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ABSTRACT

A hard challenge for wearable systems is to measure differences in emotional valence, i.e. positive and negative affect via physiology. However, the stomach or gastric signal is an unexplored modality that could offer new affective information. We created a wearable device and software to record gastric signals, known as electrogastrography (EGG). An in-laboratory study was conducted to compare EGG with electrodermal activity (EDA) in 33 individuals viewing affective stimuli. We found that negative stimuli attenuate EGG's indicators of parasympathetic activation, or "rest and digest" activity. We compare EGG to the remaining physiological signals and describe implications for affect detection. Further, we introduce how wearable EGG may support future applications in areas as diverse as reducing nausea in virtual reality and helping treat emotion-related eating disorders.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

Affect detection, Affective computing, electrogastrography (EGG), electrodermal activity (EDA), Wearable devices

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1 INTRODUCTION

Emotions are inseparable from human experience: How can computers better understand them? Since the conceptualization of affective computing (AC) in the 1990s [23], AC researchers have sought to answer this question by measuring patterns of objective data in various contexts and seeing which patterns are reliably related to human emotional experience.

Visual, audio, text, and physiological inputs have been the primary sources of labeled emotional data to perform facial expression recognition, emotional speech recognition, sentiment analysis, physiological arousal recognition, and more [7]. Many researchers have adopted a dimensional model of emotion to describe their data, representing emotion via dimensions such as its valence (positive to negative), arousal (high to low), and dominance (high to low) axis [6]. Valence can often be easily labeled by observers of video: seeing a video of a person winning a match, shouting "Yes!" and smiling as they turn to the audience is likely to be labeled as positive affect, while seeing them grimace, drop their head, and cover their face is likely to be labeled as negative affect. Similarly, in text analysis, there are passages using words that most people agree are positive, expressing a pleasurable or happy state, or that are negative, expressing sadness, anger or displeasure. However, in the modalities of pure audio (tone-of-voice), and in physiology, the valence can be hard to label without input from the individual who is experiencing the emotion [7].

In this work, we investigate electrogastrography (EGG) for its potential of detecting differences on the valence and arousal axis of the dimensional model. EGG non-invasively records stomach activity from the surface of the abdomen. We built a wearable device and tested its ability to record EGG. In addition, we ran a study recording EGG while participants viewed affective stimuli. We demonstrate how EGG changes in response to meals and affective stimuli, compare it to EDA, and discuss the significance of our results for HCI applications.

2 BACKGROUND

The "gut" is commonly used to describe emotional appraisal ("I have butterflies in my stomach"), decision-making ("trust your gut intuition"), memory ("I have a feeling we have met before"), and more. These phrases are rooted in neuroanatomical evidence. Our gut contains hundreds of millions of neurons and a trillion bacteria that affect most aspects of our physical and mental health. It stores the majority of serotonin ("pleasure hormone") in our body [11], it signals when we are hungry or when we are nauseous [14], can contribute to anxiety and depression, and can even regulate motor deficits in Parkinson's disease. But in particular, the gut-brain axis influences affect [8].

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2.1 Anatomical Background

Gut signals are recorded from gastrointestinal organs. Gastro- refers to the stomach and intestinal refers to the small and large intestines. The large intestine is also known as the colon. The organs of interest for measurement in our work are the stomach, small and large intestines. These organs have relatively large sizes, and are not fully obscured by other organs and bones, and contain a density of "gut-brain" neurons [11] known as the enteric nervous system.

The enteric nervous system (ENS) is a group of 200 to 600 million neurons that primarily innervate the esophagus, stomach, and intestines and operate autonomously. The gut-brain also includes the microbiome, a colony of a trillion bacteria in the gastrointestinal tract that impact most aspects of our health. It plays a key role in digestive function and recently has been shown to impact affect, stress, memory, and other cognitive phenomena [8].

The ENS interfaces with the central nervous system (CNS) via the gut-brain axis (GBA). The GBA includes the ENS, CNS, autonomic nervous system (ANS), and hypothalamic pituitary adrenal axis (HPA) [9]. One of its roles is to connect cognitive and emotional brain centers with peripheral intestinal functions. For example, the GBA can allow cognitive and emotional activity originating in the insular cortex to mediate intestinal permeability and enteric reflex. Its communications are neural, immune, and endocrine system-based. The microbiota has also been shown to modulate the GBA.

