THE TERTIARY BREATH SYSTEM: INQUIRY INTO ACHIEVING AUTONOMOUS BREATH

by

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Dedication

To Red, Nox, and Ever. Without you all, none of this would have been possible. I am deeply grateful for the value, love, and completeness you bring to my experience: Infinity + 1.

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ABSTRACT

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When considering the problems faced by astronauts, we find a wide gambit of opportunistic threats. Beyond standard Countermeasures, Human-countermeasures (H-CMS) – those countermeasures systems that are already engrained in our biology and can be trained or utilized through extraneous support technologies – offer unique, novel tools against these threats. One H-CMS is breath. Breath, or respiration, has a deep body of research to support numerous physiological and psychological (often creating a psychophysiological loop) response mechanisms that can have both acute and wide-ranging impacts on our human state. Further, the dualistic nature of breath (i.e., its ability to be both manually and automatically controlled) makes it the only human vital function that can be conditioned. This investigation explores the use of Galvanic Vestibular Stimulation (GVS) as a display (i.e., stimulus delivery) technology, in attending to limitations of display landscapes (e.g., audio/visual environments are heavily polluted with data demands on a user). GVS uses electrical current to stimulate vestibular nuclei and has been demonstrated to be removed from self-motion commands at high-frequency.

The study showed clear stimulus control of the subject through the GVS cue (with correct, conditioned response rates of $M = 97.1\%$, $SD = 5.08$) and showed a statistically significant effect on the reduction of breathing frequency, $t(26) = 8.36$, $p<.001$; $d = 1.61$– as is expected both by a) the presence of the deep slow breathing (DSB) behavior being cued, as well as via b) the cascading effects of parasympathetic nervous system engagement initiated by DSB design. While the study did also there was no support for the research hypothesis – that there would be a relationship between the idealized breath topography and the conditioned-gamified (i.e., distracted, conditioned) performance – for, both, duration, $t(26) = 9.95$, $p<.001$; $d = 1.91$, and depth, $t(26) = 3.28$, $p = 0.003$; $d = 0.631$, extended comparative assessments against the subject under load (i.e., gamified pacman, unconditioned) for duration, $t(26) = 21.4$, $p<.001$; $d = 4.11$, and depth, $t(26) = 13.4$, $p<.001$; $d = 2.58$, suggest that the executed breath is much more like the idealized breath than the subject's nominal breath. Overall, while further trails/time could improve the topography of the skill, there is a clear opportunity present in conditioning breath.

Expansion of this work would enable increased respiration complexity and the creation of autonomous breath pathways to enhance human potential, especially in austere environments (i.e., allowing artificial intelligence to optimize breath protocols based on other missions, self, and environmental conditions or deltas).

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CHAPTER I:

INTRODUCTION

Space Requires Countermeasures to be Symbiotic with Human-Countermeasures

When considering the problems faced by astronauts, we find a wide gambit of opportunistic threats. The presence of high amounts of radiation, especially as we extend a) travel beyond the protection of the Earth's magnetosphere and b) the effective radius of 'Earth' to include low-earth orbit (LEO), results in high rates of cellular damage, has implications to increasing likelihood of genetic mutations and cancers, and quite literally rips through DNA (Moreno-Villanueva, et al., 2017; Moretton & Loizou, 2020). The lack of gravity not only causes visual and vestibular decrements, but also results in massive changes to blood flow and, therefore, internal pressure levels in the upper body. For example, Space-flight Associated Neuro-ocular Syndrome (SANS) and changes in eye shape and performance are presumed to be directed by rising intercranial pressures (ICP) (Lee, 2021). Further, knowing that space is referred to as an Isolated, Confined, Extreme (ICE) environment, it is sensible that some of the most challenging problems revolve around the psychology, more than the physiology of the crew (Stuster, 2010). As prisoner isolation studies – and, perhaps more relevantly, the social isolation of COVID-19 – have shown, there are severe psychological implications to long-term confinement in limited quarters (Hwang, et al., 2010; Metszner & Fellner, 2010). This doesn't, however, include some of the unknown, unknowable impacts that face seeing the Earth as a faint distant blue star – all our history, and those that can help us, so far away – that face the first individuals to set foot on Mars (and further). Nor does it include the psychological implications of losing a crew member aboard a mission (Oluwafemi, et al., 2021). Space exploration is an aggressively-challenging, hairy, audacious goal and will require massive amounts of innovation to successfully navigate.

Therefore, in current practices towards attending to these “human-as-a-vehicle”-level space problems, both physiological as equally as psychological kind, we are often met with advanced technological solution sets. These include the rockets and space stations, with their Environmental Control and Life Support Systems (ECLSS), that allow astronauts to float around in jumpers, pants, and t-shirts (Carrasquillo, 2005). There are also the new-wave technologies like Augmented (AR), Virtual Reality (VR), and wearable biofeedback display countermeasures systems – the technical name for technologies intended to counter-act the degradations of space flight – that seek to enable immersed experiences and psychological intervention techniques. For example, the current use of the Hololense2 (HL2) Technology to holoport (i.e., holographically transport) a crew flight surgeon to the ISS for a crew conference (Olbrich, et al., 2018; Smith, et al., 2020; Llaca, 2022). Much of these technologies are represented in the work being done in our HumanWorks Lab at the National Aeronautics and Space Administration’s (NASA) Johnson Space Center (JSC), among many great others, institutions, and industry collaborators.

With all this advance, there also comes a cross-breeding of ideas: wherein the solutions for humanity (i.e., here on earth) overlap with those of space. Indeed, the problem set of space – and those of the cosmic residents and explorers – contains nearly all the problem sets of the metaverse, cancer treatments, cellular understanding, physics, renewable energy, etc. (NASA, et al., 2022). However, most every tool is not just based on the mere existence of the tool, but on how it interacts with the environment and the user. A hammer is just a hunk of metal until it finds a hand and a nail. In the same vein, a VR headset is really only lights and sounds, sprayed electromagnetic waves; the immersion and its effects exist at the interaction between that head-mounted display (HMD) and our physiology/psychology. So, too, is true of the physiological and psychological benefits of being able to float around a space station: they are often an extension of reducing the various constraints, limitations, and barriers around a user in the ICE environment of space (Oluwafemi, et al., 2021). This interconnection (i.e., between space and home) offers us an alternative path to examining the problems of space, leaning towards a lens of focusing on the high-value biological and psychological mechanisms that are useful to all humans (not just space-based crew). By inquiring into what tools, systems, or strategies create our most dramatic total human changes, we can identify the already existing, priority human-countermeasures (H-CMS): those countermeasures systems that are already engrained in our biology and can be trained or utilized through extraneous support technologies. Of the many that exist, one that appears to be a cornerstone for generating the desired symbiosis between technological countermeasures (CMS) and H-CMS is our deep relationship with breath, which contains a rich past of human involvement and entanglement (Russo, et al., 2017).

Breath as an Optimal Human-Countermeasure

Breath, or respiration, has a deep body of research to support numerous physiological and psychological (often creating a psychophysiological loop) response mechanisms that can have both acute and wide-ranging impacts on our human state (Forster, et al., 2011; Russo, et al., 2017; Teboul & Scheeren, 2017; Zaccaro et al., 2018). At the highest level of summary, this can be seen as a tendency toward parasympathetic responses during deep, slow breathing and towards sympathetic responses during fast, shallow breathing (Mourya, et al., 2009; Forster, et al., 2011; Russo, et al., 2017; Teboul & Scheeren, 2017). Examination of each of these aspects of our relationship with breath provides clarity as to why breath is a valuable H-CMS to a plethora of human destabilizations. Therefore, breath, or respiration, is a homeostatic optimizer and state preparation tool that this work seeks to demonstrate is capable of being conditioned to a non-standard display technology (i.e., Galvanic Vestibular Stimulation) to provide autonomous interaction with a user; aimed at informing an architecture for the development of an autonomous breath agent that optimizes a user's state and integrates user and environmental feedback in real-time.

The Biomechanical Architecture of Breath as a Metabolic Output Regulator

At its most basic level, breath is critical to our survival: if you don't breathe, you, most certainly, will die. It is responsible, not only, for the intake of oxygen, but also for the maintenance of our blood acid-base homeostasis (i.e., pH level) and removal of toxins/waste gases, for example Carbon Dioxide (CO_2) – which is produced by both aerobic and anaerobic metabolism. In fact, it is not the lack of Oxygen (O_2) that cues our brain to our need for breath, rather it is a compilation of factors that aim at stabilizing the removal rate of CO_2 through our lungs (i.e., alveolar gas exchange) with our rate of its production through our metabolic efforts (Teboul & Scheeren, 2017). For example, chemoreceptive detection of high CO_2 (as related to the rising pH, and the body's desire for that pH to reach homeostatic conditions) and the modulation of breathing to stabilize these partial pressure of CO_2 ($PaCO_2$) increases through the use of chemoreflexes (Forster, et al., 2011). Other pathways include locomotion integrated central commands and afferent feedback from skeletal muscles, such as the cardiovascular performance architecture of our bipedal nature - offered up by breaking the bind of one breath per locomotive cycle that characterizes other quadrupeds, for example, dogs and cheetahs. (Bramble & Carrier, 1983; Wientjes, 1992; Smil, 2021). It is made more sensible, then, to understand how $PaCO_2$ as a homeostatic trigger, given that it's much more prevailing effect on blood pH (a major requirement for life) ensures that the constant metabolic output of CO_2 is kept in check through the initiation of changes in breathing strategies/patterns (Forster, et al., 2011; Teboul & Scheeren, 2017).

Critical to this relationship, however, is that our ability to maintain higher levels of venous CO_2 – those metabolic wastes meant for ventilatory release – also directly impacts our capacity for higher arterial oxygenation. Further, this is not only the increased capacity to carry O_2 molecules, it also represents a higher capacity to dissociate oxygen from hemoglobin (i.e., deliver O_2 to cells). These impacts are outlined in the Haldane Effect based on mechanisms of the Bohr Effect (Jensen, 2004). This also makes sense from a lens of the relationship between supply and demand of our cells: as we begin to increase metabolic load (e.g., exercise) we begin to release higher volumes of CO_2 (e.g., Kreb's cycle, oxidative phosphorylation) – due to a rising use of (and demand for) ATP – our demands for oxygen (i.e., the fuel source) proportionately increase (Hatefi, 1985; Alabduladhem & Bordoni, 2021). Thus, the design outcome of hemoglobin to create linkages between these two molecules is hyper-necessary to aerobic species, as in homo sapiens, survival. The relationship, then, between CO_2 as a trigger for changes in respiration must also be one that generates equilibrium to load demands by an individual's cells (e.g., muscle tissue). This is upheld by the Haldane Effect, as it directly implies that hyperventilation (i.e., rapid breathing) is not linked to a state of increased oxygenation (Jensen, 2004; Forster, et al., 2011; Teboul & Scheeren, 2017). Clearly, understanding how these levels of biological and physiological connection interact with mission resources and technologies (e.g., the ECLSS systems of a station) are essential to crew survival and thriving during exploration (Carrasquillo, 2005).

Biomechanically respiration is centrally, predominantly controlled by the diaphragm, but is assisted by other respiratory muscles (e.g., sternomastoid, external intercostals). Roughly meaning 'partition,' the diaphragm is a dome-shaped skeletal muscle (i.e., in its resting state, with the dome top towards your head) that separates the thoracic cavity from the abdominal cavity (n.d.). When the muscle is contracted, the dome collapses flat; relaxed, it returns to the natural dome state through an equalization of pressure. In specific, a coordination of breathing musculatures – led by this flattening of the diaphragm – establishes a transdiaphragmatic pressure: as the contracting diaphragm and support musculature increase abdominal pressure, there is a corresponding reduction in thoracic pressure. This results in a negative pressure gradient with respect to the external environment that: 1) effectively, pulls air into the lungs, and 2) performs pulmonary gas exchange. During exhalation, the diaphragm returns to a relaxed state and the changing pressure gradient (i.e., between the abdominal and thoracic cavities) forces the air back out of the lungs and removes waste gases; this relaxation completes the effective 'pumping' of the abdominal cavity/organs (Russo, et al., 2017). While heavier breathing, especially that induced by high physical output or stress, incorporates other musculature, the process remains roughly the same (Forster, et al., 2011). Therefore, not only is breath contributing to the pumping of fresh O_2 to cells and the release of metabolic wastes like CO_2, it is also contributing to such foundational aspects as organ health (Pedersen, et al. 2012). This lens is even more useful when considering the impacts of fluid shifts due to microgravity aforementioned, and the operational changes of pressures in reduced/transitioning gravity environments that crew will face (Shelhamer, et al., 2020; Lee, 2021).

Another significant aspect of breath is the change to physiological processes that are initiated by the mechanistic type of breath utilized: 1) mouth or 2) nasal. Mouth breathing has been shown to reduce CO_2 levels, which is useful when in anaerobic tasking or high metabolic output (e.g., sprints, max efforts), but risks reducing CO_2 levels so drastically (in a non-energized state) that the Haldene Effect reaps negative implications. For example, reducing venous $PaCO_2$ also reduces arterial PaO_2 and corresponds to a decrease in cellular oxygenation (Morton, et al., 1995; Teboul &

Scheeren, 2017; Forster, et al., 2011; Russo, et al., 2017). Provided this, it is sensible that nasal breathing dominates more aerobic efforts, with the added benefits of filtering the air of harmful pollutants and offering direct sensing to our olfactory bulbs (i.e., acting as an environmental sensor; Harkema, et al., 2006; Zelano, et al., 2016; Russo, et al., 2017). Nasal breathing has also been shown to stimulate the vagus nerve, whose stimulation offers direct impacts on promoting parasympathetic (PSNS) activation (Ghati, et al., 2021). Respecting the biological design (i.e., breathing hole diameter) of the nose and mouth, it is also sensible that nasal breathing is considerably more difficult to perform at high frequency. Therefore, nasal dominates the deep slow breathing (DSB) end of the breath spectrum, characterized by parasympathetic activation (Jerath, et al., 2006; Busch, et al., 2012; Russo, et al., 2017; Jayawardena, et al., 2020). Further, humming during nasal breathing has also been shown to stimulate the paranasal to releases Nitric Oxide (NO) Synthase, becoming an airborne vaso- and bronchial-dilator to enhance recovery mechanisms and processes in PSNS subroutines (Maniscalco, et al., 2003). Lastly, nasal breath is much more coherent than mouth breathing (Herrer, et al., 2018).

Utilizing Breath as a State Shift and Preparation Tool

In considering breath and state change, then, the lens of investigation shifts to the conversation of psychophysiological interactions with the autonomic nervous system (ANS), particularly the PSNS and sympathetic nervous systems (SNS). Wherein, the PSNS is responsible for the ‘rest’ and ‘digest’ architecture of down-regulation and preparation for recovery, and the SNS is responsible for the ‘fight’ or ‘flight’ antithetical-architecture of up-regulation and preparation for activity. These two systems seek to create the proper organism state for a presented stimulus or stressor (McCorry, 2007). For example, when we see a jump scare on a tv show we feel the rush of adrenaline throughout our body that is met with an increase in ventilatory frequency (i.e., shallow, fast breathing), following a gasp to increase available oxygen in our lungs (Van Diest, et al., 2009**)**. However, the same can be engaged as a preparatory sequence, as opposed to a reactionary sequence: for example, the powerlifter who performs several fast breaths during their approach to a maximal lift attempt – seeking to engage the same adrenaline rush and SNS activation that the jump scare naturally prescribed to our system (Lamberg & Hagins, 2010). This relationship of breath, as a state modifier, has also been a significant part of yogic practices. For example, Kapalabhati, or 'fire breathing,' is characterized by high-frequency respiration rate to promote attention and awareness; whose link has also been demonstrated in laboratory settings (Stancak, et al., 1991; Raghuraj, et al., 1998; Zelano, et al., 2016). Further, the brain coordination between cortical and limbic areas driven by breath (i.e., particularly volitional breath) has been shown to be expansive, with direct impact on arousal via activation of the angular cingulate cortex. In fact, neuronal patterns in the brain have been demonstrated to show a respiration-lock (Herrero, et al. 2018). Effectively utilizing one's breath as a state tool (e.g., preparation for stressful conditions; high task/demand loads; mission-critical elements; shifting from low- to high-energy states) is critical to the success of the total human system. Therefore, as a tool for crew support, breath is not only physiologically logical, but it also has a strong psychological alignment with crew health and safety.

However, we are not always attempting to prepare for a stressed task or experience (i.e., high-load demand: cognitive or physical), we also want to recover from these efforts. This recovery can be argued as equally critical to the primary decision path as the near-term state change benefits of the, aforementioned, preparatory sequencing, as it can also be seen as a process of extended preparation. Said another way, recovery is mid- to long-term preparatory sequencing (i.e., preparation on longer timelines): for example, recovery between bouts of SNS activation (e.g., sprints, max efforts, high mental workload). Often, then, when anxious or stressed, the general prescription is to ‘take some deep breaths.’ Here the reduction of breathing frequency initiates the PSNS and starts to modify neurotransmitter and hormonal concentrations throughout our body to promote a resting, relaxed, de-stressed state (Bear, et al., 2020). Specifically, it has been theorized that this mechanism is a byproduct of the stretch experienced in lung tissues impacting slowly adapting stretch receptors (SARs), whose inhibitory signals are combined with hyperpolarization current generated by fibroblasts. These two forces – the inhibitory impulse and the hyperpolarization current – modulate the brain, decreasing metabolic activity, and are a reflection of states of PSNS activation (Jerath, et al., 2006). This PSNS activation is also used in preparing tissues for more effective stretching in yogic practice via Pranayama – or purposeful, deep slow breathing (DSB) – to relax muscle tone, increase oxygenation of tissues, clear toxins and engage in extended range stretches as an export of these combined features. Further, DSB has links to reduced pain perception, reduction of negative emotional states, and benefits to psychiatric disorders (especially depression and anxiety), a byproduct of this stress reduction and impacts on metabolic processes (Stancak, et al., 1991; Raghuraj, et al., 1998; Jerath, et al., 2006; Zelano, et al., 2016; Russo, et al., 2017; Jayawardena, et al., 2020). In the challenging deep space ICE environments, being able to downregulate will be essential to 1) timely (i.e., real-time or near real-time) and 2) sufficient recovery; these two outcomes being prerequisites for crew success, safety and sustainability.

As a necessary extension, combination practices – those where both high and low-frequency breath are used, specifically in combinations, to dynamically alter state – are the most akin to real-world conditions and are, therefore, the most applicable aspect of breath to consider for developing a crew H-CMS. For example, the Lamaze techniques used by a mother in labor, where: different stages of the birthing process transition to different combinations of breathing aimed at reducing the perception of pain and promoting a more relaxed overall state throughout the birthing process (e.g., DSB, fast mouth-breathing). In fact, this strategy intends to allow a mother to approach childbirth without the use of drugs. This highlights the capacity of breath to promote more organic methodologies for what is otherwise attended to with broad-range impacting drugs: those drugs providing the desired effect (e.g., pain reduction), but also nineteen other undesired (i.e., 'side') effects (Cicek & Basar, 2017; Russo, et al., 2017; Jayawardena, et al., 2020). Another example of a more real-world, woven tapestry of breath styles – and more applicable to an astronaut – are the changes of breath sequencing in a fighter, during sport or during exercise. The ability to control breath during physical effort like Mixed Martial Arts (MMA) and rowing becomes critical to user performance, safety, and recovery; as rounds or regattas not only demand high attention to detail, but also require a savings of metabolic resources for future, unknown high-demand moments (Mahler, et al., 1991; Welch, et al., 2018; Kipp, et al., 2021; Walters, et al., 2021; Alnuman & Alshamasneh, 2022). Further, understanding when, why, and how to apply complex breath sequencing for these unknown circumstances (e.g., a flurry of punches, EVA suit failure) is a massive advantage to both the warrior and the explorer (Norcross, et al., 2015; Shelhamer, et al., 2020; Banker, et al., 2021).

The Duality of Breath

While ultimately covered in context up to this point, but not explicitly stated, breath also offers both manual and automatic control. This means that our body will naturally (i.e., automatic) continue breathing while we attend to other tasks and, at any point, we can actively step into that role (i.e., manual) by adjusting our respiration topography (e.g., frequency, duration, depth). The duality of breath – its ability to be both manually and automatically controlled – draws a very critical distinction about respiration: “Breathing is the only vital function under both voluntary and involuntary control and thus the only vital function that can be conditioned directly by means of both Pavlovian and operant procedures” (Ley, 2001). For example, training in proper breath and biofeedback techniques has been shown to be repeatable by a subject in random trials and stimulus control over sleep respiration, towards the treatment of sleep apnea, has been demonstrated on numerous accounts (Badia, et al., 1984; Badia, et al., 1985; Badia, et al., 1986; Badia, et al., 1987; Badia, et al., 1988; Harsh and Badia, 1990; Harsh, et al., 1990; Smith, et al., 2020). For example, humans can be trained to breathe more properly: subtle hints (often beginning in youth) to “take some deep breaths” when one is stressed out; human performance groups define training protocols by functions of breathing style; assigning workloads to particular styles/structures; special forces application of box breathing to promote PSNS down-regulation and recovery; meditation breath training (e.g., Pranayama) in order to enhance (i.e., increase) theta wave amplitude (Jerath, et al., 2006; Zelano, et al., 2016; Russo, et al., 2017; Thomas & Centeio, 2020; Grossman & Christensen, 2022). Lastly, breath patterning can be learned by one’s interaction with the environment, suggesting multiple overlapping systems and a fractal nature of possibility and opportunity for modification. It is, therefore, simple to surmise that breath can be trained through instruction, so its capacity to be autonomously engaged is as simple as gaining stimulus control over (i.e., conditioning) the desired breath (Freedman, 1951; Wescott & Huttenlocher, 1961; Badia, et al., 1984; Badia, et al., 1985; Badia, et al., 1986; Badia, et al., 1987; Badia, et al., 1988; Harsh and Badia, 1990; Harsh, et al., 1990; Gallego & Perruchet, 1991; Wientjes, 1992; Ley, 1994; Miller & Kotses, 1995; Nsegbe et al., 1998; Ley, 2001, Gigliotti, et al., 2003; Fader, et al., 2004; Van Diest, et al., 2009). To understand this conjecture – and to, most effectively, apply it to the proposed – it is necessary to examine the various conditioning and learning strategies of the highest value to breath.

