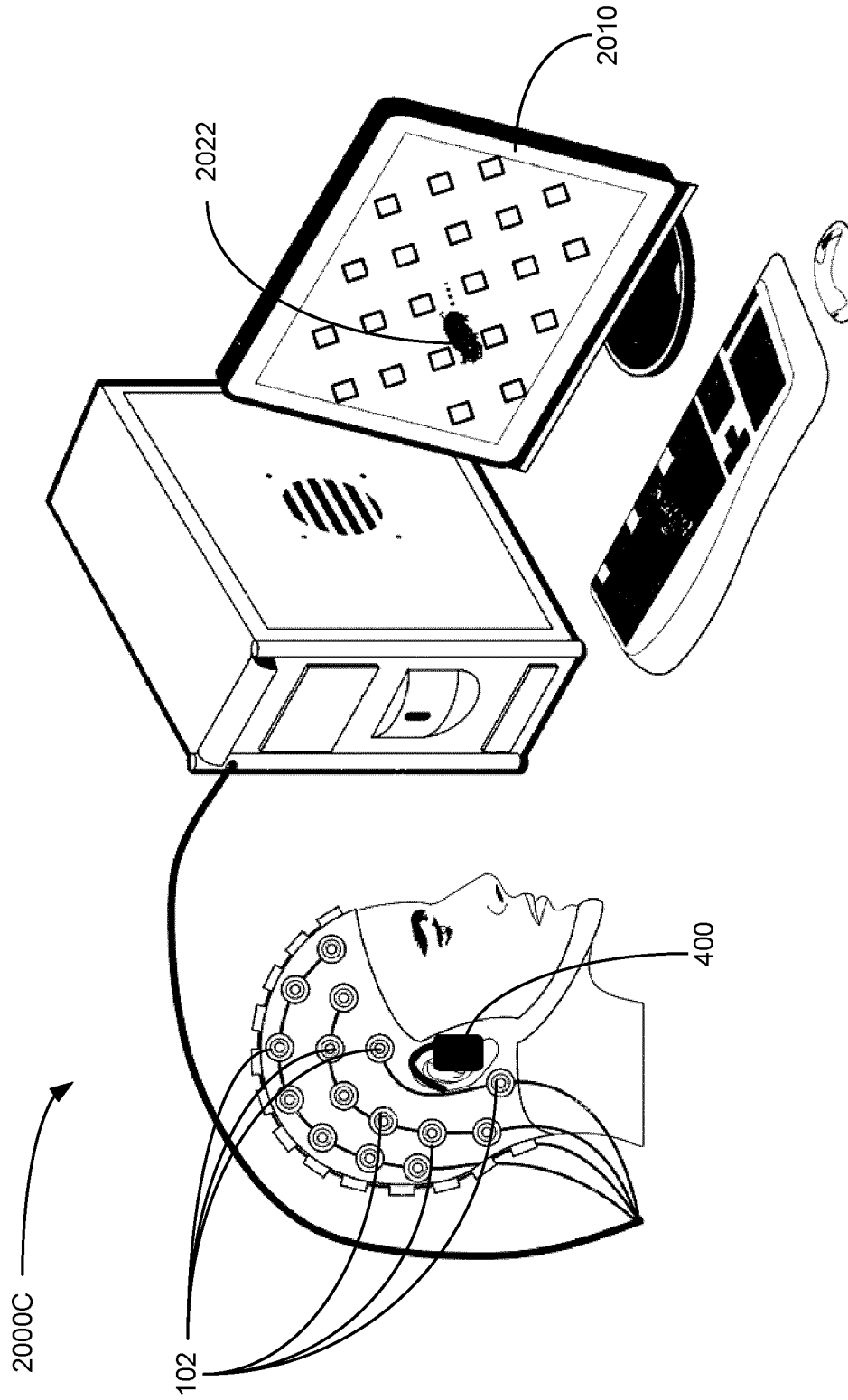


FIG. 20C