2.2 Electrogastrography (EGG)

Large scale changes from enteric pacemaker stomach cells can be detected using electrogastrography (EGG), a non-invasive (cutaneous in gastroenterology) recording of gastric slow wave propagation to the surface of the skin on the abdomen.

The ICC or pacemaker cells in the stomach produce slow-wave potentials. Like the heart's cells, the stomach also exhibits myoelectric activity that controls the frequency and paces the propagation of stomach contractions. The gastric slow wave is present all the time and originates in the pacemaker region that is lateral to the gastroesophageal junction and is characterized by regularly recurring potentials.

EGG signal is on average between 50 to 500 uV and the normal frequency is considered to be around 2-4 cycles per minute [32]. To establish our definition of what are considered "normal" EGG frequencies, we used the frequency bands defined in Yin et al. [32] (Table 1).

Frequency Band	Freq.	Freq. (Hz)	Features
Bradygastria	[0.5,2)	[0.0083, 0.03)	Relaxation
Normogastria	[2,4]	[0.033, 0.06]	Digestion
Tachygastria	(4,9]	[0.06, 0.15)	Nausea, Stress

Table 1: EGG Frequency bands and associated features in literature. [34]

The EGG recording setup also acquires signals from nearby organs and respiration rate, in addition to motion artifacts associated with electrophysiology applications. Though these signals are classically considered as artifacts in the EGG recording, upon separation they could each be used as features in a wearable system.

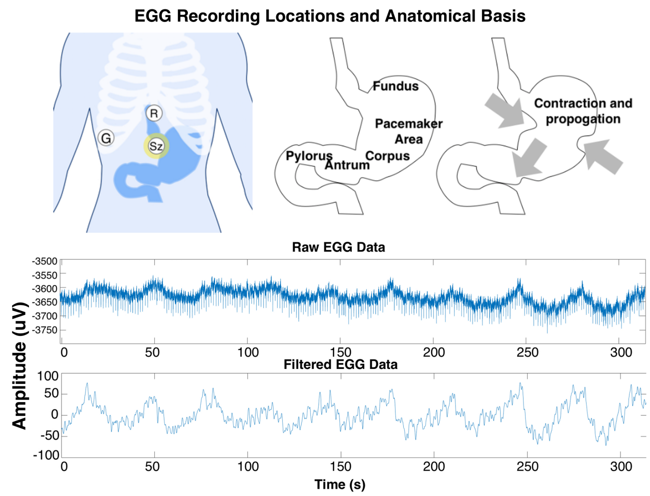

Figure 1: EGG electrode location, anatomical basis, example of raw and filtered time series data from center electrode with reference beneath the xyphoid process. Normogastria shows as distinct peaks at 3 cpm.

2.2.1 EGG Limitations. EGG recording methods have followed a single channel time series analysis in gastroenterology; high density spatial recordings and advanced signal processing techniques have only recently been introduced [12]. There currently exists no equivalent for the International 10-20 System for EEG, a standardized montage used across EEG studies [12], for EGG and the remainder of the gut-brain.

However, as microbiome research grows exponentially, there has been increasing interest in gut-brain or ENS neural mechanisms. Biomedical engineers have also recognized the need for more advanced signal acquisition and processing techniques for the ENS, with a focus on the gastric signal. Notably, Gharibans, Coleman, and others are leading efforts in non-invasive high resolution capture of gastric signal. Using simultaneous manometry and high resolution or HR-EGG, Gharibans et al. showed that electrodes on the surface of the abdomen meeting the Nyquist criterion for spatial sampling could record spatial propagation of gastric signals [12].

Current limits on EGG bio-markers, e.g. EGG's inability to capture stomach contractions [32], were within the scope of single channel time- and frequency-domain analysis. However, HR-EGG shows potential to overcome these limitations. More simultaneous internal and HR-EGG recordings are needed to establish features.

2.3 Related Work

There are comparatively few publications on EGG and affect compared to other electrophysiological recording techniques. In HCI, to the best of our knowledge, there is no previous work on integrating EGG into wearable and/or interactive interfaces. Mladenovi has proposed gut biofeedback theoretically for use in emotion regulation interfaces [21]. However, implementation does not appear to have been carried out to create a closed-loop biofeedback application.