Utilizing Conditioning to Deploy a Tertiary, Autonomous-input Breath Process

Classical conditioning (CC) is “a type of learning in which an initially neutral stimulus – the conditioned stimulus (CS) – when paired with a stimulus that elicits a reflex response – the unconditioned stimulus (US) – results in a learned, or conditioned, response (CR) when the CS is presented. (APA, n.d.)” The goal of CC, then, is the creation of a shared relationship between a stimulus (i.e., the CS) and a response, such that the presentation of the stimulus is sure to yield the coupled response (i.e., the CR). In this definition, a stimulus is any environmental or externally presented set of data that is sensorially-received by an organism, whereas a response is the output/outcome (i.e., often desired) behavior emerging from the organism. CC, therefore, examines behavior in an inflexible and reflexive manner, typically using innate patterns/processes and identifying elicited behaviors. As an overall logic, then, CC operates under a Stimulus (S) – Stimulus – Response (R) paradigm; essentially a particular behavior is based, most specifically, on what precedes its presentation. This S-S-R relationship is comprised of four specific temporal arrangements, namely: delayed, trace, simultaneous, and backward conditioning. Of these, delayed (i.e., presentation of the NS for a period of time and the concurrent presentation of the US at the end) and trace (i.e., presentation of the US after a period of break time following the presentation of an NS) are shown to be the best performers for rapid training and maintenance of the desired behavior (McSweeney & Bierley, 1984; Clark & Squire, 1998; Powell, et al., 2017; Pryor, 2019). As such, the use of these effective temporal models has been taken into effect in the design of the proposed breath conditioning procedure.

Operant conditioning (OC), on the other hand, rests upon a conversion of the CC three-term contingency to one in which there are “the discriminative stimulus, the operant behavior, and the reinforcer or punisher;” equating to an S-R-S interaction (Powell, 2017). This allows for adaptation of response based on the consequence of the stimulus – aka the user has “voluntary” control over the relationship. Therefore, OC is much more critical to behavior change based on that response (i.e., consequence), examining emitted behaviors (as opposed to the elicited behaviors of CC) in an S-R-S model flow. This is functional in nature from two perspectives: 1) it makes it easier to group sets of responses into more manageable classes, examining advanced mathematical properties of the available relationships in an experimental setting (i.e., supports improved operationalization of variables, stimuli, environment, etc.), and 2) it makes it easier to understand which of those variables share similar consequences and, thus, would face similar operant control when faced with managing the wide variation of emitted behaviors available (Fordyce, et al., 1973; Staddon & Cerutti, 2003; Powell, et al., 2017; Pryor, 2019).

This highlights the implications of Premack’s Principle on OC, stating that “high probability behavior (HPB) can be used to reinforce a low-probability behavior (LPB),” wherein probability classification is being leveraged (i.e., high v. low) (Knapp, 1976; Powell, 2017). Premack’s Principle takes into effect the individuality of the subject/organism to more fully appreciate how best to design reinforcers for enhancing learning. As such, if taking a deep breath in a stressful environment is a LPB (based on all the system-level interactions for breath aforementioned), it can be rewarded with a HPB (e.g., enhanced task performance statistics that drive bonuses) to increase its likelihood for reperformance. This in mind, the discriminate stimulus offers crucial need for control, as it creates the stimulus control for the operant conditioning (Fordyce, et al., 1973; Hernstein, 1990; Staddon & Cerutti, 2003; Powell, 2017; Pryor, 2019). Considering this, OC has numerous conditioning schedules (i.e., similar to the temporal contingencies of CC) across both fixed and variable methodologies. In particular, a variable ratio schedule – one in which a reward is offered after a variable number of responses within some bandwidth of values (e.g., every 10-30 responses, randomly), for example, a casino slot machine – is the fastest OC training model (Saari & Latham, 1982; Wanchisen, et al., 1989; Staddon & Cerutti, 2003; Powell, 2017). In fact, a strategy that utilizes randomized delivery of the target stimulus during the training and performance conditions is proposed for this investigation, leveraging the effectiveness of variable ratio scheduling. Coupling these driving design factors with the critical knowledge gleaned from the integration of CC to breath, this inquiry intends to control the delivery of the training stimuli across all user experiences (and across all users), towards a high-quality training environment for rapid learning/conditioning.

Other natural learning strategies are also effective at enhancing breath training, specifically: observational learning, imitation, and mirror neurons. First, observational learning, developed by Albert Bandura, says there are four cornerstone criteria to learning: 1) attention (i.e., if you are going to learn anything, you have to be paying attention first), 2) memory/retention (i.e., once a behavior is witnessed, one needs a way of retaining the steps and flow, etc. of that behavior to repeat it), 3) imitation/reproduction (i.e., now that one has seen and remembers the behavior, they can replay it in real-time), and 4) motivation (i.e., there needs to be a reason that the activity is being carried out, perhaps this could be a reinforcement – though generalized imitation seeks to explain this more through other instinctual exports; Bandura, et al., 1966; Douglas Greer, et al., 2006; Burke et al., 2010; Powell, 2017). Therefore, behaviors that help us with primary drivers, or instinctual needs (e.g., breath keeps one alive and helps manage one’s state) – such as those models more similar to us (i.e., watching a real human breath instead of a robot with no lungs) – can be much more effectively trained (Bandura, et al., 1966; Powell, 2017).

This adheres to the OC and Premack Principle exports, as these behaviors are highly-reinforcing; provided the reward of the eventual imitation is high. For example, successfully engaging in DSB relieves one’s anxiety and encourages the user to use DSB in future anxiety scenarios (Knapp, 1976; Stancak, et al., 1991; Raghuraj, et al., 1998; Jerath, et al., 2006; Zelano, et al., 2016; Powell, 2017; Russo, et al., 2017; Jayawardena, et al., 2020). Speaking, specifically, to this imitation (i.e., true imitation, with respect to the human species): it is a necessary function of our operational learning set, and the foundation of much of our basic forms of learning – including many of our social, humanistic, and language-based expressions (APA, n.d.) One cornerstone aspect of true imitation is the presence of mirror neurons in the human brain, which, not only, are activated during the performance of particular skills, but are, also, activated during simply the observation of those same skills in another (Cook, et al., 2014; Bear, 2020**)**. This allows for a user to, essentially, mirror the patterns of behavior occurring as though they, themselves, are the ones initiating the behavior (Oztop, et al., 2006; Iacoboni, 2009). Geographically-speaking, these mirror neurons have been found among the various motor cortices, the inferior parietal cortex, and the somatosensory cortex (Cook, et al., 2014; Bear, 2020).

Relating this back to breath, properly shaping a breath (e.g., DSB) can be best serviced – not by simply explaining the breath to the user, but – through leveraging the mirror neurons advantages of mimicking positional and motor-patterning archetypes. This can then be overlayed with those same simple vocal (i.e., explanatory) commands to more effectively support the user in resolving the accurate (i.e., desired) breath topography (Oztop, et al., 2006; Iacoboni, 2009; Busch, 2012; Cook, et al., 2014; Mehta, et al., 2016; Bear, 2020). For example, watching another who is properly using the diaphragm and noticing that, in doing so, the rib cage tilts, and the shoulders do not initially rise (as they do during a lung-based breath), and then applying similar refinements to your real-time breath topography. Thus, the application of concurrent CC, OC, and observational/imitation learning styles, in the design of subject-interfacing digital systems (e.g., generated user interface; GUI), would enable the proposed work to generate a strong training effect in the shortest timeline. This is the only sensible integration path for such a humantech (i.e., human-focused technology) product, as a long training-arch would struggle to have wide-ranging impacts (i.e., use cases), and would be especially inflexible to the sorts of unknown conditions presented to the cosmic resident and explorer.

Provided the implications of these conditioning strategies, it is sensible why breathing has been demonstrated as capable of being conditioned through both operant and classical strategies, as well as displaying success in observational and mirror neuron-based learning (Freedman, 1951; Wescott & Huttenlocher, 1961; Badia, et al., 1984; Badia, et al., 1985; Badia, et al., 1986; Badia, et al., 1987; Badia, et al., 1988; Harsh and Badia, 1990; Harsh, et al., 1990; Gallego & Perruchet, 1991; Wientjes, 1992; Ley, 1994; Miller & Kotses, 1995; Nsegbe et al., 1998; Ley, 2001; Gigliotti, et al., 2003; Fader, et al., 2004; Van Diest, et al., 2009; Harris et al., 2014). As well as why concurrently applying these strategies is the most likely path to effectively train a user and gain stimulus control over breath execution through a display technology, such that this work might examine the cue transference into unknown environments and relevant autonomous system designs. Further, considering the success of researchers in conditioning DSB via a display device intervention – appreciating the numerous benefits that are direct exports of

DSB techniques (e.g., reducing anxiety, pain perception, and engaging PSNS) – it has been determined as the optimal candidate for the proposed experiment's desired breath (Jerath, et al., 2006; Oneda, et al., 2010; Busch, 2012; Russo, et al., 2017). As discussed, though, the specific natures of breath and space (i.e., ICE) require unique considerations for the development of an ideal display technology for cueing DSB.

Such an ideal display (i.e., stimulus delivery) technology could allow the proposed inquiry to expand into enhanced training of breath protocols (e.g., more complex topography), while enabling the simultaneous creation of a pathway for autonomous intervention (i.e., allows the computer to send a command, based on some other set of data or constructs, to the user as a stimulus cue for a desired breath). Therefore, the proposed could leverage a) complexity and b) autonomous integration to inform the future development of an autonomous breath agent: capable of controlling human respiration as a tertiary breathing mode (i.e., 1) automatic, 2) manual, 3) autonomous). This would offer other users, the environment, external agents, sensing tools, systems, programs, intelligences, users, etc. (i.e., including: timeline, tasking, teaming, topography, etc.) the ability to interact directly with the core physiological and psychophysiological capacities of a specific end-user. The assumed (i.e., intended) result would be extended predictability and optimization of self for challenges regarding the present, past and future need-states (e.g., terrain navigation, weather preparation, tasking, changes in baseline parameters, etc.) For example, an autonomous agent with the ability to know that the environment ahead requires its user to perform a long breath-hold swim could initiate pre-breathe cues that are conditioned to respiratory protocols for PSNS priming of a user's physiology – akin to the breath preparations of dolphins and whales before deep dives (Williams et al., 1999). The same could be applied to a crew member that must navigate through a dangerous gas pocket on a space station. Such systems would enhance a user's situational awareness beyond the limits of their core sensation and perception systems: for example, offering a user the ability to react to information only present in the infrared spectrum via supporting optics, even though that information is nominally outside the human perceptual limits for vision (Woods, 1988; Stanton, et al., 2001).

Increases in Sensing and Biofeedback Demand Exploring Novel Display Technologies

However, adding these new sensing and display technologies aims to support the user, and there are already critical visual and audio environment features/displays facing crew members. For example, consider the visual displays of a docking monitor concurrently arriving with video and audio-displayed warning signals and procedure documentation, all while crew/ground communications occur over tightly-controlled audio loops, continuously. This further supports that understanding how to make salient training displays – beyond merely the proper strategies for training/conditioning a user that has been covered – is of foundational interest to the success of this work. Often, though, these saliency increases can contend, directly, with the task required by an agent (Lavie, 2005**).** For example, consider all the visual cues humans are presented as a visually-dominant, stereoscopic species, and, in the same vein, consider all the notifications in the current auditory environment, each, simultaneously, battling for a user's attention (Saunders & Knill, 2003; Jafari, et al., 2019**)**. Haptics also seems to be following a similar arch in human application, with the number of devices and notifications linked to haptics and vibro-tactile wearables on the rise (Ernst & Banks, 2002; International Data Corporation, 2021). In space, specifically, communications through audio (e.g., mission control communications, alert/warning signals) is critical to mission success, and needing to be kept free of excess clutter. For example, if a crew member is being asked to perform an intricate robotic operation, it could be overly salient to give them a constantly-repeating, high-decibel, audio-displayed ‘caution’ as they are approaching a close structure, as it might be overly interrupting to the required visual attention to the robot or other critically-important procedural supports (Rembala & Ower, 2009**).** Beyond this, the sensitivity to specific designs prevents many electronics from entering certain environments (e.g., an Extravehicular Activity, EVA, suit), due to flammability risks in O_2-rich environments, only magnifying the problems of over-saturation of audio and visual domains (Hoffman, 2004**)**. While this is partially due to the limitations of our cognitive (i.e., current) bandwidth, even as these systems are enhanced and/or replaced by synthetic intelligences in the future, these same limitations will likely remain gatekeepers. As is discussed later, multiple resource theory highlights that while we can ride a bike and have a conversation at the same time, it is much more difficult to have two conversations at once (i.e., Kahneman, 1973; Basil, 1994; Wickens, 2008). Thus, the determination of the right countermeasure display is likely to be one of novel orientation and configuration, beyond the standard protocols for display technologies.

One interesting option, then, for exploring display-based conditioning of breath is the use of galvanic vestibular stimulation (GVS). GVS is actually a much older, non-invasive technique than many recognize (i.e., early 19th century), involving the direct stimulation of the various vestibular command pathways (i.e., direct electrical current). Through the use of a positive cathode and negative anode, GVS can stimulate action potentials in vestibular nuclei. In particular, the dipole intends to activate the afferents of the vestibular organs (e.g., otolith organs, semicircular canal) and allows for GVS to impact not only postural and ocular response control (e.g., stability, balance, vestibular ocular reflex), but also the user’s spatial orientation. Through the ascending and descending pathways of the vestibular, neuronal handshake, GVS can impact parietal and somatosensory cortices and can, also, interact with motor neurons in the lower limbs (Lopez, et al. 2012). Through this stack of effects, GVS has even been demonstrated to have motor control and, therefore, directional navigation control – as produced by stability variation delivered with a unidirectional GVS design (Aoyama et al., 2015; Sra, 2018; Smith, et al. 2022). Additionally, GVS has been shown efficacious in: stimulating neuronal pathways; enhancing overall balance performance and reducing declination rates; support in Meniere's diseases, vestibular neuritis, and other vestibular diseases; increasing neuronal plasticity; increasing health of vestibular and motor controls in patients with Parkinson's Disease. Even further, though, there is research identifying more secondary psychological and cognitive benefits to GVS use, including: enhancing memory and cognition, reducing anxiety, as a stress treatment, and even enhancing general neuro-plasticity (Maeda, et al., 2005; Cevette, et al., 2012; Gensberger, et al., 2016; Sra, 2019; Lee, 2021).

GVS as an Ideal Countermeasure Display

While there have also been studies that examine the impacts on long-term use of GVS, much of the stimulation technology has seen design and operational improvements to its current, frequency, and electrode integration and functionality (i.e., delivery, material, sizing, localization, etc.) that suggest it will face even lower risks in the future (Wilkinson, et al., 2008; Lopez, et al. 2012; Wuehr, at al., 2017; Gutkovich, et al., 2022; Smith 2022). Considering this assumption, the first level problems to examine are surrounding GVS's integration into the human brain's central command architecture. For example, humans are used to receiving auditory and visual alerts (e.g., phone and emergency notifications), but very few have ever received electrical stimulations of their vestibular nuclei and organs. Further, if the use cases for GVS were such that it is too distracting to a user's attention, it would have definite limitations to its use cases for being as integrated as the user's breath. For example, delivering a facial muscle shock would make for a poor cue for DSB based on how other psychophysiological narratives and behavior patterns interact (e.g., SNS activation at the annoyance of a painful facial shock that is meant to encourage PSNS activation via DSB).

Of particular interest to this dilemma is the lens of multiple resource theory, which, roughly, states that there is a limited amount of processing power (i.e., resource) that we can cognitively attend to at any given moment (Basil, 1994; Wickens, 2008; Bear, 2020). While arguing that there is a limited resource pool to our mental capacities, this pool can be manipulated in ways that allow for multi-task performance without reducing integration and, therefore, output. Returning to a previous example, trying to have two conversations at once is challenging, but having a conversation while riding a bike is typically much easier (especially at low effort, reflecting the changes of the respiration concert to support offloading metabolic rate demands; Morton, et al., 1995; Teboul & Scheeren, 2017; Forster, et al., 2011; Russo, et al., 2017). Built off the early attentional models of Kahneman, multiple resource theory also aims to explain how we can watch television and listen to its audio, concurrently, with real-time variations of semantic and sensory level meaning – although there have been debates regarding pathway redundancies in the audio and visual sensory systems worth noting (Kahneman, 1973; Basil, 1994; Wickens, 2008; Bear, 2020).

Nonetheless, if we consider that the proprioceptive and interoceptive systems operate, concurrently, with other sensing modalities (e.g., audio, visual, haptic), it is possible to suggest that commands outside of the standard vestibular pathway could be used to trigger conditioned responses in a user with limited impact to current attentional and cognitive resources (Wickens, 1981; Bear et al., 2020; Smith et al. 2022**).** As these insights highlight, often we see things for their limits, instead of examining what we can do with all the scaffolding they supply. At the very least, GVS offers a unique display technology for exploration in breath due to the a) non-standard nature of the signally that can be b) communicated to a well-adapted system of inputs via the various system-wide integrations of vestibular coordination (e.g., balance, posture, gait, g-force identification, etc.)**.** Following this argument, research has identified that in varying critical aspects of the GVS signal (e.g., frequency and polarity), one can allow unique cues to be provided to a user (Aoyama et al., 2015). This suggests that GVS could be effectively linked to unique, complex, and combinatory respiratory responses/protocols. For example, a lower frequency signal may be conditioned to indicate deep, slow respiration topography, and a higher frequency could be conditioned to a shallow, quick respiration topography. Thus, with the level of signaling variation that can now be achieved with GVS (e.g., Soterix Medical, Inc.), there exists a clear opportunity for an inquiry into generating a viable GVS display technology for creating the pathways towards human (breath) response to autonomous cueing architectures (Thomas, et al., 2020).

The initial aspects of this were examined through our lab, and our collaborators, Smith et al. (Smith, et al., 2022). That work sought to move beyond standard vestibular commands to develop something more similar to Spider-Man's "Spider Sense", while taking advantage of the overlay humans already have in vestibular sensory inputs (2001; Smith, et al., 2022). For example, as you read this, your vestibular system is sending commands to keep your head balanced on top of your sacrum without interrupting your ability to read this sentence. This research found that salient signals (e.g., 0.6-0.8mA) can be passed to a user through high-frequency GVS display stimuli without impacting normal vestibular commands**.** Additionally, this work also demonstrated that such high-frequency signals can be passed to the user in numerous mobility conditions, without any apparent impact on standard proprioceptive strategies (as viewed from ambulation outcomes; Smith 2022). Further, ongoing work exists by myself, and my lab – in collaboration with Dr. Nicholas Kelling, University of Houston - Clear Lake (UHCL) – regarding GVS display impacts on cognitive vigilance, seeking to resolve further insight into the right conditions for GVS use as a display H-CMS. Lastly, efforts to explore unique impacts on brain architecture to different GVS frequencies is currently being performed, and should inform the future applications of the generalizable knowledge intended to be exported from the proposed (Lee, et al., 2021). With this background of GVS, it appears it offers a sensible strategy for application as the display technology for this effort, but understanding its future capacity for being as portable as our breath ensures it.

Thus, while highlighted briefly, another justification for the use of GVS (as the primary target display for breath commands) is exported from recent uses of GVS in advanced technologies, as well as the future design intents for the technology. Currently, GVS is experiencing an increase in relevancy as a successful accelerator in pilot training VR simulators; for example, providing a pilot trainee the vestibular commands for G-forces during a banking maneuver translating to actual flight comfort and transition of skills (Sra, et al., 2019). Following this application ecosystem, GVS can also add the g-force “feel” of flying that were previously generated through imperfect, expensive and large-scale centrifuge designs or through risks taken with untrained pilots that lead to increases in safety, cost, and budget byproducts (Moore, et al., 2011; Cevette, et al., 2012; Sra, 2019). This has unique applications to space, namely: just-in-time training practices (e.g., crew landing, reinsertion, etc.); in providing gravitational-like stimulus for training (e.g., traversing operations, robotic handling, etc.); application during exercise or socialization efforts to enhance immersion (Maeda, et al., 2005; Cevette, et al., 2012; Gensberger, et al., 2016; Sra, 2019). All of these benefits are offered, again, through an underutilized pathway for communication, which makes GVS even more attractive: if the dominant set of its future use-cases is immersivity-enhancement for simulations – or in counter-acting motion sickness/dysfunction – then they are centrally focused only in a training motif within low-frequency domains of stimulus, outside the high-frequency “Spider Sense” developed and intended for use in the proposed (Wilkinson, et al., 2008; Wuehr, at al., 2017; Gutkovich, et al., 2022). This leaves communications pathways open during most of a crew member’s day for other applications.

Therefore, GVS appears to offer the possibility of a full-spectrum solution set for the highly-overpopulated visual and auditory (and haptic) notification systems being applied to humans today. If this work is successful, it could be used to stake claim to this display technology as being directed, specifically, at our physiological and psychological interventions of breath. Even without breath, this wave of application considerations for GVS will continue to drive growth and improvement in GVS technology, with even more leverage generated as its XR, gaming, and metaverse style applications become practical and more supporting of commercialization. With direct focus from groups like Soterix Medical, Inc., we will see future GVS systems that can be worn ‘on the go’ in low size, weight, and power configurations (Smith, et.al., 2022). This allows the technology to be easily transported, worn, spared, and used in all conditions of a crew member’s day, enhancing the applicability logic for autonomous collaboration. Though these advances may still be further off, this does not limit GVS from being used, immediately, as a training tool for generating much of the same outcomes as a constant companion device. For example, if an autonomous system engages the same breath strategy each time a user is in a particular scenario, eventually the user will be conditioned to it – and may perform the target breathing without the external cueing (as a kid that learns to take a deep breath transition practices/trains towards internal, self-directives when they are an adult and get upset). This is the intent: to create a consistently active loop of training and monitoring of our breath that enhances a human user's capacity to be in the a) optimal state at the b) preferred time with c) as little impact on the user's current workload as possible.

As Nick Lane says, regarding his double-agent theory of life in his book Oxygen: the molecule that made the world, "Behavior of our genes depends on oxygen and oxidative stress, when we learn how to modulate oxidative stress with more finesse than, and only then, can we go beyond our genes and destiny" (Lane, N., 2003; Lane, N., 2002). This tertiary breathing system could offer us the most effective and universal means towards this goal of reaching our highest individual potential.

Experimental Investigation of Conditioning an Autonomous Breath Agent via GVS

Breath can be conditioned and GVS is a uniquely capable display technology for this conditioning. In this context, the intended research design will apply multiple strategies to enhance the learning process (e.g., mirror neurons, reward-based operant conditioning) of users by i) conditioning them to a relevant deep breath cue using a high-frequency GVS display stimulus, and, then, ii) demonstrate the ability for that GVS cue to evoke the desired breath behavior during a Virtual Reality (VR) gamified environment (that is intended to mimic a highly energetic environment that crew might face when breath augmentation could be desirable). **It is hypothesized that high-frequency GVS will provide a highly reliable cue for conditioning DSB-based breath protocol by demonstrating there was stimulus control, as established by the following sub-hypotheses:**

1. The frequency of the user’s breath during unconditioned baseline gamification (i.e., initial measures) will be higher than that during the conditioned gamification (i.e., final measures), representing that the high-frequency GVS stimulus is modifying (i.e., slowing) the user’s standard respiration through DSB cueing
2. Average breath depth will be similar during the baseline and conditioned phases. This result would support that the high-frequency GVS stimulus is effectively conditioning the ideal, desired respiration and is effective at evoking the ideal, desired respiration during distracted load.
3. Average breath duration will be similar during the baseline and conditioned phases. This result would also support that high-frequency GVS stimulus is effectively conditioning the desired respiration.

CHAPTER II:

METHODS

This experiment consisted of five phases, with a survey period before and after those phases. In the first phase, baseline data were collected during a gamified workload (e.g., playing Pacman in AR; intended to reflect a visually and cognitively-stimulating environment resembling crew challenges in space). In the second phase, the user was trained on the desired breath topography and the baseline of this topography was captured using a guided visual trainer (e.g., ball on track). In the third phase, the user was introduced to the GVS stimulus and the subjects' experimental viability was verified. In the fourth phase, the user was conditioned to perform the desired DSB breath to the GVS cue through a reward interface in the HL2 platform. In the fifth, and final phase, the user was presented with the same GVS stimulus, but while under the same gamified workload as in phase one (e.g., Pacman in AR). Thus, the a) baseline data from the first two phases can be used to b) help condition and validate user performance in the final two phase, while c) generating appropriate data to make determinations on the performance of the hypotheses.

Participants

The sampling of participants was convenience-oriented (i.e., total subjects, n_{total} = 38; valid-data subjects used for statistical analyses, n_{valid} = 28, due to various incomplete data collection scenarios), consisting mostly of college undergraduate and graduate level students with varying age range (M = 25.9, SD = 7.95), with normal prior sleep duration (M = 6.82, SD = 1.23), low stress levels (M = 2.90, SD = 1.40), and low levels of experience with any of the technologies or breath (reference Tables 3.1-12, for further subject details). This study was not concerned, yet, with the limitations of the GVS technology, as other work is being performed in our lab and is in current publications

(Keywan et al., 2020; Smith, et al., 2022). Participants self-confirmed that they were of good health, with no history of brain injuries or vestibular dysfunction, and that they had not consumed alcohol in the past six hours. Further, this included pre-test and post-test surveys of relevant performance and/or deflections that may contribute to data outcomes (assumed to be more viable in post-processing review of subject exports). These surveys also align with information extracted from previous collaboration work with Clark et al. (Smith et al., 2022).

Participants performed this experiment of their own volition, with most receiving course credit if they were part of the SONA subject pool system offered by the University of Houston – Clear Lake (UHCL). If at any point, the user did not feel well and could not continue, they were immediately removed from all apparatuses (receiving full credit for their participation – ensuring there was no negative loop for continuing on against discomfort). While relevant power analysis (assuming ~0.4-0.5 effect size for moderate differences, a power of 0.8, and an α of 0.05 – as this is part of early investigations into the human-machine interaction presented) suggested that at least 24 participants were needed to run the desired statistics analyzing the work's hypotheses (i.e., hypothesis testing of the frequency, duration, depth, and latency data aforementioned using repeated measures t-tests), this work sought to capture at least 30 subjects (i.e., n = 30), but did not place a cap on this number during the planned (i.e., 2-week) testing window. Final subject numbers were higher than this desired value ($n_{total} = 38$), but various data completions issues resulted in 27 valid subject data sets ($n_{valid} = 27$) for the analyses of the core hypotheses. Worth mention, with respect to this data loss, is that the study's digital experimental design makes extending data collection simple and repeatable (i.e., by many different researchers), allowing further insights to be culminated together at a later date.

Apparatus and materials

Breath topography was verified through means of a StretchSense stretch sensor attached to (e.g., sewn into) a Polar H10 Chest strap Heart Rate Monitor (HRM). The StretchSense output a changing voltage based on the total deflection of the sensor, and, thus, rough measures for depth of breath were captured – as a function of total deflection of the sensor (i.e., as driven by the expansion of the chest cavity). This breath-sensor deflection data was also used to drive the OC rewards that the user experienced during the GVS conditioning (i.e., Phase IV), leveraging baseline data captured in Phases I and II. Further, knowing the change of direction in voltage change (e.g., reflecting the change from inhalation to exhalation) allowed for breath frequency and duration to be exported, after signal post-processing was performed.

The GVS system delivering the testing stimulus was a medical-grade, custom-modified, Soterix, Inc. table-top unit that had been integrated to a controller**,** allowing the stimulus to be provided by manual or programmed input. Specifically, the GVS system used two, (12-mm) toroidal silver-silver chloride, electrodes for delivering the stimulus and preparations of subjects included cleansing (i.e., alcohol swabs), exfoliation, cleansing, and electrode gel application to the two mastoid processes (i.e., desired location for application of GVS/stimulation). Further details can be found in previous work with collaborator Clark et al (Smith et al. 2022).

The data from these technologies were linked together via a MQTT publish/subscribe data broker service (i.e., stretch sensor, GVS controller, HL2, etc.), in order to monitor the subject breath topography and generate real-time data for driving conditioning-reward architectures in Phase IV, aforementioned (*The standard for IOT messaging, n.d.*). An example of the totality of the data output from the IoT (i.e., leveraging Unity design for properly tagging all data), as extracted during post-processing of an actual run, is shown in Figure 2.1:

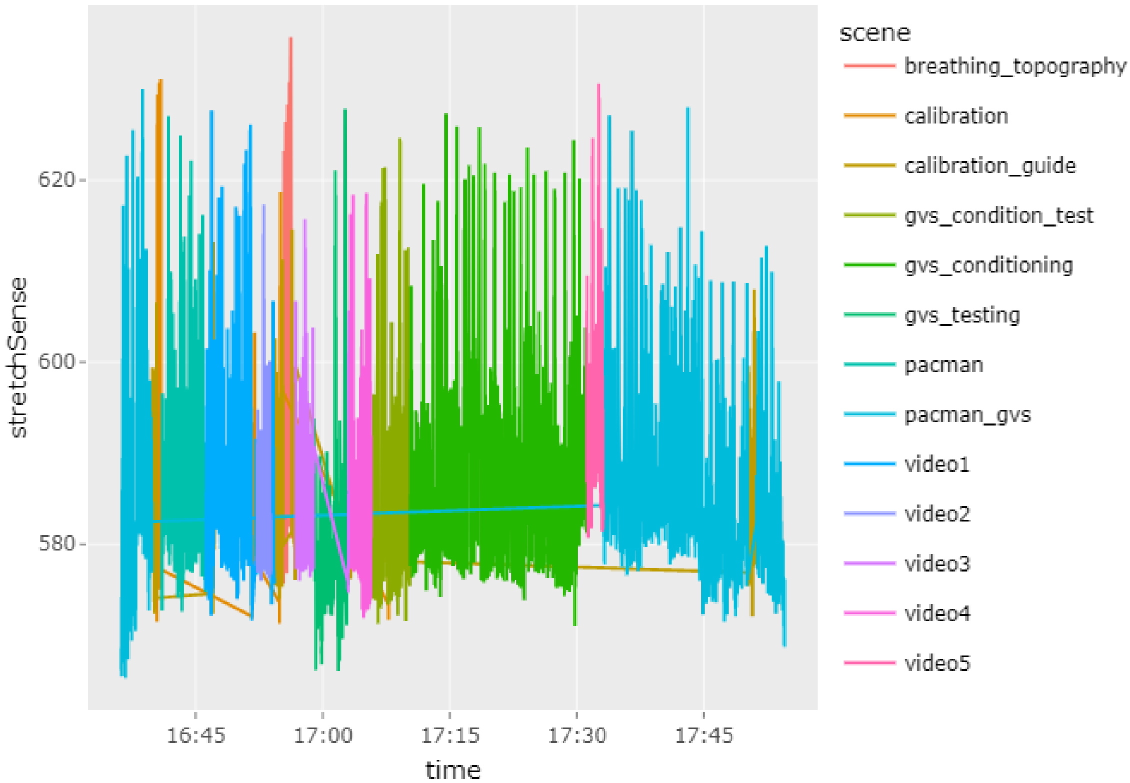

Figure 2.1
PIVOT platform data processing output of tagged data for a complete experimental run; y-axis is stretch sense deflection in p, x-axis is running time (shown in HH:MM)

AR gamification was offered through the Microsoft HL2. This gamification was a representation of Pacman, where users were encouraged to play the game any way that they desired (e.g., for enjoyment, to achieve the high score). For the significant majority of the experiment, subjects used their hands as the interactive controllers, but also utilized a dual-analog, thumb-stick interface (e.g., Microsoft Xbox dual-analog controller) – intended to present a more commonly-expected user-experience to the Pacman gamification. These experimental design and interface choices sought to reduce, or prevent, challenging technology learning curves from impacting the user during key data collection points. Further, the HL2 was utilized for administering video training elements in the study, as well as driving/hosting the generated user interface (GUI; i.e., for data collection and reinforcement delivery). In all, this was a multi-stage user experience, with the HL2 being the backbone of the human-machine and physical-human-machine interfacing (HMI, PHMI) and leveraging the unification of all digital data sensing and display systems via the IoT framework.

Procedures

Upon first entry to the UHCL Human Factors Lab, the participants (n = 38) were met by researchers, reviewed and signed the informed consent, and performed the pre-survey questionnaire through Qualtrics on a laptop. This Pre-Study Survey (located in Appendix D) confirmed that the subject did not meet the exclusionary criteria (e.g., no history of vestibular dysfunction, no alcohol consumption within the last six hours) and delivered relevant proximal-to-performance data that could be useful in future data analysis (e.g., number of hours of sleep, recent caffeine use). Upon completion, the subject entered the study area, which was removed of any obstacles, and was seated in a chair staring at a non-distracting wall (i.e., white wall with nothing on the walls). In this position, the participant completed the significant majority of the study, including the breath topography training videos, the familiarization with Galvanic Vestibular Stimulation (GVS) and cue teaching, the Conditioning GVS to Breath, and the Validation via a gamified experience. These sessions took roughly two hours, depending on the time of preparation and the rate at which the participant successfully completed the breath protocols and phasing (e.g., if breaks were taken, the procedure timeline expanded).

Prior to the start of the session, the researcher carefully detailed the full procedure, risks, and benefits associated with the study, reminding the subject that, if there were any issues or discomfort, there were multiple ways to help alleviate and support them (e.g., flipping up the HL2 visor immediately removes the AR stimulus, the HL2 could be removed to alleviate pressure concerns, etc.). The participant was then asked to don the chest-mounted HRM band with integrated stretch sensor, noting to locate the sensor underneath the left pectoral with as much tightness as was comfortable; this ensured that the critical breath data was correctly captured (note: during the times when the subject was donning or doffing the HRM, the researchers left the room to give the subject appropriate privacy). Next, the researcher located the mastoid processes on the participant, cleared hair away as required, cleaned the skin with alcohol wipes, and exfoliated the same area over the mastoid using NuPrep Skin Prep Gel (note, further details and clarity on the following procedure can be found in Appendix C). The GVS electrode cups, filled with electrode gel and containing the GVS electrodes secured by a plastic retaining cap, were then positioned on top of the exfoliated area and fit securely with a 3D-printed head-mount and supplementary tie-down headband. After these preparations were complete, the researcher verified the overall impedance of the skin contact to ensure proper electrode placement and connectivity (i.e., with the researcher adjusting the set-up until properly under desired kΩ limits). If any adjustments were required, the researcher made them at this point, verifying that the user was comfortable with the placement and no immediate hot spots (i.e., pressure contact points) were present. Lastly, the participant donned the HL2 HMD, performing the internal calibration (i.e., gaze tracking, focal adjustments) if requested. This completed the setup phasing for the subject.

Following this user set-up, the PIVOT software was launched via a Remote Holographic mode to the HL2 via Unity. This began the AR-guided experience for the subject, as delivered by the HL2. First, this required that the subject calibrate the stretch sensor while the researcher verified good data receipt and placement. After modifying placement for any perceived issues, the participant was told they were being rewarded for their patience by getting to play a 5-minute Pac-Man gamification (i.e., AR); this, however, was also a critical data collection point as their baseline breathing frequency was captured. Per the use of the GVS and AR based systems, the subjects were consistently monitored for their experience such that either a) severe discomfort (i.e., defined as subject, self-identified, discomfort that they felt a break could not resolve and did not stem from the GVS – pain from the GVS stimulation was not an acceptable testing condition) or b) nausea was not present. To help with the limitations of the 3D-printed headband pressure and the weight of the HL2, users were encouraged to take breaks, especially before the longer duration Phases. Any breaks were set to a 2min timer, but it was made clear to the subject that a) this timer could be extended, as they desired, and b) they were entirely welcome to elect not to continue with the experiment. In one case, a subject felt that they could no longer handle the discomfort of the headset weight and the subsequent pressure of the GVS 3D-printed mount and they were dismissed and given full credit for their time. Multiple other subjects also utilized the breaks, and provided feedback (i.e., shown in Tables 3.8-10) of the pain and discomfort attributed to the mount and weight of the total system. These design issues are already being addressed to correct for this negative aspect of the experimental apparatus design. Further, more specific, analysis – including further corroboration with collaborators – of any possible root cause for the pain linked to the GVS stimulation is also warranted and discussed in the Conclusion.

Phase I focused on training the appropriate breath topography to the subject. The participant viewed instructional videos on the HL2 HMD, outlining proper breath mechanics/topography, and were given time/prompts to practice these desired breaths (i.e., as they followed along with the PIVOT software interface). After watching these instructional videos, the subject followed the on-screen, visual breath guide for five (5) full, deep, slow breaths (i.e., the user followed a blue ball on an orange plot line that generated breath hills and phasing – inhale, inhale hold, exhale, and exhale hold – as the model for imitation). During these five (5) breaths, the subject's respiration was recorded using the calibrated stretch sensor as the second set of baseline data, providing: a) depth and b) duration of each respiration cycle, as well as continuing to examine the overall frequency of the subject.

Phase II focused on teaching the GVS cue. Subjects watched another training video introducing the GVS technology and were given time to ask any questions they may have after the, generally, novel information that was shared. Once the subject had confirmed readiness, they were met with their first set of GVS stimulations. These stimulations, however, were not randomly delivered (i.e., as the rest in the experiment), rather the user controlled on-screen firing buttons. After interacting with the 'Fire GVS' button the system delivered a GVS stimulation to the user (e.g., 50Hz, bipolar, sinusoidal, 0.6mA, no sham), and subjects were asked to provide feedback using the on-screen 'Yes' and 'No' buttons. The researcher also verbally followed up with the user as to how the stimulations specifically felt to ensure that they were sufficiently perceived, that the stimulus was vestibular as opposed to haptic (e.g., zapping or prickling on the skin), and that the setup was not providing the user any form of new discomfort. Three (3) total stimulations were given to the majority of the users, with some subjects needing another set of cues to validate (note: this was also another time that the researcher was allowed to make manipulations to the GVS setup before entering the conditioning phase to help with providing the intended vestibular display). It was also at this time that some users had to be removed from the study due to an inability to find the low 0.6mA level cue salient enough to register.

Phase III focused on conditioning the subject's breath to the GVS cue. First, the participant was asked to, again, verbally verify that they were not feeling nauseous or experiencing any distress from the use of GVS or HL2 up to this point, letting them know they would be entering a longer, far less distracting, 20-minute conditioning cycle. Upon confirmation of comfort, the user clicked a next button to watch another video regarding the impending conditioning; wherein, subjects were reminded to use the same deep breath mechanics (i.e., topography, DSB) that they had practiced in the previous phases. Following this introduction, another three (3) GVS cues were provided, this time at random intervals between 15 and 20s from the initiation of the program (with the stimulus interval immediately restarting following each stimulus presentation, as in all remaining phases of GVS stim in the experiment). The user was instructed to perform the DSB with each of these test stimulations to make sure both subject and researcher felt that the subject understood the plan for the conditioning. After which the user moved to the actual conditioning GVS delivery, which offered random stimuli between 15 and 90s. Based on biofeedback collected from the calibrated breath sensor, the subject was given positive reinforcement messages (i.e., during these conditioning phases) if they successfully achieve different aspects of the breath (e.g., "Hooray, you took a XX% deep breath," "Stellar, you also took a XXs slow breath," etc.). These GVS cues continued until 20 successful GVS-breath cues were delivered, and users were notified when they were 50% and 75% done with the stimulations by the researcher. Immediately following conditioning, the researcher checked on the subject by encouraging the user to stretch out, checking in with their levels of comfort, and making sure they didn't need a break before moving on to the final phase.

The final phase for the subjects was the validation of the conditioning performed in Phase III via the same gamified Pacman experience, as was utilized for baseline breath frequency collection. Prior to the gamification, the participant watched a final instructional video informing them of the intent to stimulate the breath via the GVS cue presentation during a gamified environment (note: this also let them reset to more of a baseline breathing pattern before examining the impact of the GVS stimulations). At the subject's launch of the gamification, they again used the Xbox controller for operation and were met by a similar random delivery of 20 stimulations between 15 and 90s apart.

Completion of this gamification marked the end of the AR experience and the researcher immediately worked to remove all of the hardware and supporting materials. It was also during this time that the researcher cleaned up the gel from the GVS system, the subject was offered lotion to hydrate the exfoliated area, and the researcher verified that the user was feeling well. Lastly, the researcher left the room to have the user doff the HRM stretch sensor in private and returned with the laptop to provide the post-study survey via Qualtrics (i.e., details can be found in Appendix E). This survey offered the subject feedback points to relevant qualitative data on the experience (e.g., "did you find it easy to recognize the GVS cue?"). The subject was, finally, graciously thanked for their participation and was allowed to leave, such that the researcher could fully sanitize the space and prepare the IoT, AR and GVS for the next subject.

CHAPTER III:

DATA ANALYSIS & RESULTS

Returning to the core hypotheses of this work – supported by the data collected via the connected data architecture, IoT, and various sensed elements of the subject experience via the PIVOT software platform – baseline data (i.e., pre-conditioning, pre-treatment) and performance data (i.e., post-conditioning, post-treatment) for each subject were used for running repeated measures t-test statistics. These established rejection criteria of the works' null hypotheses. Specifically, these analyses were performed for qualities of the stretch sensor data sets (i.e., frequency, depth, duration), individually, with an assumed α of 0.05.

First, a repeated measures t-test analysis was run (i.e., utilizing Jamovi) on the average subject respiration frequency, comparing the respiration rate during the initial 5-minutes play of Pac-man to the respiration rate during the final Pac-man play (i.e., with the GVS cues). The results of the breathing frequency analysis were found to be statistically significant, $t(26) = 8.36$, $p<.001$; $d = 1.61$; wherein this effect size ($d = 1.61$) greatly exceeds the convention for a large effect of $d = 0.8$ (Cohen, 2013). Data for this calculation was generated from the use of a) a software smoothing filter (e.g., initial data sets had a 60Hz noise frequency from the HL2 power adapter, such that later runs were not plugged into power to eliminate this noise), a b) a peak identification algorithm, and was supported by the tagging functions of the IoT platform. These software elements, in conjunction with the picofarad (pF) output of the stretch sensor upon deflection, allowed for highly accurate breath frequency to be extracted from subjects. Results, therefore, indicate that conditioning the user to a DSB archetype ($M = 16.2$, $SD = 2.70$) resulted in the GVS countermeasure (i.e., set on a random stimulus between 15 and 90 seconds for 20 stimulations) reducing breathing frequency from the initial baseline ($M = 20.4$, $SD =$

2.68), this statistical difference supports identifying GVS breath conditioning as an effective countermeasure strategy for modulating (i.e., specifically: reducing) breathing frequency (i.e., Hypothesis 1). Second, a repeated measures t-test analysis was run on the average subject breath depth (i.e., as measured by total pF deflection of the stretch sensor) during the similar phases of performance (i.e., pre-conditioning, post-conditioning) as the aforementioned frequency analysis: comparing the depth during the initial baseline (i.e., collected while following the graphical topography-training ball along its path) to the depth of breaths taken after each successful GVS cue (i.e., during the final Pac-man gamification). Results of the breathing depth analysis run were also found to be statistically significant, $t(26) = 3.28$, $p = 0.003$; $d = 0.631$, with an effect size ($d=0.631$) that exceeds the criteria for medium effect ($d = .5$; Cohen, 2013). Particular to note, when examining this data, is that the indicated measure of depth was generated by individually-normalizing the stretch depth to a breath transform coefficient (BTC; i.e., extracting, calculating, and applying an individual normalization value for each user’s breath style, physique and sensor setup). The BTC was derived by extracting the three largest depth breaths (i.e., the most idealized) during the baseline visual tool trainer phase. This allowed for the total five breaths in that trained architecture to be relative to the same level of depth performance as any breath taken throughout the entire experiment. These results, therefore, indicate that the ideal topography of breath depth at baseline (i.e., the desired breath; $M = 0.929$, $SD = 0.040$) was not reflected in the conditioned performance (i.e., when cued by GVS; $M = 0.769$, $SD = 0.250$), failing to support the research hypothesis (i.e., Hypothesis 2) and identifying that the current (PIVOT process x GVS breath cue) architecture is not sufficiently effective as a countermeasure strategy for modulating ideal breathing depth (i.e., specifically shaping and cuing maximal depth). Lastly, a similar repeated measures t-test analysis was run on the average subject breath duration (i.e., duration = [time of inhale] + [time of inhale hold, until subject breath sensor deflection reduces to under 95% of the most recent breath's maximum depth] – with depth still measured by the breath sensor's pF output of deflection) research hypothesis: comparing the duration during the ideal breath baseline (i.e., the visual ball trainer phase) to the duration of breaths taken after each GVS cue (i.e., during the final Pac-man gamification). The results of the breathing duration analysis were also found to be statistically significant, $t(26) = 9.95$, $p<.001$; $d = 1.91$. This analysis effect size ($d=1.91$) also greatly exceeds the convention for a large effect ($d = .80$; Cohen, 2013). These results, therefore, indicate that the ideal topography of breath duration at baseline (i.e., the desired breath; $M = 5.81$, $SD = 1.09$) was not reflected in the conditioned performance (i.e., when cued by GVS; $M = 3.90$, $SD = 1.11$), failing to support the research hypothesis (Hypothesis 3), and identifying, again, that the current training architecture design is not an effective countermeasure, training, and display strategy for ideally modulating breathing duration (i.e., specifically extending duration). The combined results of each of these three analyses indicates existence of statistically significant support for the overall trainability of breath through GVS, particularly reinforced by the high percentage of accurate responses displayed during the gamified conditioned phase shown in Table 3.1. As an extension to this and all following assessments, Appendix F includes more detailed information on how the various data were extracted via an example of the R-code HTML output for one subject.