Method	Recording Setup	Signal Target	Freq. Range	Power
Electrogastrography (EGG)	**Abdomen**	**Stomach**	**0.017 Hz - 0.25Hz**	**50 uV - 500 uV**
Electrocardiography (ECG)	Chest	Heart	1 Hz - 1.67 Hz	500 - 3000 uV
Electromyography (EMG) (surface)	Likely arms, legs	Muscle	5 Hz - 450 Hz	0 uV - 1000 uV
Electroencephalography (EEG)	Head	Brain	1 Hz - 100 Hz	2 uV - 200 uV
Electrodermal Activity (EDA)	Likely wrist, finger	Sweat secretion [4]	0.16 Hz - 5 Hz [5]	0 uS - 100 uS

Table 2: EGG compared with other common electrophysiological modalities in emotion regulation.

Electrophysiology is widespread in emotion regulation research, where signal data representing bodily activity is used to categorize emotional states. For example, electrocardiography (ECG) can provide different values of heart rate variability (HRV) to represent relaxation and arousal. Here, we compare EGG to other commonly used methods: electromyography (EMG), electrocardiography (ECG), electroencephalography (EEG), and electrodermal activity (EDA). In Table 2, we summarize the comparisons between these methods. Below, we expand on them.

EGG differs from other electrophysiology methods primarily in its recording location and timescale. EGG samples the gastric slow wave from the surface of the abdomen. The known frequency range is roughly 0.017 to 0.25 Hz with key features occurring between roughly 0.03 to 0.1 Hz [27, 32]. HR-EGG may introduce new features of the gastric signal, perhaps even event-related or evoked potentials. However, the most well-known feature remains the dominant frequency or high power of the brady-, normo- and tachygastria bands.

EGG can be reliably recorded at a sampling rate of 1 - 5 Hz. Because this sampling rate factors into the minimum required rates for EMG, ECG and EEG, the same hardware can be repurposed to record EGG as long as the electrodes can be placed on the abdomen and the raw signal can be separated from the filtered signal. In this paper, we have used OpenBCI, which outputs a raw signal from a Texas Instruments ADS1299 analog to digital converter (ADC). It transfers the data via Bluetooth Low Energy (BLE) or stores it onboard a micro SD card. The hardware and software are open-source, allowing for complete customization of the end application for EGG.

2.3.1 EGG and Affect. Researchers have reported various relationships between EGG and self-reported affect in the EGG frequency bands. Vianna et al. [27] reported normalized total spectrum EGG peak power correlated with increased arousal but not with valence. In one of these studies, participants with Chron's disease, a chronic inflammatory bowel disease, reported higher subjective affect "intensity" and also had higher EGG peak power [27]. Yin and Zhou et al. [35, 37] reported that stressful stimuli inhibited EGG power in the normogastria band, where an increase in power was supposed to occur after a meal. These studies demonstrate that affective or stressful stimuli could alter EGG total power and dominant frequency.

Neuroanatomical links between enteric pacemaker cells and distinct subregions of the insula have been shown to be mediated by conscious interoceptive regulation [19], affective processing of "neutral" and "disgust"-label films [16], and subjective report of state anxiety [17]. The sub-regions overlap with others also involved in cognitive and integrative functions [17], providing evidence for the potential to influence self-reported affective and cognitive states originating in the insula by means of enteric feedback.

2.3.2 Wearable EGG. Gharibans et al. demonstrated a wearable EGG system with 8 24-hour ambulatory recordings on a single "free-living" subject [13]. Their design used disposable electrodes in combination with a wearable amplifier and event-logging mobile application. They developed an artifact rejection methodology that enabled continuous recording. Their results showed a distinct time-effect of EGG power throughout the day, especially when aligned with sleep onset. They also found mean power increases throughout the day aligned with meals and snacks. Further, in our previous work [29] we presented the design and pilot of a hydrogel waistband, with a focus on recording EGG signal for extended periods (e.g. 6 hours or longer) in-the-wild. While both works briefly mention the connections between affect, stress, and EGG, they did not explicitly investigate the relationship between affect and EGG.

3 DESIGN

Our goal was to further evaluate the relationship between EGG and affect. However, a commercial device to record these signals was not available. Thus, we used the literature to design a wearable EGG device. The focus of this part of our work was to accurately record signals. Based on the features of the EGG signal and principles of wearable technology [36], we assumed the following system requirements:

(1) Long wear period: Gastric slow wave at low frequency (0.05 Hz)
(2) Low profile, concealable: Must record on abdomen underneath clothing
(3) Battery life for at least 6 - 8 hours, relatively stable impedance,
(4) Reliable data storage protocol for long wear period

We created a wearable EGG interface consisting of a biosignal amplifier with a 3D printed case, a silver/silver-chloride electrode montage, and a laser-cut scuba-knit neoprene patch. The design can be worn below clothing for ambulatory applications. In our prototype, data are streamed from each of seven electrodes with a sampling rate of 250 Hz via Bluetooth Low Energy (BLE) to a BLE-enabled connected device with the option to save to an SD card.

To record EGG data, we selected the OpenBCI, an open-source TI ADS1299-based bioamplifier. This allowed us to create custom hardware and software to record and analyze data. The default sampling rate for this device is 250 Hz, which far exceeds the Nyquist rate for EGG signal [13]. We housed the hardware in a 3D printed case modeled using Solidworks 2017 SP3 and printed using a FormLabs

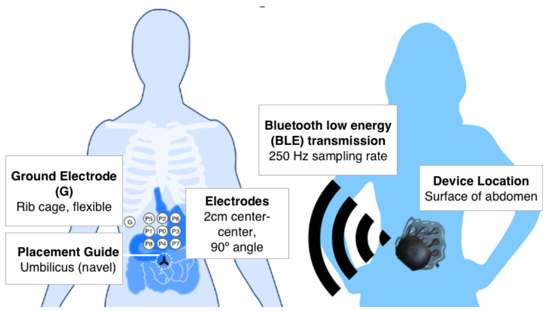

Figure 2: Montage with approximated location of stomach. Electrode montage based off of Gharibans et al. [13]

Figure 3: Wearable components. Includes laser-cut scuba knit neoprene, 3D printed case with bioamplifier, LiPo battery, and powerboost converter.

Form 2 with FormLabs V3 white resin. The resin was subsequently spray painted black. A Lithium Ion 3.7V 1800mAh battery was used to power the OpenBCI after being boosted from 3.7V to 5V by an Adafruit Powerboost 500.

We laser cut scuba knit neoprene (80% polyester, 20% spandex) to create precision electrode placement. We selected scuba knit polyester mix for its fine polyester fibers which connect two layers of fabric and hold its structure. This laser cut scuba knit technique ensures the electrode montage stays in an explicit grid while allowing for stretch.

3.1 Pilot Test

A single participant with normal to corrected-to-normal hearing and vision, and no known gastrointestinal, neurological, or psychiatric disorders wore the device before and after consumption of a 454 calorie meal. A built-in laptop camera simultaneously recorded during the full duration of the signal recording and screen capture software recorded activities being conducted on the computer. Protocols were approved by the MIT COUHES. Any video or screen recording was used exclusively for signal labeling purposes and deleted at the completion of analysis. Before placement of the device, the abdomen was prepared using disposable 70% isopropyl alcohol swabs.

We found that the wearable captured the EGG signal and corresponding ECG artifact. In addition, a visual study showed the waveforms present for ECG. Though the P and T waves are not as clear as in electrode montages intended for ECG, the QRS was

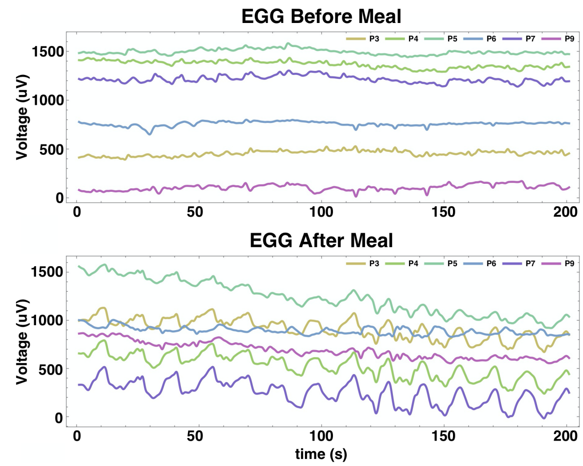

Figure 4: Here, we demonstrate the EGG normogastria signal time series recorded from our device before and after a 454 calorie meal.

present in our signal. Though this signal is an artifact in the GBCI montage, it may also be used as a feature of the system.

4 METHODS

In our affect elicitation study, we sought to record data from a wearable device that could be eventually used to interpret affect in HCI applications. Our methods closely follow Vianna et al. [27] in which EGG signals are recorded during affective film sequences with grounded ratings. Given that results from Yin et. al. [32] demonstrated that emotional stress induced by viewing a horror movie induced gastric dysrhythmias in healthy subjects across both fasting and fed states, we focused on within-subject effects without requiring a 2 - 6 hour fast or test meal (a standardized meal provided to each participant) before the study.