Table 3.1
Descriptive statistics of the usable subjects (n_{valid} = 27) successful response rate to the GVS during conditioned gamification – note: this is not of the overall subjects (n = 38), but of successfully captured data sets that met completeness criteria

Descriptive Statistics (GVS Stim Response)

	GVS Stim Response (%)
N	27
Mean	97.1
Median	100
Standard deviation (STD)	5.08
Minimum	80.0
Maximum	100

Thus, while the ability to condition to a GVS display is possible, the precise apparatus for how to accurately shape the topography of the cued breath behavior chain still requires enhancement – especially if complex breath archetypes (e.g., conditioning multiple, unique breath topographies) are to be conditioned to a user. The learning models (i.e., imitation, AR/visual models, classical and operant conditioning, etc.) were successful at introducing a change to breath performance (i.e., accurately conditioning and then cueing DSB breath responses, directly leading to a reduction of breathing frequency), but refinement of their application might eventually lead to a more accurate reproduction of the ideally trained breath topography (i.e., depth and duration).

When examining the data below, which is representative of all the subjects that participated in this experiment, it is particular to discuss the differential between overall subject number and degrees of freedom of the previously discussed statistical analyses.

Table 3.2 identifies the validity of a particular hosted subjects' data set, or specifies what level of impact resulted in the data set not being viable for use in the statistical subject number. System failure identifies any failure of the PIVOT architecture to gain a complete data set, which included: AR system crash issues that were unrecoverable and resulted in ending the study early, IoT platform data loss, loss of battery on sensor during a data-blind period, and issues with subject movement or sensor placement on collecting accurate breath data. One subject requested to end the experience early due to the discomfort of the 3D printed GVS mounting headband plus the weight/tension of the HL2 (i.e., Table 3.8). Lastly, subjects identified as non-responders were those that could not sense the GVS stimulus at the low 0.6mA threshold. These percentages reflect similar performance with our other collaborators and studies, and may identify limitations of GVS as a display for a certain subset-user worth particular exploration (Smith, et al., 2022). Some preliminary data on particular aspects of performance – which might attend to understanding who 'is' v. who 'is not' a likely GVS display responder – were collected as part of pre and post surveys to the AR x GVS experience. These results are also shown in the tables to follow. Beyond this, and to harness capturing any partially complete data sets, a completion criterion was set at a minimum of 10 responses worth of data in a particular phase. For example, if a subject had proper baseline gamification data collection (i.e., 5-minutes of unconditioned Pac-man) and at least 10 stims worth of captured data in the conditioned gamification (i.e., the ~20min final conditioned Pac-man) they were still considered valid subjects. This was mostly applicable to battery or sensor dropouts that were caught be researchers and corrected for during the experimental data collection process:

Table 3.2
Frequency count breakdown of valid data sets v. rationale for unsuccessful data collection

Frequencies of DATA SET VALIDITY CHECK

Levels	Counts	% of Total	Cumulative %
SYSTEM FAILURE	5	13.2 %	13.2 %
YES	27	71.1 %	84.2 %
NON-RESPONDER	5	13.2 %	97.4 %
SELF-REMOVAL	1	2.6 %	100.0 %

While various factors impacted collecting data from all subjects (n =38), the following breakdowns of the overall subject population helps to better understand possible system limitations; and to properly provide as much core feedback to evolving future experimental designs as possible. Therefore, Tables 3.3-3.12 represent all data collected from all the subjects, understanding that some users did not complete all feedback points. These cover aspects of the general subject pool, their various levels of experience (i.e., both experience level with various technologies and the actual quality of the experimental experience, itself), and other critical feedback (e.g., symptoms and impactors). This is meant to paint as broad a picture of the experience as possible:

Table 3.3
Descriptive statistics of key subject background data, highlighting novelty of technology and breathwork

Descriptives of SUBJECT POPULATION

	AGE	SLEEP (HRS)	STRESS LVL	VR/AR EXP	GVS EXP	BREATH EXP
N	38	38	29	25	6	7
Miss	0	0	9	13	32	21
Mean	25.9	6.82	2.90	2.72	0.333	2.65
Med.	23.0	7.00	3	1	0.00	3
STD	7.95	1.23	1.40	3.02	0.816	1.97
Min.	19	5	0	0	0	0
Max.	51	9	5	8	2	7

Table 3.4
Frequency count breakdown of biological sex of total subject pool

Frequencies of BIOLOGICAL SEX

Levels	Counts	% of Total	Cumulative %
Male	11	28.9 %	28.9%
Female	27	71.1 %	100.0 %

Table 3.5
Frequency count breakdown of gender identity of total subject pool

Frequencies of GENDER IDENTITY

Levels	Counts	% of Total	Cumulative %
Male	25	71.4 %	71.4 %
Female	9	25.7 %	97.1 %
Non-binary	1	2.9 %	100.0 %

Table 3.6
Frequency count breakdown of subject caffeine consumption before study

Frequencies of CONSUMED CAFFEINE

Levels	Counts	% of Total	Cumulative %
No	32	84.2 %	84.2%
Yes	6	15.8 %	100.0 %

Table 3.7
Frequency count breakdown of subject meditation before study

Frequencies of MEDITATION

Levels	Counts	% of Total	Cumulative %
No	37	97.4 %	97.4 %
Yes	1	2.6 %	100.0 %

Table 3.8
Frequency count breakdown of general user experience

Frequencies of GENERAL EXPERIENCES

Levels	Counts	% of Total	Cumulative %
Pain	2	5.9 %	5.9 %
Anxiety, Other	1	2.9 %	8.8 %
Other	3	8.8 %	17.6 %
Discomfort	6	17.6 %	35.3 %
Cyber Sickness + Discomfort	1	2.9 %	38.2 %
Pain + Anxiety + Discomfort	1	2.9 %	41.2 %
Discomfort + Other	1	2.9 %	44.1 %
Pain + Discomfort	2	5.9 %	50.0 %
Anxiety	1	2.9 %	52.9 %
none	16	47.1 %	100.0 %

Table 3.9
Frequency count breakdown of other symptoms (or details of the general experience), as defined by the subject

Frequencies of OTHER SYMPTOMS

Levels	Counts	% of Total	Cumulative %
headache	4	11.1 %	11.1 %
sleepy, relaxed	1	2.8 %	13.9 %
stress	1	2.8 %	16.7 %
tired eyes	1	2.8 %	19.4 %
none	28	77.8 %	97.2 %
pressure	1	2.8 %	100.0 %

Table 3.10
Frequency count breakdown of other impactors, as defined by subject

Frequencies of OTHER IMPACTORS

Levels	Counts	% of Total	Cumulative %
none	33	91.7 %	91.7 %
unable to feel	2	5.6 %	97.2 %
distracted by pain	1	2.8 %	100.0 %

Table 3.11
Descriptive statistics on GVS display saliency throughout the experimental design flow, as well as overall subject rating of the experimental experience as a whole; 1-10, self-selected scale

Descriptives of GVS SALIENCY and OVERALL EXPERIENCE

	GVS SALIENCY (initial)	**GVS SALIENCY (conditioning)**	**GVS SALIENCY (conditioned)**	**OVERALL EXP.**
N	32	30	29	36
Missing	6	8	9	2
Mean	6.09	7.43	6.00	8.92
Median	6.00	8.00	6	10.0
Std. Dev.	2.87	2.27	2.35	1.68
Minimum	2	3	2	4
Maximum	10	10	10	10

Table 3.12
Descriptive statistics of subject self-rating (1-10) on likelihood of pursuing future breathwork activities after this experimental experience

Descriptives on FUTURE BREATHWORK LIKELIHOOD

	FUTURE BREATHWORK LIKELIHOOD
N	34
Missing	4
Mean	6.68
Median	6.50
Std. Dev.	2.01
Minimum	2
Maximum	10

Worth mentioning, before any further breakdown, are the performance data outcomes reflected in Tables 3.8-3.11. Specifically, there were a higher number of subjects than expected (i.e., based on results of pilot testing and other collaborator feedback) that identified pain and discomfort as part of their post-survey results. While there was knowledge that the long-duration use of the system hardware might have impact on the quality of the experience, the experimental design allowed for multiple points for subject to take a break. Further, researchers were particular to consistently check in with the subject as to their comfort level and need for any breaks, responding to those requests immediately. It is unlikely that GVS produced significant levels of pain since the overall experience level was still high (M = 8.92, SD = 1.68). However, it is critical that future exploration of pain and discomfort be performed as part of GVS application; this is covered in more detail in the Conclusion.

Given that the data down-selected (i.e., $n_{valid} = 27$) from this total subject field ($n_{total} = 38$) still met the lower end of the studies presumed power analysis (n = 24 – 34), the data certainly reflects that there is sufficient proof that the system design and GVS display can accurately control breath, but does not support the research hypothesis that it can be used for idealizing topography (i.e., depth and duration). However, it is still worth showing some of the visual representations of breath performance that this data is being extracted from, as it creates a much more compelling story for a) the ability to condition breath and for b) resolving the right method to condition ideal topography in the future. Figures 3.1 and 3.2 demonstrate that the actual breath responses during the conditioned gaming are visually much more akin to the baseline (i.e., visual ball tool training) structure than they are to those breath dynamics seen whilst playing Pac-man without DSB x GVS conditioning (i.e., unconditioned) – the blue lines represent the GVS displays given to the subject and it is apparent (peaks) that the response is conditioned:

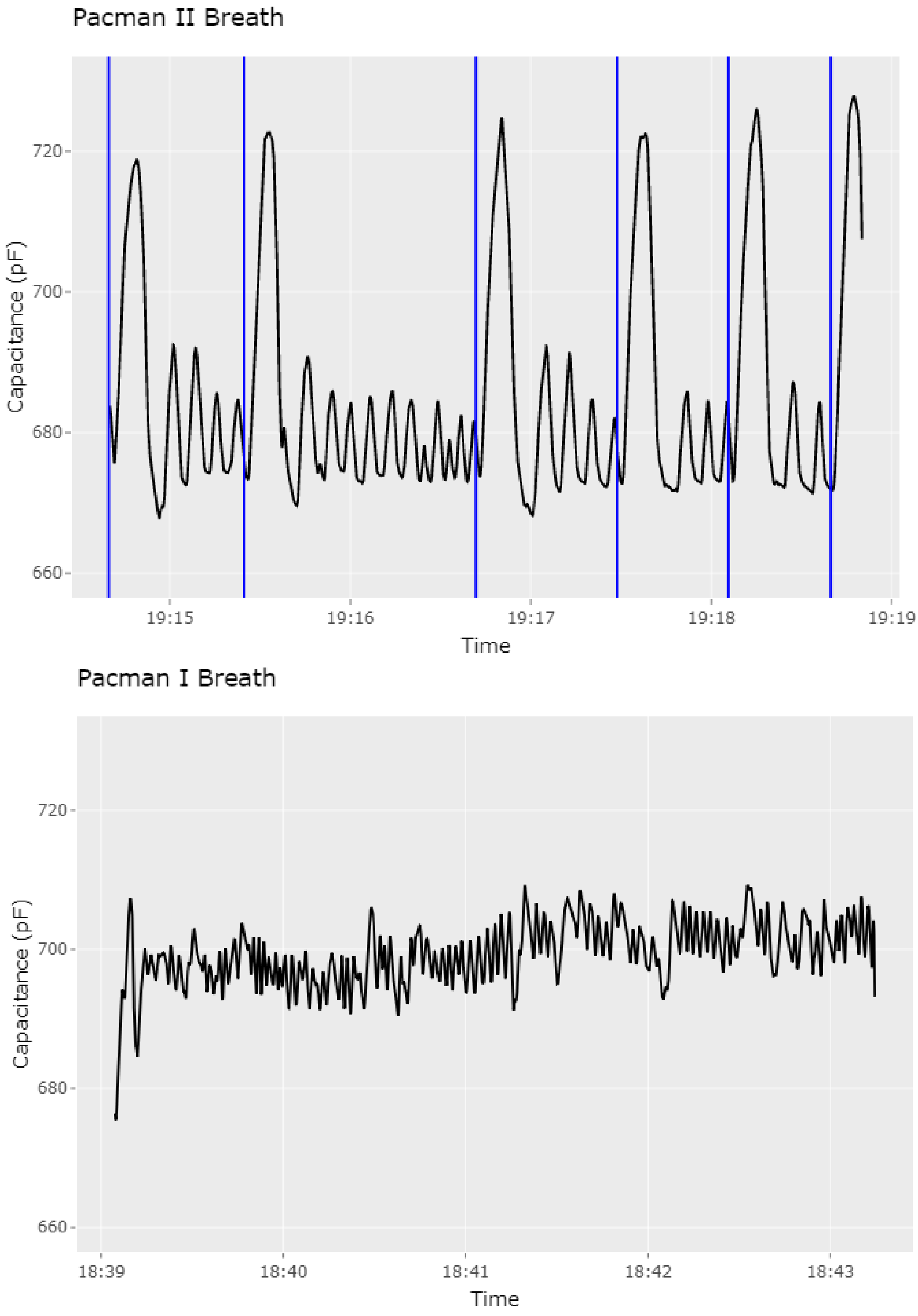

Figure 3.1
Example 5-minute data sets (for the same subject) of actual breath patterns seen during (top) Pac-man gamification while experiencing delivery of conditioned GVS display cues and (bottom) as seen during initial (i.e., unconditioned) Pac-man gamification – blue lines represent when a GVS display was administered to the user, y-axis is breath sensor deflection (p)F, x-axis is time (mm:ss)

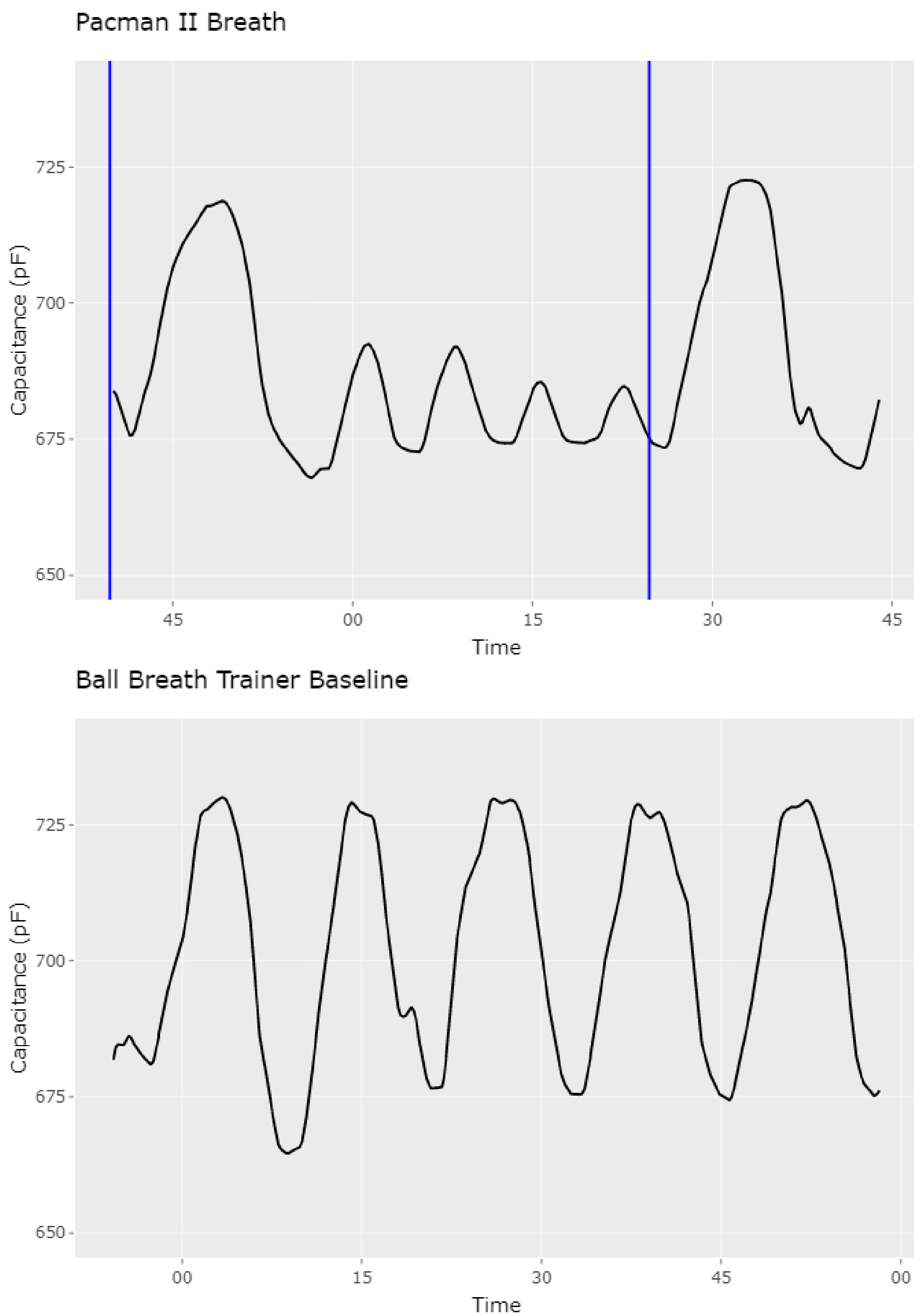

Figure 3.2
Corresponding example data sets (same subject as Figure 3.1) of actual breath patterns seen during (top) Pac-man gamification while experiencing delivery of conditioned GVS display cues) and (bottom) as seen during visual ball trainer baselining (i.e., idealized topography training (i.e., unconditioned) – blue lines represent when a GVS display was administered to the user, y-axis is breath sensor deflection (pF), x-axis is time (s)

Beyond compelling visual evidence throughout each subjects' performance, examination of the extended, but similar, statistical relationship explorations – for whether the GVS might have cued something more similar to a standard breath than the desired DSB breath – were performed. The data clearly reflect that (while not a particularly liked reference to make when discussing statistics) the response breaths are less 'not-like' baseline (i.e., ideal) breath topography than they are 'not-like' a subject under load (i.e., under the attentional visual and motor demand of playing Pac-man) topography. When comparing conditioned depth to under load depth (i.e., Hypothesis 2), $t(26) = 13.4$, $p<.001$; $d = 2.58$, and reflecting on the core thesis analysis results of the same for conditioned v. baseline, $t(26) = 3.28$, $p = 0.003$; $d = 0.631$, it is suspected that there is evidence of support that topography training is already occurring. Similar analysis of comparing conditioned duration to under load duration (i.e., Hypothesis 3), $t(26) = 21.4$, $p<.001$; $d = 4.11$, and reflecting, again, on the core thesis analysis results for conditioned v. baseline, $t(26) = 9.95$, $p<.001$; $d = 1.91$, yields similar relationships of support for emerging qualities of depth and duration (i.e., as hypothesized in this work)

Also critical in the above, is how accurately the user repeats breath topography during the visual ball training phase. This, coupled with these additional, supporting, repeated measures t-tests**,** demonstrate a high-correlation between that visual tool and proper breath topography training. This suggests that an intelligent next step in adjusting this experimental design is increasing time utilizing the visual trainer. For example, offering the ball trainer tool immediately to the user after the GVS cue instead of the current operant rewards (or concurrently). Therefore, while not a perfect implementation of conditioning the user and conditioning the ideal topography, simultaneously, deeper analysis uncovers a more complete picture of what is possible via these technologies.

CHAPTER IV:

CONCLUSION

As demonstrated in the presented work and analyses, the data exported from this work identifies GVS as a viable display modality for cueing breath, and, therefore, opens it up its use as a display for generating autonomous breath countermeasures. These results further suggest that GVS cues can be trained quickly, and (i.e., through extraneous exploration of data collected during specific training phases/strategies) offers clear trajectories to sensible enhancements of the current PIVOT design. Specifically, GVS was able to quickly train an appropriate breathing strategy (i.e., DSB), and the user was able to respond to the cue in a distracted environment (i.e., gamification tasking), that directly reduced the users breathing frequency. This is assumed to be contributed to by two particular aspects. The first is the presence of a high response rates (M = 97.1%, SD = 5.08), combined with the much longer duration breaths resultant from these cues, reducing time to breath at a higher nominal frequency – thus an interruption of normal breathing topography to meet conditioned behavior. The second mechanism involved, as discussed in the introduction, is that DSB inherently activates PSNS engagement, directly leading to such responses as reduced breathing frequency (Jerath, et al., 2006; Busch, et al., 2012; Russo, et al., 2017; Jayawardena, et al., 2020). Specific to the latter point, numerous subjects mentioned feeling sleepy after/during the experience, yawned, and others even discussed how the experience reminded them of meditation. These aspects of the experimental experience highlight a need to add brain monitoring to this inquiry to understand other mechanisms that may be coupled, neurologically, by Breath x GVS display architecture. We also plan to examine cognitive, attentional impact of GVS cues – as a function of visual, auditorial, and haptic displays during visual and auditorial tasking – to better understand the proper application space for GVS. This looks beyond the constrained visual and motor control task (i.e., load) that subjects in this experiment experienced (i.e., no audio during Pac-man gamifications). In order for GVS to replace a core sensorial input such as audio, visual, or haptic cue/warning structures, the assumptions of multiple resource theory (i.e., easier to talk and ride a bike v. having two conversations at the same time) not being a bottleneck for these commands must be confirmed. However, while it is not always optimal to interrupt a user for a breath, there are also critical situations where this is, in fact, highly 'desireable'; as such, limitations in this proposed study also create opportunities (i.e., Kahneman, 1973; Basil, 1994; Wickens, 2008).