Environment The experiments were performed in an office environment with controlled temperature. Each participant was seated approximately 31.5 inches away from a 24-inch monitor and wore sound-cancelling headphones during film sequences.

Participants All procedures were approved by the MIT Committee on the use of Human as Experimental Subjects (COUHES) and every participant provided informed consent. Participants (N = 33, ages 20 to 59, mean age 27.43, 16 males, 17 females) with normal to corrected-to-normal hearing and vision, no known gastrointestinal, neurological, or psychiatric disorders, and the ability to sit still and stay awake during movie sequences were recruited. Participants were compensated for their participation.

Electrogastrography (EGG) Skin was prepped using 70% isopropyl alcohol swabs. EGG signals were recorded using disposable Ag-AgCl electrodes (Skintact, F-301 gel electrode) connected to the OpenBCI amplifier sampled at 250 Hz with no filtering in hardware.

Electrodermal Activity (EDA) EDA signals were recorded using two E4 wristbands (Empatica) which records EDA at 4 Hz with no filtering in hardware. One E4 was placed on each wrist to align with the middle and ring fingers, and participants were asked to keep sensors "snug" without causing pain or discomfort.

Procedure After arrival, consent procedures, and equipment setup, participants completed a pre-study survey evaluating hunger, last food intake, stimulant consumption, alertness, affect [6], and personality. Participants then followed a 4-minute breathing exercise to establish a resting baseline. Next, participants were shown two blocks of films, each consisting of either three negative films (total 7 minutes 53 seconds) or of three positive films (total 7 minutes 48 seconds). The two blocks were in random order. Afterwards, a neutral clip was shown. Finally, participants answered a post-experiment demographic survey.

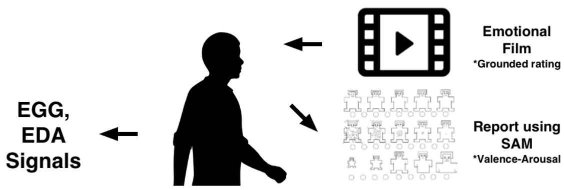

Figure 5: The experimental setup included the recording of physiological signals during movie sequences, with self-report of affect.

Affective Stimuli We selected four clips from Uhrig et al. [26] to elicit specific target emotions. Clip criteria used in Uhrig's work excluded "outdated" films (e.g., silent films, films shot in black-and-white or that used outdated technologies), and primarily selected live-action, mainstream film materials that aim for viewers to experience specific emotional responses. Standardized cinematographic styles (e.g., lighting, camera angles, sound) ensured comparability across the set of video clips. We selected six movie clips, 3 positive and 3 negative, for our study. Uhrig et al. did not designate any movie clips in their work as neutral; we selected a neutral clip previously used in literature by Rotternberg, an excerpt of *Alaska's Wild Denali: Summer in Denali National Park* [24].

No.	Film Source	Tag	Valence
31	Coach Carter	Happiness	Positive
32	Moulin Rouge	Love	Positive
42	The Gladiator	Sadness	Negative
54	Silence of the Lambs	Fear	Negative
57	When Harry Met Sally	Amusement	Positive
78	Kill Bill	Disgust	Negative

Table 3: Affective stimuli movie clip selections from Uhrig et al. [26].

Self-Report of Affective State At the end of each movie clip, participants answered a self-assessment of their levels of valence, arousal, dominance, liking and familiarity. Participants were provided with the following instructions: "Use the Valence mannequin to describe if the video made you feel upset, neutral, happy, or somewhere in between. Use the Arousal mannequin to describe if the video made you sleepy, neutral, or stimulated (i.e. raised heart rate, etc.). Use the Dominance mannequin to describe your level of control, from without control to being in control."

We used self-assessment manikins (SAM) [6] for subjective, pictorial reports of the emotional experience for valence, arousal, and dominance (on a scale of 1 to 5). The valence scale ranged from negative to positive; the arousal and dominance from low to high. Participants also reported liking and familiarity modeled after Koelstra et al. [18] and, if applicable, free response describing the most important scene used for creating their response.