Leveraging off this example, while this work is deemed to be a successful investigation, there are several limitations to the design. Besides being a pilot study – thus lacking the double-blind and random needs of a large clinical level trial – there are many other unique, individual-user issues that must be examined about using GVS. First, though discussed at multiple points throughout this work, the discomfort and pain experienced by the subjects needs to be explored before further research can occur. Initial work has already yielded a first iteration of a new design that attends, not only, to the reduction of pressure points, but also to such issues as enhancing the sealing of the electrode gel (i.e., to reduce chance of arching) using soft rubber seals, and gentle pre-load, of a multi-degree of freedom electrode cup. If this work is to move towards sleep and other proposed environments, the subject's quality of experience need to be engaged as top priority. Along these same lines, the post-survey questionnaires will also be updated to provide better indices of measuring the perceived discomfort or pain. For example, providing specific questions on the resulting symptoms of each technology experienced (i.e., GVS stimulation, HL2, breath sensors, ergonomics of subject area) to properly tag the subject's experience and better clarify the limitations of each element in the experimental chain. Further – especially provided that a critical aspect of GVS's future as a display modality is repeatable, measurable, adherence to its safety and quality control of stimulations – being able to more correctly classify what the subject is sensing in this vestibular "Spider Sense" display is crucial. Leveraging scales and surveys used in early research of other brain stimulation modalities (e.g., TES. TMS), for instance, could provide a richer vocabulary for recognizing true limits of the technology to a) keep the subject safe, and b) provide opportunities to more appropriately inform the iterative trajectory of this, still, quite young, GVS technology. These lessons learned will be directly applied to our lab's next GVS study; proper updates are being made to informed consents, experimental designs, etc., and will be coordinated with the appropriate human subject board amendment and approval process.

Another critical assumption to explore is whether or not the 0.6mA current level is completely removed from stimulation of tactile touch sensors in the touch receptors around the mastoid (e.g., such that this is purely a GVS signal, and not a dual haptic + GVS activation). Particularly, is raising the current value to 0.8mA or 1.0mA – provided proper skin contact impedance levels – acceptable for administration without haptic response in some users? For example, while the lowest skin conductance of any subject was measured at 0.4 kΩ, this subject was still unable to feel the stimulus. Therefore, opening up the allowable current level might also open up the technology to an even higher number of responders than the 86.8% ($n_{responders} = 33$; $n_{total} = 38$) seen in this study – again, noting that other collaborators using similar GVS applications also experience around a 90% responder rate. However, this engages a benefit-to-risk analysis regarding the gain of responders to the, aforementioned, lack of total clarity surrounding the root natures of subject pain and discomfort indications (i.e., including the notion that use of terms like pain and discomfort, may only signify a lack of properly-qualifying lexicon for the subject to describe the novel, high-frequency GVS sensation). Specifically of concern, are any notions or specific products of pain associated, directly, with the GVS stimulation or current level. The GVS must be safe as the first level focus, less than salient. This should be more informed by improving methods for collecting subject quantitative and qualitative feedback and human factors assessment before further subject testing, and is planned to be completed before the end of the calendar year.

Other, related, limitations include that this, particular, series of experimental designs has not yet considered other activity environments/ecosystems – having fixed the user to a seated configuration. While our previous research identifies that any condition of mobility is applicable for GVS use, as one stacks sensorial inputs together, they begin to strain, again, the foundational assumption of the multiple resource theory opportunity space being leveraged: that narrative of the, seemingly, free bandwidth demonstrated by such human abilities as navigating the bike trail and effectively crafting meaningful dialogue, concurrently (i.e., Kahneman, 1973; Basil, 1994; Wickens, 2008, Smith, et al., 2022). A final limitation is that, while the age range is wide, the actual data reflect a lack of diversity in the set of users. This study had a high female to male ratio, was mostly college and early graduate age students, and most had very little experience with VR or AR. Novel to this younger mean age (M = 25.9, SD = 7.95) is that most in this age range were raised with the technology, such that their trust (or attention to the system) may have been relatively higher than someone trained outside of a technological society. Any sort of bias like these positive and negative relationships with the technologies utilized – which this work knowingly elected to push the edge of possible to create a platform that can evolve into the future pipeline of technologies the future will operate on – could be a confounding variable (e.g., perhaps too much risk for the gain). Lastly, the subjects are told, from the onset, that they are being conditioned, changing their attention to particular details. Therefore, a future study, again, could contain double-blind methodologies to bolster stronger outcomes for general public acceptance – particularly the relevance of GVS as a display technology (e.g., breath can most certainly be conditioned, as such the display technology can be replaced with audio, etc.) – and generating future extended works (Badia, et al., 1984; Badia, et al., 1985; Badia, et al., 1986; Badia, et al., 1987; Badia, et al., 1988; Harsh and Badia, 1990; Harsh, et al., 1990).

The best way to attend to these identified limitations will be through further, iterative, experimentation and PIVOT enhancement. Knowing that subjects are able to distinguish variation in frequency between high and low, there exists many strong pathways to begin diving into for establishing, essentially, a GVS language (e.g., morse code). For example, examination of conditioning different stimuli frequencies to different breath structures for understanding limitations of, both, a) the stimulation and b) the user's ability to classify specific cues with specific breathing styles (Smith et al. 2022)**.** Specifically, a high frequency could be conditioned to a fast respiration, whereas a lower frequency could be conditioned to the DSB; thus, the ability of the user to differentiate between the two signals – and the relative performance to the cue – could be researched. Another opportunity for innovation could be using the display cues to encourage a user to breathe through either the mouth or the nose, while maintaining a fixed breathing pattern. Such extended examples demonstrate how this work can be leveraged to establish a basic framework for building all other breath sensing modalities of the desired tertiary, autonomous, breathing-intelligence. The likely first steps being a) the successful use of the visual trainer tool to condition topography, b) identification of a better training apparatus (e.g., an active, compressive garment technology), or c) determining that identical breath topography is not required in most use cases (i.e., perhaps breath dynamics are still far too controlled by competing homeostatic subsystems that prevent identical replication, or the need thereof).

Beyond real-time performance changes for breath, another sensible inquiry would also be to condition breath for use during sleep studies – as in the work done by Harsh and Badia on sleep apnea – provided that it may be less intrusive to sleep than audio and haptic inputs. It may also be less susceptible to the increasing latency of response from cue to behavior noticed in similar research (Badia, et al., 1984; Badia, et al., 1985; Badia, et al., 1986; Badia, et al., 1987; Badia, et al., 1988; Harsh and Badia, 1990; Harsh, et al., 1990). As part of sleep – besides attending to deflected sleep conditions (specifically those related to breath; apnea) – this system could be used to promote specific typesets of sleep, or total sleep modification. For example, changing patterns of breath to alter Rapid-Eye Movement (REM) and Non-Rapid-Eye Movement (NREM) sleep timing and quantity outcomes. Doing so might offer options at enhancing learning, reducing traumatic experience recovery times, or, ideally, offering users the ability to decide what sort of sleep they want. For example, selecting creative sleep v. recovery sleep, based on their perceived needs – offered in conjunction to the personalized recommendations that such a tertiary breath system would offer (Gallego & Perruchet, 1991; Wientjes, 1992; Walker, 2017). This is also relevant to explorations of respiration’s relationship to cerebral spinal fluid (CSF) influx/efflux, as well as experiential data collected in work on Alzheimer’s. For example, there is a natural pumping mechanism that exists in the exchange of blood for CSF as part of our respiration (which can be seen clearly in MRI videos and is, particularly, impacted by deep abdominal breathing – such as the DSB performed in this study), which may be useful in helping clear out (i.e., pump out) crystalized amyloid proteins in the brain’s vascular system via breath. For example, breath strategies administered following trans-electric stimulation (TES) with the intent of supporting clearing of loose protein structures broken up by the TES (Santarnecchi et al., 2014; Yildiz, S., et al., 2017; Romanella et al., 2020). Switching the lens, the knowledge gained from this work also relates to physiological and psychological control – especially of CO_2 tolerance levels in the body – in extreme physiology (e.g., ICE environments) responses. For example, application of mammalian deep-dive breathing sequences for hypoxic-condition-preparation in astronaut populations could reduce pre-breath time for crew or enhance overall readiness level (Williams et al., 1999).

The nature of this work – an initial exploration towards the desired end-state of a tertiary, autonomous breathing capacity – opens a plethora of opportunities to augment and enhance the, already, well-tuned (i.e., through millions of years of evolutionary pressures and responses, genes, memes, values, and languages), human physiological and psychological adaptation capacities. As Nick Lane summarized, having considered the entire evolutionary process of Earth, Life, and the shared relationship of both to Oxygen: "Behavior of our genes depends on oxygen and oxidative stress, when we learn how to modulate oxidative stress with more finesse than, and only then, can we go beyond our genes and destiny" (Lane, N., 2003; Lane, N., 2002). In our human-present environments (i.e., those locations where humans have been able to innovate sufficiently enough to promote survival, whether through use of technology, methodology, or mentality), crew members – and all of humanity – face ever-expanding demands for technological integrations of the cutting-edge. For example, the cognition expansion of the human mind to an autonomous other – not so dissimilar to our cognitive expansion into our smartphones – that the future of artificial general intelligence offers a user in exchange for their data. Space exploration offers yet another example, wherein the Earth already appears to be stretching its inhabited-diameter to LEO and our expansion into the cosmos offering up hints at the dynamic coexistence that technology plays in its success. The homo astra, this cosmic resident of the future, is positioned to be a critical part of a recurring future demonstrating a symbiotic relationship between humans and technology. Such narratives set the tone for a rising need to help offload these amazing H-CMS with extended real-time data and prediction strategies, ensuring safety in austere environments – as well as back home, here, on Earth – that meets the new rapidity, and scale, of the problems of the future.

Simply put, this rapidity outpaces evolutionary speed; a fact that is terribly concerning to the innovation demands required to solve our most wicked problems and prevent the stagnation of the human species. A shared partnership between human and humantech offers exponential opportunity, but only if we are constant gardeners of promoting the branches that elevate human health, values, existence and experience over those that elevate advertisement, power-dynamics, ego, and manipulation for the sake of control. This work – the validated thesis that a tertiary breathing system is plausible – offers one such ‘small step’ in such a direction.

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APPENDIX A:

STUDY OVERVIEW

A brief study outline with anticipated time durations of each experimental phase

System Set-Up (to be completed prior to Participant arrival)	[*duration: 45 min]*
Pre-Study Procedure + Gamification	[*duration: 25-35 min]*
Phase I – Teaching Breath + Baselining Breath	[*duration: 10-15 min]*
Phase II – Teaching GVS Cue	[*duration: 10-15 min]*
Phase III – Conditioning Breath to GVS Cue	[*duration: 25 min]*
Phase IV – Validation: GVS Cueing + Gamification	[*duration: 25 min]*
Post-Study Procedure	[*duration: 10-15 min]*

APPENDIX B:

EQUIPMENT CHECKLIST

A complete list of testing materials + resources broken down by relevant subsection.

Physiology Sensing

- Polar Chest strap + integrated stretch sensors (note: cleaned)
- Polar HR unit (snaps into HRM with two buttons)

GVS System

- GVS unit + Extension leads + trigger (BNC connector cable + Arduino) (connected to IoT framework)
- Extra batteries (9V)
- Impedance gauge
- 12 mL toroidal silver silver-chloride electrodes with plastic retainers (note: check log for current projected life, test leads tagged with white tape)
- GVS placement Head strap (note: cleaned)
- Securing Head band options + Hair support (bobby pins + hair ties)
- Soterix 3D printer head mount
- Exfoliant gel (NuPrep Skin Prep Gel)
- Soterix HD Gel (electrode gel)
- Alcohol swab sticks (at least 10x)
- Moisturizer
- Non-latex gloves
- Red Marker

Hololense

- Hololense2 (HL2) headset (note: cleaned)
- Power extension cable (USB C) + extension cable (secured onto test chair for strain relief)
- IoT Desktop – Alienware (i.e., drives HL2 and data collection)
- PIVOT (Platform for the Investigation of Ventilatory Optimization and Training) Software (Unity)

APPENDIX C:

DETAILED STUDY PROCEDURE

Subsections for each study phase identified in the Study Overview section.

System Set-Up or Pre-Check (to be completed prior to Participant arrival):

General overview of system set-up for all supporting assets (specifically technology and data collection resources).

1. IoT system/database setup and running
    a. Login to PC
        i. un: ./Psion
        ii. pw: P$ionL@b_2021
    b. Run: 'wsl'
        i. Admin login onto wsl
        ii. Will see cmd screen for wsl appear
        iii. Type:
            1. docker container ls
        iv. Check status of broker
            1. If not running, type:
                a. cd ../ ../
                b. cd psion_iot/
                c. docker-compose up - this will spin up the IoT SW
                d. *if you need to stop it - type:
                    i. docker-compose down in a new wsl window
        v. Open cmd, type:
            1. cd ../ ../
            2. cd humanworks-mqtt-hardware-intergration
            3. cd examples
        vi. Open second cmd
            1. cd ../ ../
            2. cd humanworks-mqtt-hardware-intergration
            3. cd examples
        vii. In one cmd type:
            1. python subscriber.py - should say subscriber connecting...
        viii. In second cmd, type:

            1. python publisher.py - other cmd should now start seeing data/text
            2. To stop press 'ctrl+c' in each cmd
    c. Open a web browser
        i. First tab is localhost:3001 - opens react app
        ii. Second tab localhost:8086 - opens influx db
            1. Password saved in edge
            2. un: psionlab
            3. pw: psion_lab_426580
2. Check Custom Polar H10 and stretch sense to verify operational battery
    a. Don the polar H10 + stretch sensor strap.
    b. Power on the stretch sensor via the small black slider switch on the board stack), a blue light will turn on
    c. Open cmd, type:
        i. cd ../ ../
        ii. cd humanworks-mqtt-hardware-intergration
        iii. cd Bluetooth
        iv. python StretchSense.py
    d. Ensure polar h10 and stretch sense variables are displaying data as expected in IoT data management interface. (verify in influxdb or react)
3. GVS startup
    a. Connect extension leads to GVS unit (these do NOT include the electrodes, rather terminate at a female end)
    b. Connect BNC + Arduino trigger stack to GVS unit
        i. Connect BNC + Arduino to rear male BNC on GVS unit (located next to the electrode lead insertion points)
    c. Configure GVS to testing conditions (all are marked with either white or yellow electrical tape)
        i. Set GVS to 1second duration using radial dial
        ii. Set GVS to 0.6mA current using sliders + radial dial
        iii. Set GVS to sin mode using radial dial
        iv. Set GVS to 50 Hz frequency using radial dial, displays values on red display (i.e., 50.0)
    d. Power on GVS unit and verify functionality via IoT
        i. Check low battery light, if active replace batteries (2x9v)
        ii. Test that GVS activates by pressing manual button and watching that units displays 0.6mA for approximately 1 second (all other modes are minutes and will be obvious)
        iii. Test GVS cueing, verify trigger functionality
            1. Type python in the command window (in windows start type ‘cmd; to open cmd window)

            2. In the python shell, type:
                a. import paho.mqtt.client as mqtt
                b. import json
                c. c = mqtt.Client()
                d. c.connect(“localhost”)
                e. c.publish(json.loads({}))
                    i. Every publish should fire the GVS
    e. If GVS does not fire through this command, ensure the Arduino port is available
        i. The following steps will open a port proxy such that the remote device can connect to the broker
            1. Open powershell terminal as admin, type:
            2. Netsh interface portproxy add v4tov4 listenaddress=0.0.0.0 listenport=<port> connectaddress=<destaddress> connect=<port>
                a. Destaddress – replace with IP address of linux shell (not typical IP – inside wsl type ‘ifconfig | grep eth0’)
                b. Port – 1883
    f. Power off GVS unit and leave on researcher table to connect to user
        i.

4. Hololense setup + PIVOT testing
    a. Pull up VR
        i. Go to unity hub program
            1. open gvs-breath
        ii. You will click on the play button at the top when ready for subject
    b. Connect HL2 to extended usb-c power cable (ensure the charger is plugged into the wall mount and secured to the chair for strain relief)
    c. Launch Unity on the desktop
    d. Don HL2 and launch HL2 by pressing the power button on the back left of the device near the charging cable
        i. Complete calibration (if requested)
        ii. Open menu by lifting left hand up like it’s a book you are reading and then touching your left wrist with your right pointer finger… a menu should appear
        iii. Verify that the wi-fi connection is ‘HumanFactorsLab’
        iv. Then click on all apps and launch the Remote Support
        v. Your screen should present a yellow ip address that should match that of the remote support menu on the unity app
        vi. Ensure audio is enabled in the Unity remote connection menu and press play on Unity to verify game correctly launches

vii. Stop the unity game, which should cause the HL2 to return to the screen with the yellow ip address requesting that it is ready for remote support
viii. Leave the HL2 in this configuration

e. Power Down and doft the HL2, ensuring that it is still connected to the charging cable
f. Leave Unity running on the desktop in support of the test subjects

5. Check to see that IoT is still publishing sensor data
   a. Remove HRM breath strap and clean with alcohol wipes
6. All desktop systems should be left up and running, but steps 1-5 are in case this is not the current state of the test system.

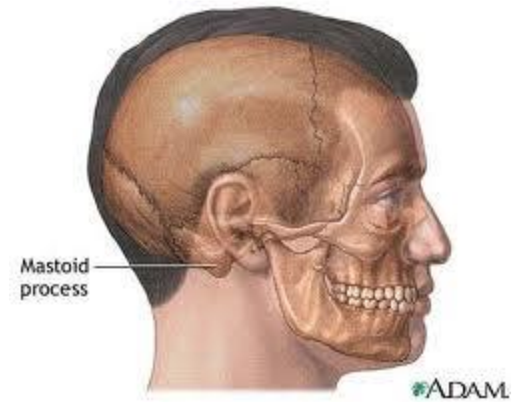
Pre-Study Procedure (to be completed upon Participant arrival):

Pre-Study Procedure includes all tasks to be completed with the Participant prior to the start of data collection.

1. Verify all systems are up and running (including HL2, GVS, and IoT system that may have been powered down or gone to sleep) from pre-check (also, in case running back-to-back subjects).
   a. Pull up the unity display in the left monitor
   b. Pull up influx db (i.e., url: localhost:8086), the cmd window (i.e., run + cmd), the python script window for GVS fire commands, and the react app (i.e., url: localhost:3001) to create testing dashboard.
2. Perform Informed Consent process with Participant signature, if not already done so through SONA (securely store after completion)
3. Identify Participant subject number and ensure to record for proper data file saving/creation.
   a. Go to react app and click on middle icon with the plus sign
   b. Enter: subject in tag name
   c. Enter: GVS_SXX (in Tag Value)
   d. Select all sensors in Sensors
   e. Click Submit
   f. Click Start
4. Provide Pre-Study Survey to Participant on laptop (i.e., Qualtrics) – *Breath Study – Pre-Study Survey*
   a. Should use Subject tag for filling out qualtrix (GVS_S1, GVS_S2, etc.)

5. Don HRM + integrated stretch sensor, as shown below (be sure to place the sensor over your solarplexus – where ribs come together – such that sensor rests on the lower portion of your rib cage)

6. Situate Participant in study area away from any obstacles: seated in a chair at empty table with a second table behind them (for the GVS unit, desktop computer, and other test support equipment). **Be sure to mention to the subject that the stretch sensor is sensitive to posture and to try to sit upright and reduce extraneous motions during the testing times.** The researcher will spend their time at the second table to oversee the system and to remove them from the direct visual frame of the subject. The wall opposing the subject should be relatively bland and clear of decorations, providing a solid backdrop for the HL2 visuals and to provide less chance of distractable content
7. Turn on the active study (red) light, and close the door.
8. Launch Breath sensor
    a. Open cmd, type:
        i. cd ../ ../
        ii. cd humanworks-mqtt-hardware-intergration
        iii. cd Bluetooth
        iv. python StretchSense.py
            1. this turns on the sensor
9. Go to the react app and click start using the home icon
    a. Check the dashes icon (bottom) to pull up sensor feed and verify that breath sensor is publishing
10. If participant wears glasses have them remove them to prevent connection issues with GVS electrodes.
11. Locate mastoid processes on Participant (small, triangular bone formations at base of skull behind ear, behind ear lobe; (n.d.))



12. Ask participant to hold hair and help to clear extra hair from the area (may require hair ties or bobby pins, but hand is acceptable). Also, may require having longer hair placed in a higher angle ponytail or using the beard brush to move the hair out of the mastoid area.
13. Use 1x alcohol swab for each side/mastoid to sufficiently clean skin of dirt and debris, prepping skin for exfoliant. Use a circular motion with a firm pressure to remove as much dirt as possible. Rub for at least 15 seconds per side.
14. Exfoliate skin over mastoid using NuPrep Skin Prep Gel; perform this with 1x fresh alcohol swab stick with new gel each time, on each side). Use a circular motion with a firm pressure to remove as much dead skin as possible. Rub for at least 30 seconds per side (skin should be noticeably red)
15. Again, use 1x alcohol swab for each side to clean off remaining exfoliant and loose skin (may also require use of paper towel to capture all residue).
16. Wipe the remaining residue off the participant using the wet wipes and paper towels.
17. Locate the center of the mastoid and draw the outside of the enclosure with dry erase to locate the electrodes.
18. Insert Soterix 12mm electrodes to the plastic retainers and seal with the enclosure cap, then proceed to fill the cups with HD gel to ensure total fill is achieved
19. Position electrode caps to mastoid processes (using the guide lines drawn with the dry erase) using closest matching hole sets on the notched, 3d-printed head band to align the cups. This will be secured with the blue rubber locking band via the notches in 3d-printed headband to provide a relatively snug fit on the user.
20. Secure headband/electrodes with secondary headband:

14. Check the impedance of the Participant (i.e., idealized at 1.3kΩ) using the impedance gauge
    a. If not lower than 2.5kΩ, adjust the setup of the bands and check electrode positioning, gel consistency (e.g., any air pockets) and re-perform impedance check
    b. If still over 2.5kΩ , reperform skin preparation or continue to adjust locations of cup
        i. If still unable to get below 2.5kΩ and/or subject is unable to feel, or if experiencing any pain, please ask them to remove the system – they are excused from participation.
15. Connect the electrodes to the GVS Extension leads
    a. Configure GVS to testing conditions (all are marked with either white or yellow electrical tape)
        i. Set GVS to 1second duration using radial dial
        ii. Set GVS to 0.6mA current using sliders + radial dial
        iii. Set GVS to sin mode using radial dial
        iv. Set GVS to 50 Hz frequency using radial dial, displays values on red display (i.e., 50.0)
        v. Leave batteries out of unit until the GVS portion of the procedure (Phase 2) – batteries should always be left out of unit when not in use
16. Have Participant don Hololense 2 (HL2)
    a. Have Participant calibrate HL2, if requested
    b. If not already in remote mode (they should see a screen with a yellow IP address)
        i. Have them open the menu using the 'left-hand book, right finger wrist' method and click on the 'all apps' button

        ii. Have them select the remote app – this should return them to the yellow IP address screen

17. Ensure participant is comfortable in the chair and turn off the lights (to improve HL2 experience)
    a. Double-check react app to ensure breath sensor is still publishing to broker (check dashboard)
    b. Inform participant that you will only lightly be communicating with them throughout the experiment, and are available for any questions, but that the PIVOT software will be guiding them through a majority of the experiment through interactive menus. To click the button, let them know they may either click a button by touching to it or they can point at the object and pinch it with their pointer and thumb. Again, remind them to maintain a good postural position and to reduce extra motions during the testing time frames, noting that they will have time during the videos and break periods to move around as needed.
    c. Verify Participant is properly wearing the device, and intelligent data is being delivered, by having Participant click next (using method of preference) to perform 20 seconds of deep breathing to calibrate the stretch sensor thresholds for training
18. Run the unity program
    a. Subject should see a screen appear with directions: "Hit the next button and breath as deep as possible for the next 30 seconds to calibrate the sensors"
    b. Have them press the next button (explaining that they may either touch it or pinch it)
    c. System should perform a background data collection on the breath depth and set as a baseline for the user – this completes the breath sensor calibration
19. Thank the subject for participating in all the "unfun part" of getting ready for an experiment by letting them know that when they push next on the HL2 that are going to be playing PacMan for 5min as an appreciation (and to make sure they are comfortable with the graphics in the HL2)
    a. Inform the subject that the xbox controller under the desk will be their game controller for all the gamification sessions. Note: have them watch for the interference with the breath sensor wire and remind them to keep their hands under the table so that the HL2 does not pick up their hands as controllers, themselves
    b. If subject is experiencing aggressive nausea or discomfort, help them immediately remove the HL2 and GVS to relax, and when they are well enough to relocate, help them to the couches to recover. When they are well, thank them for their time and remove them from the experiment

c. After completion of gaming, have them place the controller back onto the under table rack (again, watch for the stretch sensor cable

Study 1 Phase 1 – Training Breath

Each component of the data collection portion of the study includes a step-by-step description of the role of the researcher in completing the study.