4.1 Data Analysis

In order to establish a reference point for our work and validate our signal acquisition method and hardware, we modeled our data analysis after Vianna et al.'s previous work [27]. We applied a 4th order Butterworth bandpass filter over the entire frequency range of interest (0.0083 to 0.15 Hz), computed the power spectral density using Welch's average periodogram method with a Hanning window and 75% overlap, and an IIR notch filter to remove power line interference. To account for between-subject variability, peak dominant spectral values during affective stimuli were transformed into z-scores.

$$z_{EGG} = \frac{max(P_{xx}) - \overline{P_{xx}}}{\sigma_{P_{xx}}} = \frac{x - \mu}{\sigma} \quad (1)$$

Where P_{xx} is the power spectral density. The formula for EGG z-scores took x as the max spectral value of the power spectral density between 0.0083 to 0.15 Hz, μ as the mean spectral value between 0.0083 to 0.15 Hz, and σ as the standard deviation of the power values. For EDA z-scores, the same formula applied but without power spectral density. First, we removed any recordings with a mean threshold below 0.1 microsiemens from analysis. Next, the wristband with the greater mean power in microsiemens was selected as the wristband for the window of analysis. The formula took x as the peak value detected from the wristband, μ as the mean of its values, and σ as the standard deviation of its values.

5 RESULTS AND DISCUSSION

We hypothesized that 1. EGG peak amplitude would increase with increased arousal, as well as EDA, based on work by Vianna et al. [27, 28] 2. Negative but not positive videos would have a statistically significant impact, given well-established issues with in-laboratory positive affect elicitation [7].

To account for between-subject variability, we transformed EGG and EDA into z-scores [27, 28]. This score is the normalized response to each video. We fitted a linear mixed-effects model, looking at the response to self-reported Valence and Arousal (two runs), and Positive and Negative video conditions (one run), controlled by self-reported dominance, with random effects grouped by participant. For EGG signal, we analyzed a single channel corresponding with the greatest percentage of normogastria. For EDA, we selected the wrist with greater mean power.

We failed to reject the null for our 1st hypothesis, but reject it for the 2nd. Normalized EGG values did not correlate with arousal ratings (P = 0.714, t = -0.367, SE = 0.059, DF = 120). However, there was a significant positive correlation for normalized EGG with valence ratings (P = 0.026, t = 2.254, SE = 0.051, DF = 120) (see Figure 7).

Normalized EDA values had a significant negative correlation with valence ratings (P = 0.0278, t = -2.230, SE = -.12, DF = 108), but

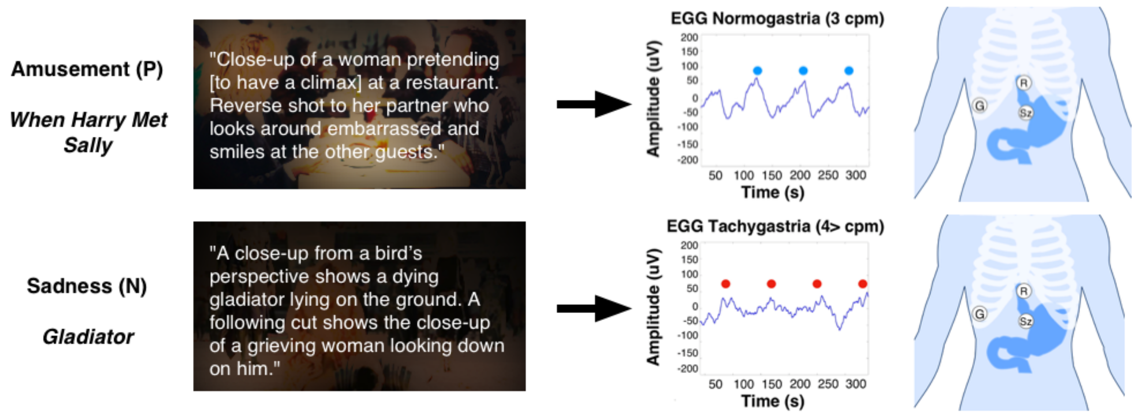

Figure 6: EGG normogastria under positive film sequence (Participant 17), top. EGG tachygastria under negative film. Recorded using disposable electrodes and referenced below xyphoid process.