1. Instruct Participant to click ‘next’ in order to play Video 1, outlining breath mechanics and allowing the subject to practice breaths as they follow along (i.e., initial topography training)
    a. Note: please remind the user that their hands will be the remote for all interactions with the menus in this experiment, outside of the gamifications
2. Following Video 1, prompt Participant to ask any questions (Participant to select “Next” when ready)
3. Instruct Participant to play Video 2, introducing visual breath model training tool to Participant
4. Following Video 2, prompt Participant that the next task will be to follow the visual breath model training tool for 5 deep, full, slow breaths to collect their Baseline breath measurement data (Participant to select “Next” when ready)
5. PIVOT software runs visual breath model training tool and records Participant Baseline breaths, publishing them to the database via the IoT broker (e.g., Polar H10 and stretch sensor data streams)

Study 1 Phase 2 – Teaching GVS Cue

6. Following baseline activities, ask the user if they have any questions, and if they are feeling well; if ready to proceed, Instruct Participant to play Video 3, introducing GVS (Participant to select “Next” when ready)
    a. Place batteries into GVS unit, being sure to note the battery pair number and number of stims left on battery life
7. Following Video 3, encourage Participant to initiate GVS cue by pressing **“Fire GVS”** button on screen, noting that they will be providing themselves three such stimulations and will be asked whether or not they sufficiently perceived (e.g., felt) the stimulus via a button click yes or no
    a. Stimulation should be sent as sin @ 50 Hz, 0.6 mA for 1s duration (marked with white tape)
    b. When researcher sees: “GVS FIRED!” Command on the cmd, press the manual button on the GVS

   c. Software will record positive or negative confirmation of stimulation receipt through user self-report
8. Confirm Participant sensitivity to GVS cue (participant must feel 2 out of the 3 cues; if not, the software will reperform the check)
   a. If the participant is still unable to clearly feel the GVS stimulus after a recheck
      i. Check the electrodes and gel for any issues, if none, then the Participant will be excluded from the study. Thank the Participant for their time and terminate session.
      ii. If gel / electrodes needs support, correct and use manual fire to recheck
   b. Ask participant how it feels to receive the stimulation, if there is pain, verify connection and repeat.
      i. If still pain, then the Participant will be excluded from the study. Thank the Participant for their time and terminate session

Study 1 Phase 3 – Conditioning GVS to Breath

1. Verbally verify that the user is not feeling nauseous or experiencing any distress from the use of the GVS or the HL2 (e.g., discomfort, cyber sickness) up to this point, and then Instruct Participant to play Video 4, outlining impending Conditioning (**Reminding user they will be taking the same deep breath they have been practicing, each time they feel the GVS cue – noting that the cue will not come at the same time after each countdown,** to ensure the user is classically conditioning the breath to the GVS - and not including the visual cues of the countdown timer)
   a. Participant to select "Next" when ready
2. PIVOT software will then provide (3) practice GVS stimulations for Participant to practice GVS + Breath response conditioning
   a. PIVOT SW will provide a cue to the researcher each time the subject presses the button
      i. When researcher sees: "GVS FIRED!" command on the cmd, press the manual button on the GVS
   b. Upon successful GVS + Breath response, a positive reinforcer message will appear on-screen.
      i. At 2 seconds, the system will display the topography reward for taking the breath
         1. If greater than equal 35% depth, system displays "Great! Keep Inhaling."

            2. If less than 35% depth, system displays “Don’t forget to breathe!”
        ii. At 4 seconds, the system will display the topography reward for depth
            1. If greater than equal 50% depth, system displays “Fantastic! XX% depth.”
            2. If less than 50% depth, system displays “Breathe deeper next time.”
        iii. At 6 seconds, the system will display the topography reward for duration
            1. If greater than 4 seconds duration, system displays “Stellar! You took a XX second breath.”
            2. If less than 4 seconds duration, system display “Remember, 4s Inhale, 2s Hold”
    c. Repeat until 3 successful GVS + Breath responses are completed.
3. Ask the user if they have any questions before the Conditioning session begins; if not, instruct Participant to select “next” when ready
4. PIVOT SW begins randomized GVS cues at a random time between **15 and 90s** from the initiation of the program, resetting this timer after each stimulus (ensuring there is sufficient time to perform the desired 6s – 4s inhale, 2s hold – breath)
    a. PIVOT SW will provide a cue to the researcher each time the subject presses the button
        i. When researcher sees: “GVS FIRED!” Command on the cmd, press the manual button on the GVS
    b. Same cue structure for reward of topography is provided as in the checkout (step 2.b, above)
5. Randomized cues will continue until 20 successful GVS + Breath responses are completed (confirmed by positive reinforcer messages)
6. Following Phase 3 completion, inquire into subject comfort (e.g., cyber sickness, electrode discomfort, head band discomfort, etc.) and provide up to a 10min break (but encourage participant to move forward if they can to prevent impact to stretch sensor positioning.
    a. Ask participant if they need to use the restroom, would like to get up and walk around, stretch, etc.
        i. If they are interested in moving around, doff the HL2, and unplug the GVS electrode cables (but keep the headband GVS setup and HRM on, reminding them to not move the location of the HRM)

Study 2 – Validation: GVS + Game

7. Don GVS and HL2 (if doffed) to previous configuration (See "Pre-Study Procedure above) if any manipulations were made for user break
8. Inform user they are about to have another gamified session and to select "Next" to proceed, to watch Video 5, informing the user of the intent to stimulate them while they are in a gamified environment to see the effectivity of the GVS cue for the desired deep slow breath (DSB)
9. PIVOT SW will then launch Pac-Man game and begin randomized GVS cues during gaming (following the same 15-90s random interval nature – i.e., off the proceeding stimulus – as was used in the conditioning phase)
    a. PIVOT SW will provide a cue to the researcher each time the program sends a randomly generated cue call
        i. When researcher sees: "GVS FIRED!" Command on the cmd, press the manual button on the GVS
    b. No positive reinforcers or extraneous mentions of the GVS will be provided during this time
    c. Randomized cues will continue until 20 successful GVS cues have been provided (regardless of whether an appropriate breath was taken by the user or not)
    d. Record total stim number for subject and add to battery n number for GVS (i.e., swap out limit)

<u>KEY TROUBLESHOOTING STEPS FOR UNITY/HL2 CRASHES:</u>

- A critical issue that has been witnessed in the system performance are hang ups of any one of the elements in the loop for the Unity Remote Display to the HL2. If the subject experiences a glitch or program/hardware crashes, perform the following:

1. Click play button on unity on the right display to stop unity connection
    - If this occurs during a GVS stim session time (such as pacman) or a video, be sure to record the time and number of stims completed (e.g., 13/20)
2. Check that react app timer is still running meaning that the subject data is still connected
3. Open the cmd window in the left display and run the command: c.publish("psion/frontend/tags/reset",json.dumps({})
    - This will retag the user data in the IoT
4. Rerun the unity program
    - Click on the check marks in the active menu selection (upper righthand bar – the inspector - of the gui when a location of the scene is selected, e.g., "CalibrationGuide")
    - Must uncheck Calibration Guide

        - If the issue is with the pacman elements, remember to deselect the cover - located in the left drop down under the pacman regular - that is covering the pacman display
        - Check as active the location you want to start from and it should jump to that part of the scene
        - Be sure to apply the time adjustment you recorded in step one before letting user continue
5. Verify participant is back and track and continue

Post-Study

Post-Study Procedure includes all tasks to be completed following the end of data collection.

1. Remove HL2, GVS, and Polar HRM from Participant
2. Wipe off remaining gel on mastoid processes with an alcohol wipe
    a. Remove access with wet wipes / paper towels and then moisturize the entire area with the lotion
3. Provide Post-Study Survey to Participant on second desktop (Qualtrics) – *Breath Study – Post-study Survey*
4. Thank and dismiss Participant
5. Clean HL2, Polar HRM, and Headband as necessary with disinfectant for next participant
6. Record and update GVS electrode hours on tracking log (to maintain 100-hour max on electrodes limitations)
7. Save files from influx db
    a. Open file explorer and locate the D: drive
    b. Right click on influxdb folder, select send to, and send to a compressed zip folder
    c. Name the folder influxdb_XX_YY_ZZ (with the month, date, year as the X, Y, Z, respectively)
    d. Transfer these files to the thumb stick drive
    e. Transfer this drive to a NASA computer and drop in the secure thread to ensure data is stored on the cloud in case of system crash.
8. On the react app, remove the user
9. Press Ctrl+C to keyboard interrupt the three active cmd/python windows

APPENDIX D:

PRE-STUDY SURVEY

Subject, Please enter your subject ID: "GVS_SX", where X is your number from the researcher:

____

Biological Sex What is your biological sex (i.e., sex assigned at birth)?

- ○ Male (1)
- ○ Female (2)
- ○ Non-binary / third gender (3)
- ○ Prefer not to say (4)

Identity What is your gender identity?

- ○ Male (1)
- ○ Female (2)
- ○ Non-binary / third gender (3)
- ○ Prefer not to say (4)

Age How old are you?

____

Vestibular Do you have a history of vestibular dysfunction (e.g., vertigo)?

- ○ Yes (1)
- ○ No (2)

Motion/Cyber Sick Have you ever experienced severe issues with motion sickness or cyber sickness?

- ○ Yes (1)
- ○ No (2)

Alcohol Have you consumed alcohol within the last 6 hours?

- ○ Yes (1)
- ○ No (2)

Caffeine Have you consumed caffeine within the last 6 hours?

- ○ Yes (1)
- ○ No (2)

Caffeine Normality How would you describe your caffeine intake today (relative to you)?

- ○ More caffeine than typical (1)
- ○ Typical (2)
- ○ Less caffeine than typical (3)

Meditation Have you meditated within the last 6 hours?

- ○ Yes (1)
- ○ No (2)

Q18 How would you describe your meditation time today (relative to you)?

- ○ More time than typical (1)
- ○ Typical (2)
- ○ Less time than typical (3)

Sleep quantity Approximately how many hours of sleep did you get last night?

	0 2 4 6 8 10 12 14 16 18 20 22 24
Number of hours ()	

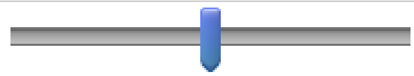
Sleep quality How would you describe your sleep quality last night (relative to you)?

- ○ Adequate (1)
- ○ Nuetral (2)
- ○ Not Adequate (3)

VR/AR Experience What is your experience level with using Virtual (VR) or Augmented Reality (AR) devices?

	0 1 2 3 4 5 6 7 8 9 10
None (0) - Expert (10) ()	

GVS Experience What is your experience level with using Galvanic Vestibular Stimulation (GVS)?

	0 1 2 3 4 5 6 7 8 9 10
None (0) - Expert (10) ()	

Breath Experience What is your experience level with breath work?

	0	1	2	3	4	5	6	7	8	9	10
None (0) - Expert (10) ()											

Stress What is your current level of stress?

	0	1	2	3	4	5	6	7	8	9	10
None (0) - Critical (10) ()											

Misc. Would you like to report any other factors that may impact your performance today?

____

APPENDIX E:

POST-STUDY SURVEY

Subject, Please enter your subject ID: "GVS_SX", where X is your number from the researcher:

____

GVS cue How apparent did you find the GVS cue to be?

	0 1 2 3 4 5 6 7 8 9 10
Initially (First experienced) ()	
During Conditioning ()	
During PacMan ()	

Experience How would you rate your experience, today?

	0 1 2 3 4 5 6 7 8 9 10
Terrible (0) - Excellent (10) ()	

Symptom Check Did you experience any of the following?

- ☐ Motion Sickness (1)
- ☐ Cyber Sickness (2)
- ☐ Pain (3)
- ☐ Confusion (4)
- ☐ Discomfort (5)
- ☐ Anxiety (6)
- ☐ Depression (7)
- ☐ Other (8)

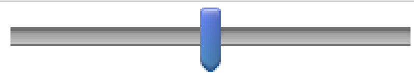
Other symptoms - If you selected other to the previous question, please list these other symptoms you experienced:

____

Impactors Would you like to report any other factors that impacted your performance today?

____

Breathwork - Do you feel you will be more focused on your breath work in the future?

	0 1 2 3 4 5 6 7 8 9 10
Never (0) - Always (10) ()	

APPENDIX F:

PIVOT POST-PROCESSING, DATA-GENERATION EXAMPLE

R Notebook – HTML output

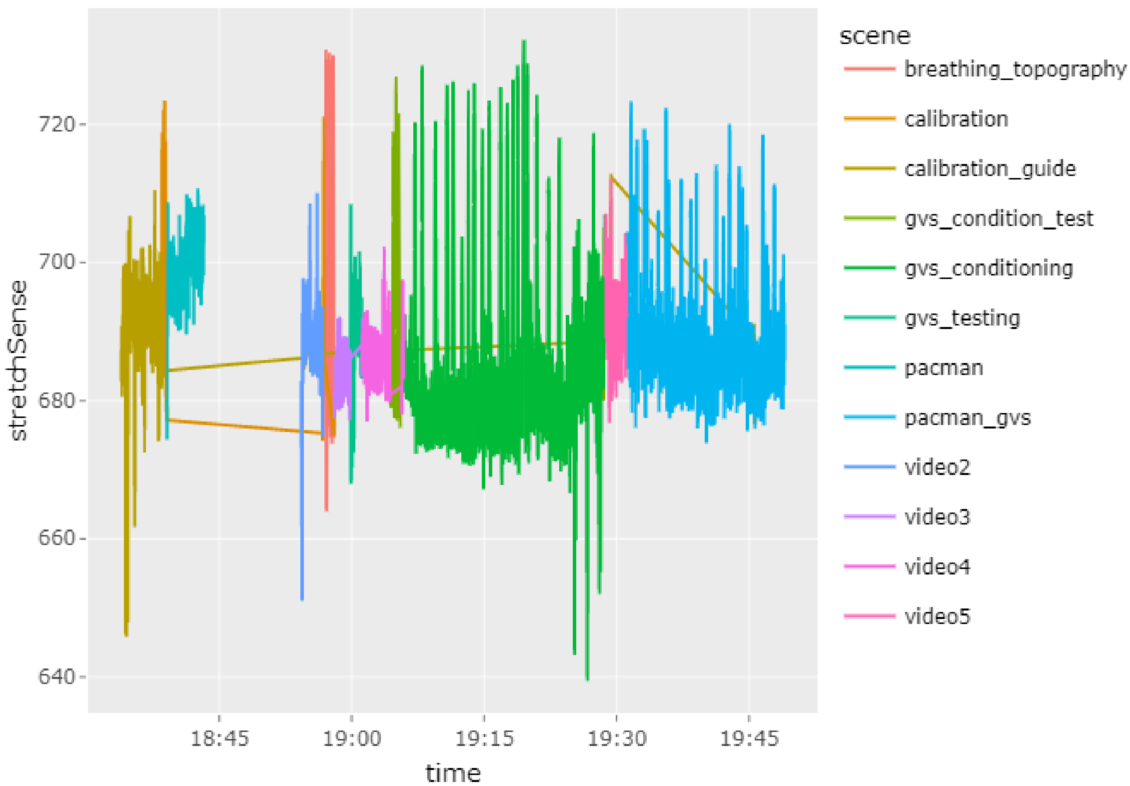
- All breath data
- Breath Topography Baseline
- Pacman
- Pacman II
- GVS Conditioning

R Notebook

```
library(tidyverse)
library(ggplot2)
library(dbplyr)
library(dplyr)
library(plotly)
library(zoo)
library(pracma)
is_one_file <- T
if (is_one_file) {
    data <- read.csv("data/GVS_BREATH_S16.csv")
} else {
    data1 <- read.csv("data/GVS_BREATH_S27_p1.csv")
    data2 <- read.csv("data/GVS_BREATH_S27_p2.csv")
    data <- rbind(data1, data2)
}
data$time <- as.POSIXct(strptime(data$time, "%Y-%m-%dT%H:%M:%OSZ"))
```

All breath data

```
ggplotly(ggplot(data, aes(x = time, y = stretchSense,
    color = scene)) + geom_line())
```

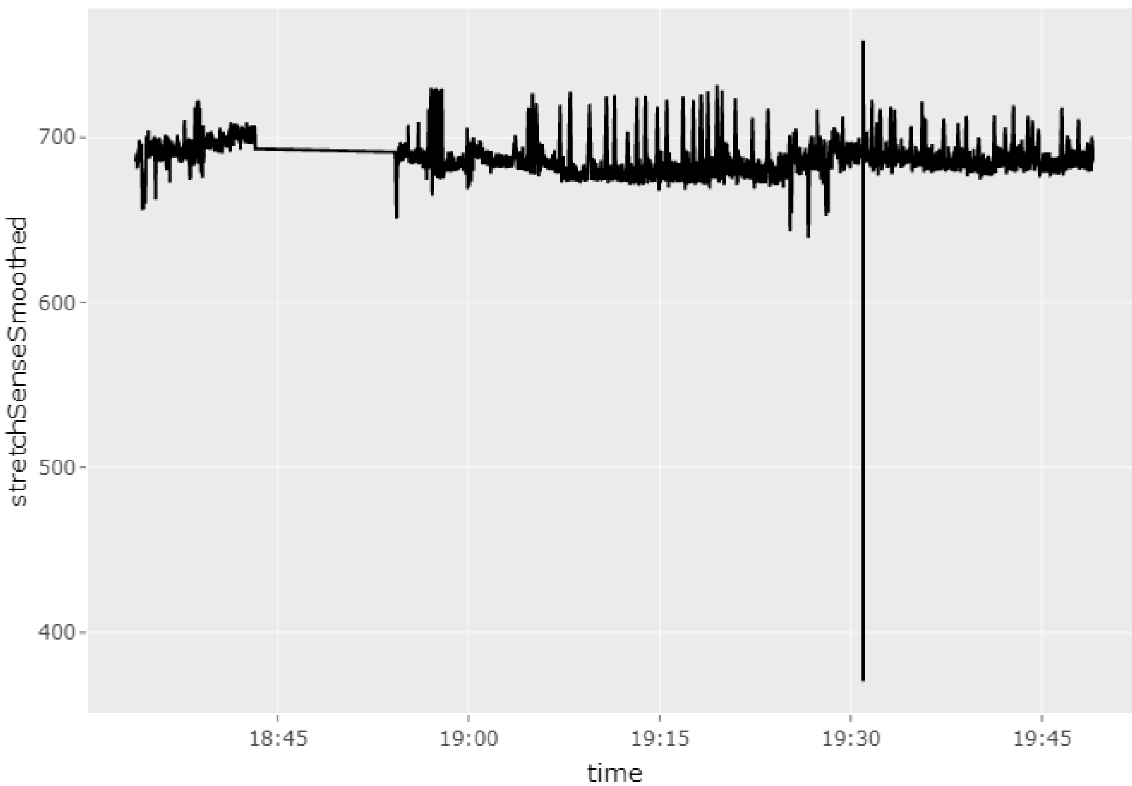


Get GVS stim times

```
if (class(data$fire) == "character") {
    gvs_stim_times <- data[which(data$fire == "true"),
        ] %>%
        select(fire, scene, time)
} else if (class(data$fire) == "logical") {
    gvs_stim_times <- data[which(data$fire == T), ] %>%
        select(fire, scene, time)
}
```

Apply savitsky-golay smoothing to all of data

```
data <- data %>%
    drop_na(c("stretchSense")) %>%
    filter(stretchSense > 400)
data$stretchSenseSmoothed <- savgol(data$stretchSense,
    51)
ggplotly(ggplot(data, aes(x = time, y = stretchSenseSmoothed)) +
    geom_line())
```



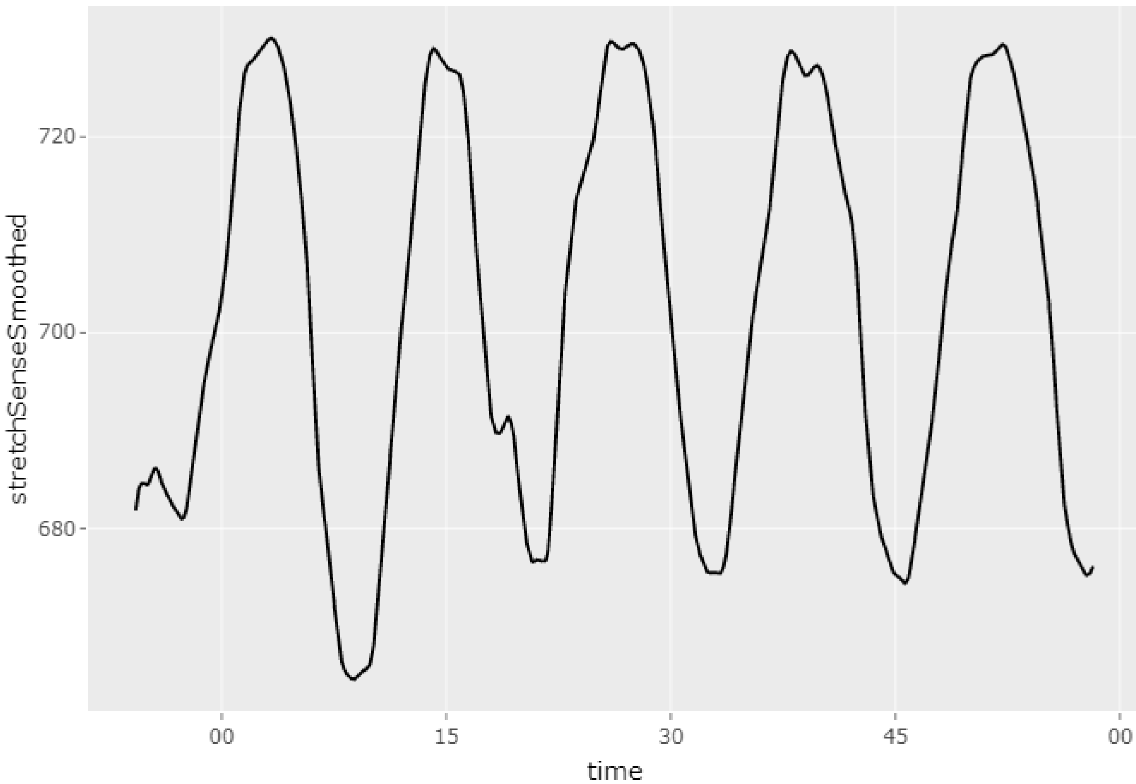

```
find_peaks <- function(x, m = 3) {
    shape <- diff(sign(diff(x, na.pad = FALSE)))
    pks <- sapply(which(shape < 0), FUN = function(i) {
        z <- i - m + 1
        z <- ifelse(z > 0, z, 1)
```

```r
        w <- i + m + 1
        w <- ifelse(w < length(x), w, length(x))
        if (all(x[c(z:i, (i + 2):w)] <= x[i + 1]))
            return(i + 1) else return(numeric(0))
    })
    pks <- unlist(pks)
    pks
}
cycle_count <- function(breath, m) {
    peaks <- find_peaks(breath, m)
    return(length(peaks))
}
```

Breath Topography Baseline

BREATH PLOT

```r
ball_breath <- data %>%
    filter(scene == "breathing_topography")
ggplotly(ggplot(ball_breath, aes(x = time, y = stretchSenseSmoothed)) +
    geom_line())
```




```
ballBreathData <- ball_breath$stretchSenseSmoothed
peaks <- find_peaks(ballBreathData, 20)
crit_threshold <- min(ballBreathData) + 0.9 * (max(ballBreathData) -
    mean(ballBreathData))
true_peaks <- peaks[which(ballBreathData[peaks] > crit_threshold)]
double_peak <- c()
for (i in 1:length(true_peaks)) {
    if (i == 1) {
        next
    }
    if (as.numeric(ball_breath[true_peaks[i], ]$time -
        ball_breath[true_peaks[i - 1], ]$time, units = "secs") <
        5) {
        double_peak <- c(double_peak, i)
```

```
    }
}
if (!is.null(double_peak)) {
    true_peaks <- true_peaks[-(double_peak)]
}
valleys <- find_peaks(-ballBreathData, 20)
true_valleys <- c()
for (i in 1:length(true_peaks)) {
    true_valleys[i] <- valleys[tail(which(valleys <
        true_peaks[i]), 1)]
    while ((ballBreathData[true_peaks[i]] - ballBreathData[true_valleys
[i]]) <
        3) {
        true_valleys[i] <- valleys[which(valleys ==
            true_valleys[i]) - 1]
    }
}
remove <- !is.na(true_valleys)
true_valleys <- true_valleys[remove]
true_peaks <- true_peaks[remove]
```

DEPTH

```
depths <- (ballBreathData[true_peaks] - ballBreathData[true_valleys])
top3_depths <- sort(depths, decreasing = T)[1:3]
avg_depth <- mean(top3_depths, na.rm = T)
max_depth <- max(top3_depths)
min_depth <- min(top3_depths)
print(paste("Top 3 Average depth: ", as.character(avg_depth)))
## [1] "Top 3 Average depth:  57.6189883069743"
print(paste("Max depth: ", as.character(max_depth)))
## [1] "Max depth:  64.441991720231"
print(paste("Top 3 Min depth: ", as.character(min_depth)))
```

```
## [1] "Top 3 Min depth:  53.3948117271053"
BTC <- avg_depth

baseline_depths <- depths/avg_depth
print(paste("Baseline depth: ", as.character(mean(baseline_depths,
    na.rm = T))))
## [1] "Baseline depth:  0.873289457874664"
```

DURATION

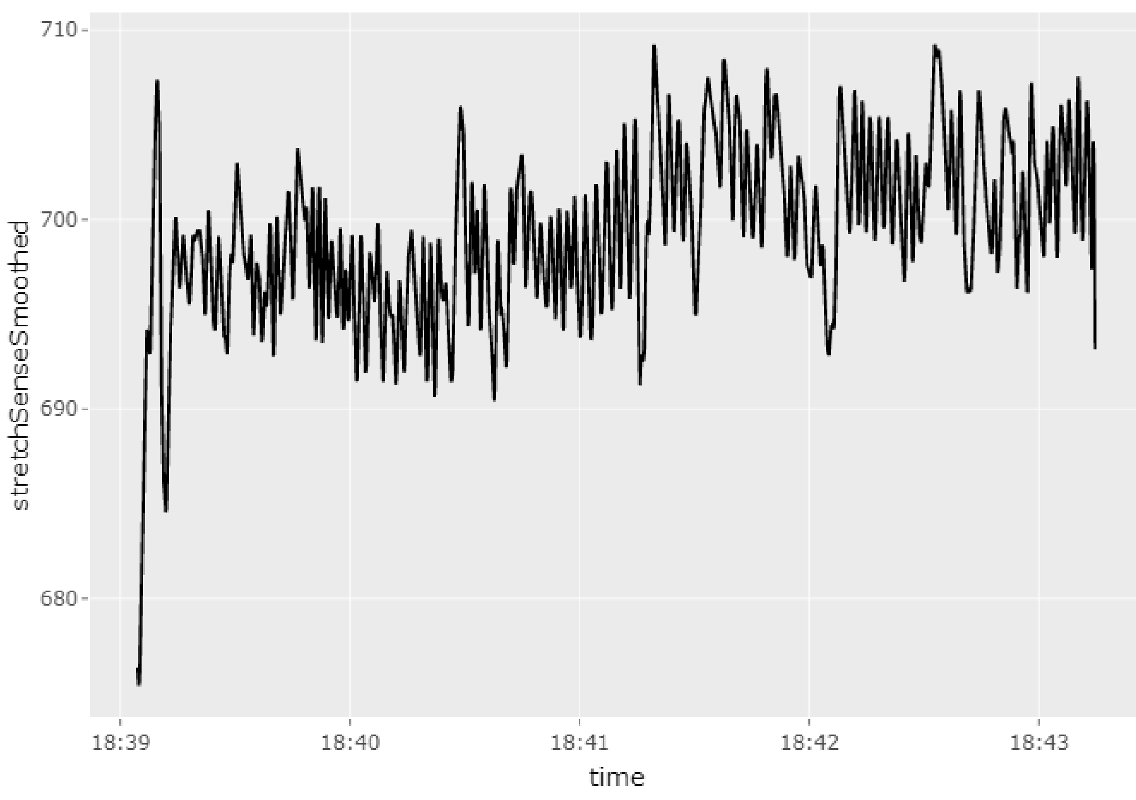
```
exhale_inds <- c()
for (i in 1:length(true_peaks)) {
    cur_index <- true_peaks[i]
    max_val <- ballBreathData[cur_index]
    min_val <- ballBreathData[true_valleys[i]]

    while (ballBreathData[cur_index] >= max_val - 0.05 *
        baseline_depths[i] * (max_val - min_val)) {
        cur_index <- cur_index + 1
    }
    exhale_inds[i] <- cur_index
}

durations <- as.numeric(ball_breath[exhale_inds, ]$time -
    ball_breath[true_valleys, ]$time, units = "secs")
avg_duration <- mean(durations, na.rm = T)
max_duration <- max(durations)
min_duration <- min(durations)

print(paste("Average duration: ", as.character(avg_duration)))
## [1] "Average duration:  7.44986355304718"
print(paste("Max duration: ", as.character(max_duration)))
## [1] "Max duration:  10.4696319103241"
```

```
print(paste("Min duration: ", as.character(min_duration)))
## [1] "Min duration:  5.71498847007751"
```

Pacman

BREATH PLOT

```
breath_top <- data %>%
    filter(scene == "pacman")
ggplotly(ggplot(breath_top, aes(x = time, y = stretchSenseSmoothed)) +
    geom_line())
```

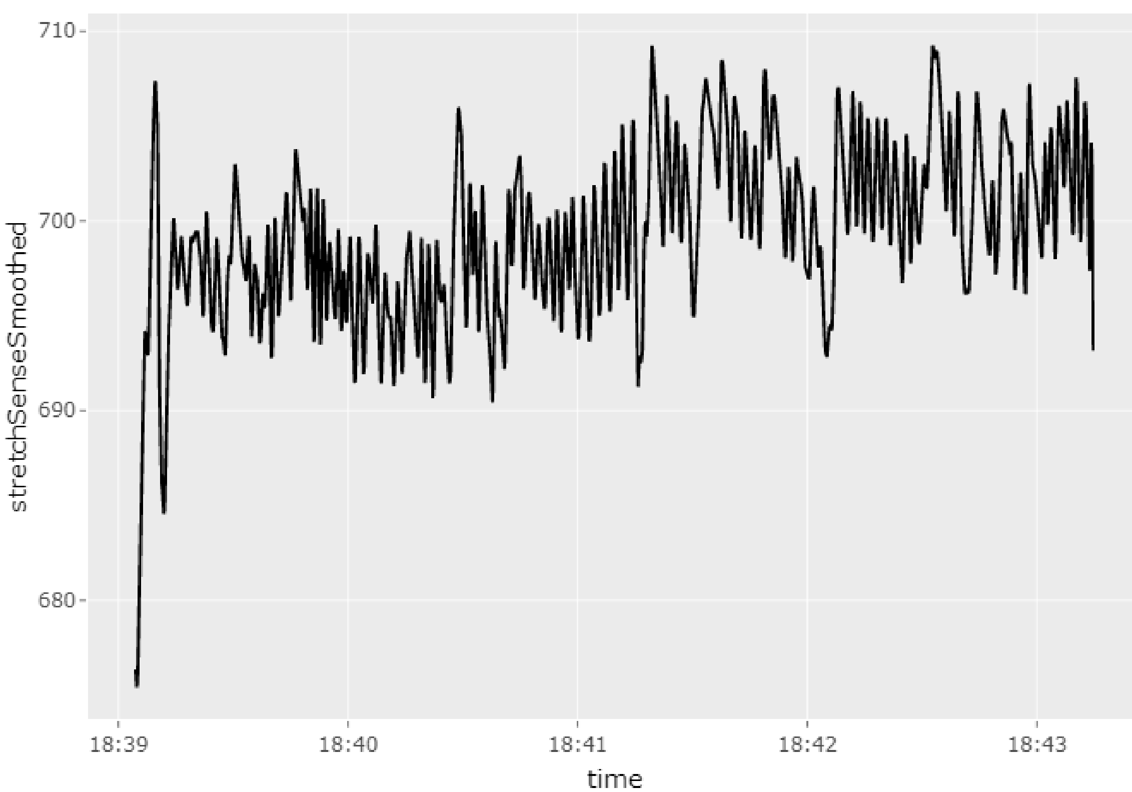


FREQUENCY ANALYSIS

Constrain time if needed and calculate rolling average

```
is_time_constraint_needed <- F
```

```
if (is_time_constraint_needed) {
    t1 <- as.POSIXct(strptime("2022-10-28 14:39:14.7",
        "%Y-%m-%d %H:%M:%OS"))
    t2 <- as.POSIXct(strptime("2022-10-28 14:44:14.7",
        "%Y-%m-%d %H:%M:%OS"))

    breath_data <- breath_top %>%
        filter(time > t1, time < t2)
} else {
    breath_data <- breath_top
}
ggplotly(ggplot(breath_data, aes(x = time, y = stretchSenseSmoothed)) +
    geom_line())
```



Breathing frequency calculation

```r
tot_breaths <- cycle_count(breath_data$stretchSenseSmoothed,
    20)
bpm <- tot_breaths/as.numeric(tail(breath_data$time,
    1) - breath_data$time[1], units = "mins")
bpm
```

```
## [1] 21.83194
```

```r
pacmanBreathData <- breath_data$stretchSenseSmoothed
peaks <- find_peaks(pacmanBreathData, 20)
true_peaks <- peaks
double_peak <- c()
for (i in 1:length(true_peaks)) {
    if (i == 1) {
        next
    }
    if (as.numeric(breath_data[true_peaks[i], ]$time -
        breath_data[true_peaks[i - 1], ]$time, units = "secs") <
        1) {
        double_peak <- c(double_peak, i)
    }
}
if (!is.null(double_peak)) {
    true_peaks <- true_peaks[-(double_peak)]
}
valleys <- find_peaks(-pacmanBreathData, 20)
true_valleys <- c()
for (i in 1:length(true_peaks)) {
    true_valleys[i] <- valleys[tail(which(valleys <
        true_peaks[i]), 1)]
}
remove <- !is.na(true_valleys)
```

```
true_valleys <- true_valleys[remove]
true_peaks <- true_peaks[remove]
```

DEPTH

```
depths <- (pacmanBreathData[true_peaks] - pacmanBreathData[true_valleys
])/BTC
avg_depth <- mean(depths, na.rm = T)
max_depth <- max(depths)
min_depth <- min(depths)
print(paste("Average depth: ", as.character(avg_depth)))
## [1] "Average depth:  0.120861217713297"
print(paste("Max depth: ", as.character(max_depth)))
## [1] "Max depth:  0.325597278432462"
print(paste("Min depth: ", as.character(min_depth)))
## [1] "Min depth:  0.0163430027192716"
```

DURATION

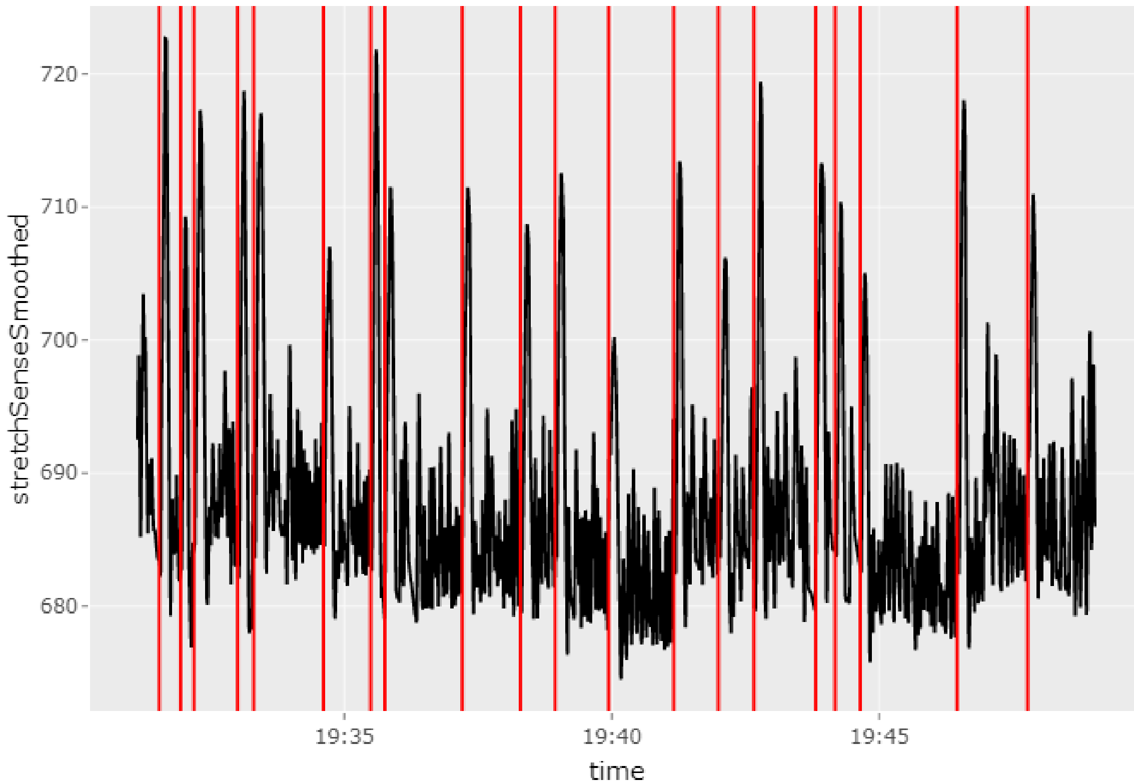
```
exhale_inds <- c()
for (i in 1:length(true_peaks)) {
    cur_index <- true_peaks[i]
    max_val <- pacmanBreathData[cur_index]
    min_val <- pacmanBreathData[true_valleys[i]]

    while (pacmanBreathData[cur_index] >= max_val -
        0.05 * depths[i] * (max_val - min_val)) {
        cur_index <- cur_index + 1
    }
    exhale_inds[i] <- cur_index
}

durations <- as.numeric(breath_data[exhale_inds, ]$time -
    breath_data[true_valleys, ]$time, units = "secs")
```

```
avg_duration <- mean(durations, na.rm = T)
max_duration <- max(durations)
min_duration <- min(durations)

print(paste("Average duration: ", as.character(avg_duration)))
## [1] "Average duration:  1.33720994519663"
print(paste("Max duration: ", as.character(max_duration)))
## [1] "Max duration:  3.88523721694946"
print(paste("Min duration: ", as.character(min_duration)))
## [1] "Min duration:  0.555346488952637"
```

Pacman II

BREATH PLOT

```
pacman2_breath <- data %>%
    filter(scene == "pacman_gvs")
pacman2_stims <- (gvs_stim_times %>%
    filter(scene == "pacman_gvs") %>%
    arrange(time))$time

plt <- ggplot(pacman2_breath, aes(x = time, y = stretchSenseSmoothed))
+
    geom_line() + geom_vline(xintercept = as.numeric(pacman2_stims),
    col = "red")
ggplotly(plt)
```



FREQUENCY

Constrain time

```
# t1 <- as.POSIXct(strptime('2022-10-25
# 19:17:34.2','%Y-%m-%d %H:%M:%OS')) t2 <-
# as.POSIXct(strptime('2022-10-25
# 19:40:07.3','%Y-%m-%d %H:%M:%OS'))
t1 <- pacman2_stims[1] - 15
t2 <- tail(pacman2_stims, 1) + 15

pacman2_data <- pacman2_breath %>%
    filter(time > t1, time < t2)
```

Breathing frequency calculation

```
tot_breaths <- cycle_count(pacman2_data$stretchSenseSmoothed,
    20)
bpm <- tot_breaths/as.numeric(t2 - t1, units = "mins")
bpm
```

```
## [1] 11.89404
```

CALCULATING DEPTH AND DURATION

```
gvsBreathData <- pacman2_data$stretchSenseSmoothed
peaks <- find_peaks(gvsBreathData, 100)
crit_threshold <- min(gvsBreathData) + 0.2 * (max(gvsBreathData) -
    mean(gvsBreathData))
true_peaks <- peaks[which(gvsBreathData[peaks] > crit_threshold)]
# true_peaks <- peaks

valleys <- find_peaks(-gvsBreathData, 20)
true_valleys <- c()
for (i in 1:length(true_peaks)) {
    vals <- which(valleys < true_peaks[i])
    k <- length(vals)
    val <- vals[k]
    while ((gvsBreathData[true_peaks[i]] - gvsBreathData[valleys[val]])
/BTC <
        0.2 && k != 0) {
        k <- k - 1
        val <- vals[i]
    }
    if (k == 0) {
        k <- length(vals)
    }
    true_valleys[i] <- valleys[k]
```