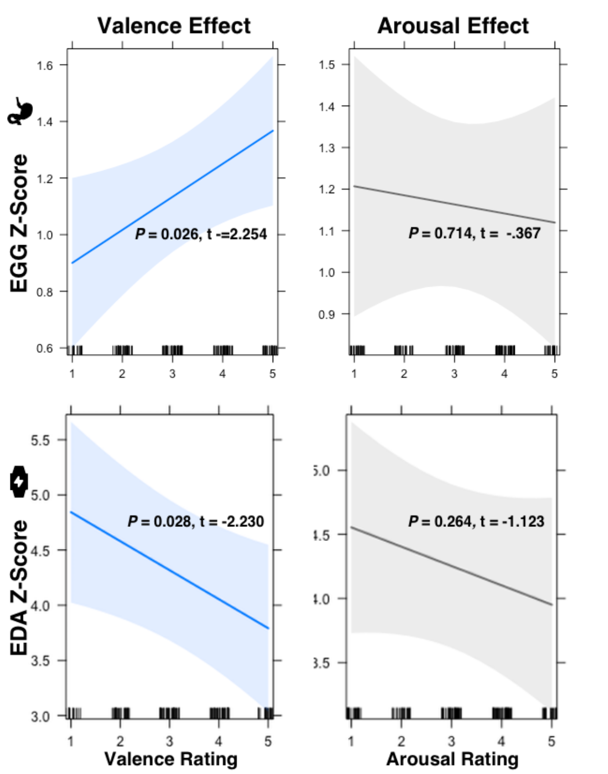

Figure 7: Both EGG and EDA signals significantly correlated with valence but not arousal scores.

Film	Valence(M, SD)	Arousal(M, SD)	Dom.(M, SD)
Happiness (P)	(2.50, ±0.76)	(3.00, ±0.97)	(3.30, ±1.22)
Love (P)	(4.10, ±0.77)	(2.62, ±1.20)	(4.19, ±1.25)
Amusement(P)	(4.76, ±0.70)	(3.76, ±0.77)	(3.33, ±1.43)
Fear (N)	(1.95, ±1.00)	(3.65, ±0.81)	(2.70, ±1.34)
Sadness (N)	(2.95, ±1.24)	(2.91, ±1.18)	(3.19, ±1.53)
Disgust (N)	(2.84, ±1.50)	(4.11, ±1.20)	(2.73, ±1.24)
Neutral (N)	(3.43, ±0.98)	(1.16, ±1.16)	(4.19, ±1.43)

Table 4: Mean valence, arousal, and dominance ratings with standard deviation for each video, rounded to 2nd decimal place

did not significantly correlate with arousal ratings (P = -2.230, t = -0.0278, SE = 0.13, DF = 108). This negative correlation with valence is inverse the positive correlation found with EGG.

Controlling for the dominance (our measure of stimuli effect), negative movies produced statistically significant changes in the linear effects model (P = 0.0209, t = -2.341, SE = 0.208, DF = 119). Positive movie segments in comparison did not produce statistically significant changes (P = 0.4706, t = -0.724, SE = 0.197, DF = 119). The dominance ratings for positive movie clips were significantly higher than for negative movie clips (P = 0.003, DF = 119, t = 2.95, Welch's two sample t-test) with a mean score that suggests higher control in emotional response (μ = 3.613) (see full results in Table 4).

Prototype Validation. The normal percentage of gastric slow wave in humans is defined as 70% of normogastria power in the total range of EGG signal [33] and is used as a measure of EGG signal quality [13]. We analyzed the recording electrode in our study, and found (normogastria / frequency range of interest)*100 has: mean 62.03%, SD 15.6%, median 66.33%, first quartile 49.86%, third quartile 73.83%. A lower percentage may have been due to the OpenBCI bioamplifier having no signal filtering in hardware or electromagnetic (EM) shielding. However, it suggests our results were in a supportable range of quality.

5.1 Comparison to Related Work

In comparison with the protocol used by Vianna et al. [27, 28], we also observed statistically significant changes in EGG z-scores based on self-reported affect in the dimensional model. However, we observed a significant correlation with valence instead of a significant correlation with arousal. We can explain our contrast to Vianna et al.'s work by contextualizing our results. In [35], negative films have an inhibitory effect on normogastric activity; in Lin et al. [20], participants who said that they did not enjoy a music intervention had significantly lower EGG power than at baseline. In our own study, we can demonstrate a similar effect seen in Participant 17's EGG signal during "amusement" versus "sad" movie sequences (Figure 6). Signal power was generally higher for positive or neutral stimuli, but due to the difficulty of positive in-lab affect elicitation, we cannot confirm the impact of positive stress. We believe there must have been an additional factor impacting [27, 28], as our results, the literature, and EGG's physiological source support negative stimuli inhibiting gastric activity. An inhibitory effect of stomach pacemaker cells is more expected under negative valence or possible stress states [32].