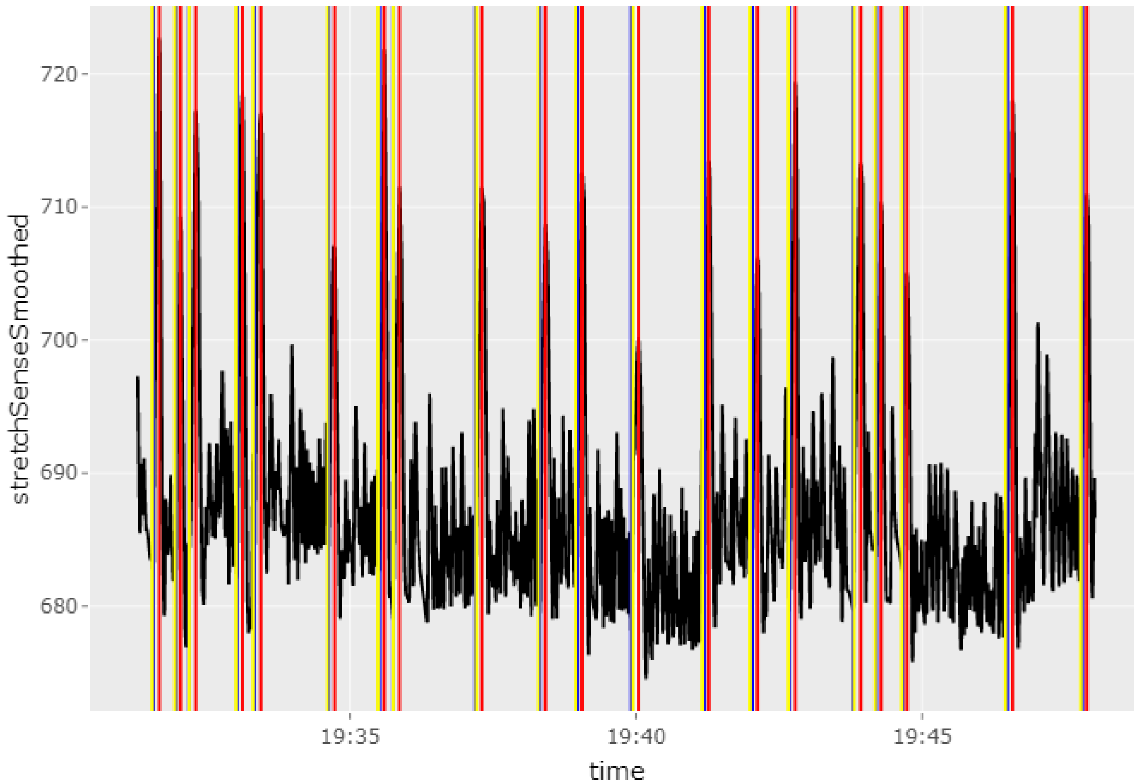
```
}

gvs_true_peaks <- c()
gvs_true_valleys <- c()
fill_na <- T
not_found_count <- 0
for (i in 1:length(pacman2_stims)) {
    t <- pacman2_stims[i]
    peak_found <- F
    for (j in 1:length(true_peaks)) {
        peak_time <- pacman2_data[true_peaks[j], ]$time
        if (peak_time > t && peak_time < t + 15) {
            if ((gvsBreathData[true_peaks[j]] - gvsBreathData[true_vall
eys[j]])/BTC <
                0.2) {
                print(paste(as.character(i), "depth too small"))
                next
            }
            peak_found <- T
            gvs_true_peaks[i] <- true_peaks[j]
            gvs_true_valleys[i] <- true_valleys[j]
            break
        }
    }
    if (!peak_found) {
        not_found_count <- not_found_count + 1
        print(paste("peak not found for stim ", as.character(i),
            as.character(t)))
        if (fill_na) {
            gvs_true_peaks[i] <- NA
            gvs_true_valleys[i] <- NA
            next
        }
```

```r
        time_inds <- which(pacman2_data$time > (t -
            7) & pacman2_data$time < (t + 10))
        gvsData <- pacman2_data$stretchSenseSmoothed[time_inds]
        peaks <- find_peaks(gvsData, 10)
        true_peak <- time_inds[1] + peaks[1]
        gvs_true_peaks[i] <- true_peak
        gvsDataVal <- gvsData[1:peaks[1]]
        valleys <- find_peaks(-gvsDataVal, 10)
        if (length(valleys) != 0) {
            true_valley <- time_inds[1] + tail(valleys,
                1)
        } else {
            true_valley <- time_inds[1] + which.min(gvsDataVal)
        }
        gvs_true_valleys[i] <- true_valley
    }
}

double_peak <- c()
for (i in 1:length(gvs_true_peaks)) {
    if (i == 1) {
        next
    } else if (is.na(gvs_true_peaks[i]) || is.na(gvs_true_peaks[i -
        1])) {
        next
    }
    if (as.numeric(pacman2_data[gvs_true_peaks[i],
        ]$time - pacman2_data[gvs_true_peaks[i - 1],
        ]$time, units = "secs") < 3) {
        double_peak <- c(double_peak, i)
    }
}
```

```
if (!is.null(double_peak)) {
    gvs_true_peaks <- gvs_true_peaks[-(double_peak)]
    gvs_true_valleys <- gvs_true_valleys[-(double_peak)]
}
```

Plot peaks and valleys

```
peak_times <- as.numeric(pacman2_data[gvs_true_peaks,
    ]$time)
valley_times <- as.numeric(pacman2_data[gvs_true_valleys,
    ]$time)
plt <- ggplot(pacman2_data, aes(x = time, y = stretchSenseSmoothed)) +
    geom_line() + geom_vline(xintercept = peak_times,
    col = "red") + geom_vline(xintercept = valley_times,
    col = "blue") + geom_vline(xintercept = as.numeric(pacman2_stims),
    col = "yellow")
ggplotly(plt)
```



Responses total

```
total <- length(pacman2_stims)
responded <- total - not_found_count


print(paste(as.character(responded), "/", as.character(total),
    " total responses."))
## [1] "20 / 20  total responses."
```

Depth

```
depths <- (gvsBreathData[gvs_true_peaks] - gvsBreathData[gvs_true_valle
ys])/BTC
print(paste("Average depth: ", as.character(mean(depths,
    na.rm = T))))
## [1] "Average depth:  0.526607108004412"
```

```r
print(paste("Max depth: ", as.character(max(depths,
    na.rm = T))))
## [1] "Max depth:  0.702416035584251"
print(paste("Min depth: ", as.character(min(depths,
    na.rm = T))))
## [1] "Min depth:  0.343702212600579"
```

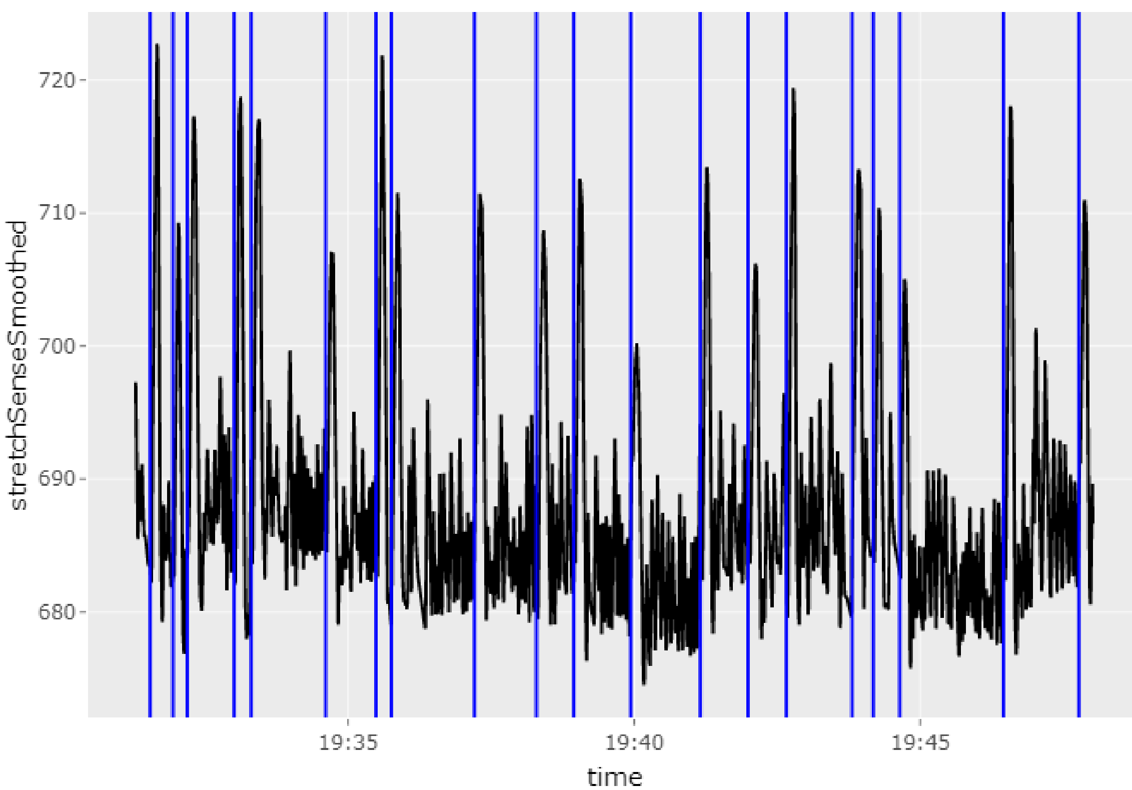
Duration

```r
gvs_true_peaks <- gvs_true_peaks[!is.na(gvs_true_peaks)]
gvs_true_valleys <- gvs_true_valleys[!is.na(gvs_true_valleys)]
depths <- depths[!is.na(depths)]

exhale_inds <- c()
for (i in 1:length(gvs_true_peaks)) {
    cur_index <- gvs_true_peaks[i]
    max_val <- gvsBreathData[cur_index]
    min_val <- gvsBreathData[gvs_true_valleys[i]]

    while (gvsBreathData[cur_index] >= max_val - 0.05 *
        depths[i] * (max_val - min_val)) {
        cur_index <- cur_index + 1
    }
    exhale_inds[i] <- cur_index
}
durations <- as.numeric(pacman2_data[exhale_inds, ]$time -
    pacman2_data[gvs_true_valleys, ]$time, units = "secs")
print(paste("Average duration: ", as.character(mean(durations,
    na.rm = T))))
## [1] "Average duration:  6.812808573246"
print(paste("Max duration: ", as.character(max(durations,
    na.rm = T))))
## [1] "Max duration:  9.52420854568481"
```

```
print(paste("Min duration: ", as.character(min(durations,
    na.rm = T))))
## [1] "Min duration:  4.70968747138977"
```

5 min Plot

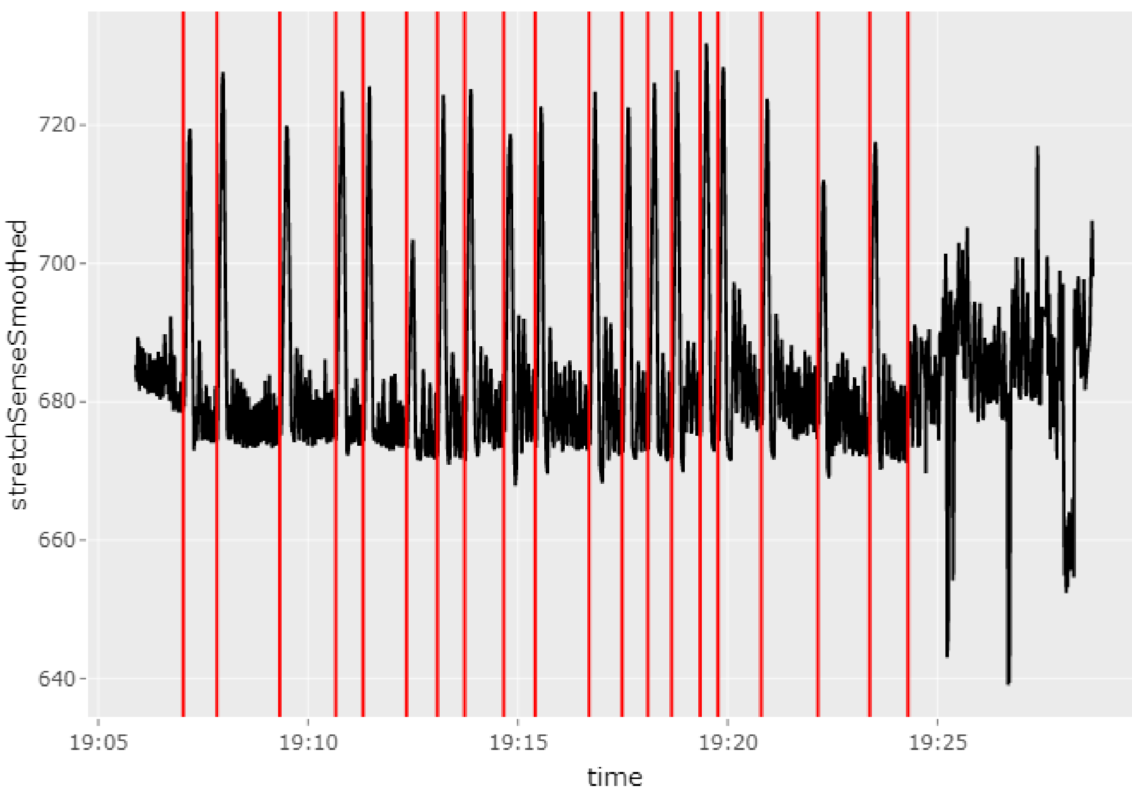
```
total_time <- as.numeric(t2 - t1, units = "mins")
pacman2_data$time_diff <- as.numeric(pacman2_data$time -
    total_time, units = "mins")
pacman2_5min <- pacman2_data %>%
    filter(time_diff > 3, time_diff < 8)
plt <- ggplot(pacman2_data, aes(x = time, y = stretchSenseSmoothed)) +
    geom_line() + geom_vline(xintercept = as.numeric(pacman2_stims),
    col = "blue")
ggplotly(plt)
```



GVS Conditioning

BREATH PLOT

```
pacman2_breath <- data %>%
    filter(scene == "gvs_conditioning")
pacman2_stims <- (gvs_stim_times %>%
    filter(scene == "gvs_conditioning") %>%
    arrange(time))$time

plt <- ggplot(pacman2_breath, aes(x = time, y = stretchSenseSmoothed))
+
    geom_line() + geom_vline(xintercept = as.numeric(pacman2_stims),
    col = "red")
ggplotly(plt)
```



FREQUENCY

Constrain time

```
# t1 <- as.POSIXct(strptime('2022-10-25
# 19:17:34.2','%Y-%m-%d %H:%M:%OS')) t2 <-
# as.POSIXct(strptime('2022-10-25
# 19:40:07.3','%Y-%m-%d %H:%M:%OS'))
t1 <- pacman2_stims[1] - 15
t2 <- tail(pacman2_stims, 1) + 15

pacman2_data <- pacman2_breath %>%
    filter(time > t1, time < t2)
```

Breathing frequency calculation

```
tot_breaths <- cycle_count(pacman2_data$stretchSenseSmoothed,
    20)
bpm <- tot_breaths/as.numeric(t2 - t1, units = "mins")
bpm
## [1] 9.397959
```

CALCULATING DEPTH AND DURATION

```
gvsBreathData <- pacman2_data$stretchSenseSmoothed
peaks <- find_peaks(gvsBreathData, 100)
crit_threshold <- min(gvsBreathData) + 0.2 * (max(gvsBreathData) -
    mean(gvsBreathData))
true_peaks <- peaks[which(gvsBreathData[peaks] > crit_threshold)]
# true_peaks <- peaks

valleys <- find_peaks(-gvsBreathData, 20)
true_valleys <- c()
for (i in 1:length(true_peaks)) {
```

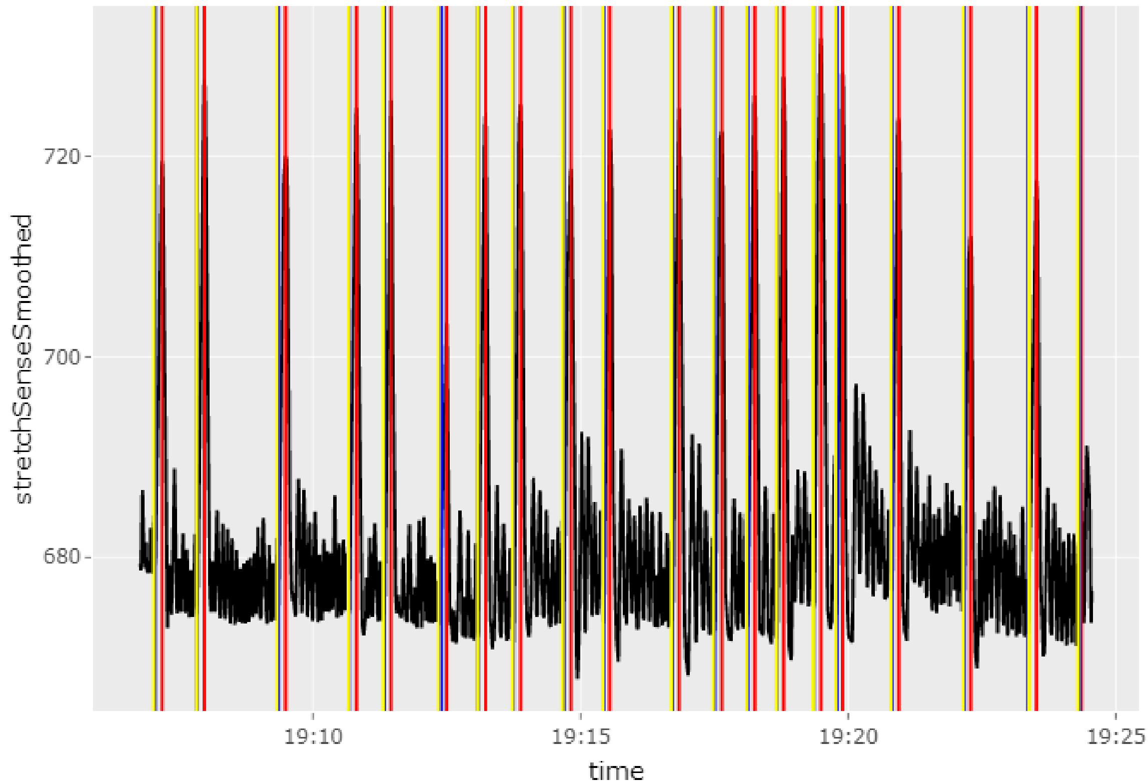
```
    vals <- which(valleys < true_peaks[i])
    k <- length(vals)
    val <- vals[k]
    while ((gvsBreathData[true_peaks[i]] - gvsBreathData[valleys[val]])
/BTC <
        0.1 && k != 0) {
        k <- k - 1
        val <- vals[i]
    }
    if (k == 0) {
        k <- length(vals)
    }
    true_valleys[i] <- valleys[k]
}


gvs_true_peaks <- c()
gvs_true_valleys <- c()
fill_na <- T
not_found_count <- 0
for (i in 1:length(pacman2_stims)) {
    t <- pacman2_stims[i]
    peak_found <- F
    for (j in 1:length(true_peaks)) {
        peak_time <- pacman2_data[true_peaks[j], ]$time
        if (peak_time > t && peak_time < t + 15) {
            if ((gvsBreathData[true_peaks[j]] - gvsBreathData[true_vall
eys[j]])/BTC <
                0.1) {
                print(paste(as.character(i), "depth too small"))
                next
            }
            peak_found <- T
            gvs_true_peaks[i] <- true_peaks[j]
```

```
            gvs_true_valleys[i] <- true_valleys[j]
            break
        }
    }
    if (!peak_found) {
        not_found_count <- not_found_count + 1
        print(paste("peak not found for stim ", as.character(i),
            as.character(t)))
        if (fill_na) {
            gvs_true_peaks[i] <- NA
            gvs_true_valleys[i] <- NA
            next
        }
        time_inds <- which(pacman2_data$time > (t -
            7) & pacman2_data$time < (t + 10))
        gvsData <- pacman2_data$stretchSenseSmoothed[time_inds]
        peaks <- find_peaks(gvsData, 10)
        true_peak <- time_inds[1] + peaks[1]
        gvs_true_peaks[i] <- true_peak
        gvsDataVal <- gvsData[1:peaks[1]]
        valleys <- find_peaks(-gvsDataVal, 10)
        if (length(valleys) != 0) {
            true_valley <- time_inds[1] + tail(valleys,
                1)
        } else {
            true_valley <- time_inds[1] + which.min(gvsDataVal)
        }
        gvs_true_valleys[i] <- true_valley
    }
}

double_peak <- c()
```

```
for (i in 1:length(gvs_true_peaks)) {
    if (i == 1) {
        next
    } else if (is.na(gvs_true_peaks[i]) || is.na(gvs_true_peaks[i -
        1])) {
        next
    }
    if (as.numeric(pacman2_data[gvs_true_peaks[i],
        ]$time - pacman2_data[gvs_true_peaks[i - 1],
        ]$time, units = "secs") < 3) {
        double_peak <- c(double_peak, i)
    }
}
if (!is.null(double_peak)) {
    gvs_true_peaks <- gvs_true_peaks[-(double_peak)]
    gvs_true_valleys <- gvs_true_valleys[-(double_peak)]
}
```

Plot peaks and valleys

```
peak_times <- as.numeric(pacman2_data[gvs_true_peaks,
    ]$time)
valley_times <- as.numeric(pacman2_data[gvs_true_valleys,
    ]$time)
plt <- ggplot(pacman2_data, aes(x = time, y = stretchSenseSmoothed)) +
    geom_line() + geom_vline(xintercept = peak_times,
    col = "red") + geom_vline(xintercept = valley_times,
    col = "blue") + geom_vline(xintercept = as.numeric(pacman2_stims),
    col = "yellow")
ggplotly(plt)
```



Responses total

```
total <- length(pacman2_stims)
responded <- total - not_found_count


print(paste(as.character(responded), "/", as.character(total),
    " total responses."))
## [1] "20 / 20  total responses."
```

Depth

```
depths <- (gvsBreathData[gvs_true_peaks] - gvsBreathData[gvs_true_valle
ys])/BTC
print(paste("Mean depths: ", as.character(mean(depths,
    na.rm = T))))
## [1] "Mean depths:  0.801301578989142"
```

```r
print(paste("Max depths: ", as.character(max(depths,
    na.rm = T))))
## [1] "Max depths:  0.9848759066027"
print(paste("Min depths: ", as.character(min(depths,
    na.rm = T))))
## [1] "Min depths:  0.194544748019726"
```

Duration

```r
gvs_true_peaks <- gvs_true_peaks[!is.na(gvs_true_peaks)]
gvs_true_valleys <- gvs_true_valleys[!is.na(gvs_true_valleys)]
depths <- depths[!is.na(depths)]

exhale_inds <- c()
for (i in 1:length(gvs_true_peaks)) {
    cur_index <- gvs_true_peaks[i]
    max_val <- gvsBreathData[cur_index]
    min_val <- gvsBreathData[gvs_true_valleys[i]]

    while (gvsBreathData[cur_index] >= max_val - 0.05 *
        depths[i] * (max_val - min_val)) {
        cur_index <- cur_index + 1
    }
    exhale_inds[i] <- cur_index
}
durations <- as.numeric(pacman2_data[exhale_inds, ]$time -
    pacman2_data[gvs_true_valleys, ]$time, units = "secs")
print(paste("Mean duration: ", as.character(mean(durations,
    na.rm = T))))
## [1] "Mean duration:  8.19878487586975"
print(paste("Max duration: ", as.character(max(durations,
    na.rm = T))))
## [1] "Max duration:  10.6649973392487"
```

```
print(paste("Min duration: ", as.character(min(durations,
    na.rm = T))))
## [1] "Min duration:  1.96533131599426"
```

5 min Plot

```
total_time <- as.numeric(t2 - t1, units = "mins")
pacman2_data$time_diff <- as.numeric(pacman2_data$time -
    total_time, units = "mins")
pacman2_5min <- pacman2_data %>%
    filter(time_diff > 3, time_diff < 8)
plt <- ggplot(pacman2_data, aes(x = time, y = stretchSenseSmoothed)) +
    geom_line() + geom_vline(xintercept = as.numeric(pacman2_stims),
    col = "blue")
ggplotly(plt)
```