Further, EDA not displaying a significant correlation with arousal ratings was an unexpected result. Upon further inspection, we can see that the increased EDA during low-valence rating films may have been a result of those films having higher arousal ratings (see Table 4), in combination with the significantly lower dominance ratings for negative films (P = 0.003). Thus, this may have still been an expected result, in combination with the attenuation of EGG signal (see next section).

5.2 Possible Mechanisms of EGG Signal

Further studies are needed to understand if EGG is a reliable approximation of valence in the dimensional model of emotion. In this study, we also observed that EDA had a significant negative correlation with valence ratings, and no significant correlation with arousal ratings, which is unexpected given prior work [27, 28]. However, given their inverse relationship with valence ratings, we can approach the mechanism of the EDA and EGG signals to hypothesize about how they can be used together.

The EGG signal is most clearly recorded upon digestion of a meal (see Figure 4) when EGG signal power increases upon parasympathetic activation. Parasympathetic activity is colloquially referred to as "rest and digest." On the other hand, EDA captures sympathetic activation - colloquially referred to as "fight or flight." ECG can be analyzed spectrally to identify a parasympathetic component, but heart rate can increase with both an increase in sympathetic activation and with the parasymnpathetic system releasing the "vagal brake" – thus, it is not possible with present knowledge to extract symnpathetic activation from the ECG. When we combine these signals into a multimodal system, we may be able to better approximate the dimensional emotion model, even better than has been attempted with the classic parasympathetic - sympathetic activation axis, as the autonomic nervous system's third branch, the enteric nervous system, can finally be measured in tandem with the other two branches. While it may be that the increased parasympathetic activation from EGG may correlate with valence, further studies are needed in a variety of contexts to continue to reveal these relationships .

5.3 EGG for Physiological, Wearable Affect Detection

In our study, we saw a significant relationship between normalized EGG and self-reported valence scores and not arousal scores. Autonomic physiological measures are well-established to correlate with subjective report of arousal on the valence-arousal axis [16]. It is much more difficult to capture valence granularity. Correlations between EEG and valence have been established [22]; however, these changes are difficult to record and occur on the order of 1 - 5 uV. In addition, they typically require active gel electrodes integrated into full EEG caps, which may not be comfortable or socially acceptable for everyday environments.

In emotion regulation applications using wearable devices, EGG's unique advantage is digestive activity. The relationship between emotions and eating behaviors is well-studied. Measurements such as the Emotional Eating Scale (EES) have been formulated to quantify the relationship between affect and eating habits [2]. Psychologists have studied the relationship between emotion and obesity [10] and eating disorders [15]. In the post-prandial (meal) stage, EGG power increases in the normogastria band are inhibited by stressful stimuli [35]. Unlike other electrophysiology methods, EGG shows an individual may be experiencing stress during digestion. This has important implications for emotion regulation applications tied to eating behaviors. However, there are also important advantages and disadvantages to consider when using wearable EGG (Table 5).

Advantages	Disadvantages
Acquire signals from multiple organs, concealable beneath clothing, possible significance for circadian rhythm, digestive activity	Long time scale for gut signals, can be difficult to access device directly without privacy, design is worn in a not typically acceptable area

Table 5: Primary advantages and disadvantages of abdominal-based systems and gastrointestinal myoelectric interfacing.

5.4 Potential Applications and GBCI

To the best of our knowledge there has been little to no study of gut biofeedback applications. Using gut biofeedback from the ENS, we can create gut-brain computer interfaces (GBCIs). A GBCI acquires data on the gut-brain of an individual and returns feedback that enables the individual to change a behavior or activate a stimulation to influence gut-brain activity or input gut-brain activity into other devices. Based on the known features of the gastric signal, individuals can receive haptic, audio or visual feedback on their digestive activity, stress and affect, motion sickness and nausea, and more. An abdominal wearable also records respiration rate and heart rate. These signals can be used together with gastric activity for feedback. Here, we focus on EGG activity standalone.

5.4.1 Eating Habits and Emotional Eating. An increase in power and percentage of normogastria (see Table 1) occurs after a meal. However, it has been shown that stress can inhibit this increase [32, 37], suggesting that stress interferes with normal post-meal digestive activity. At the same time, the study of eating disorders has shown it is in part caused by poor interoceptive sensitivity with regard to visceral gut signals. It is possible that the stress-induced inhibition of gastrointestinal signals results in digestive information not being communicated to the brain. Barbarin et. al. [3] also found that women who engage in emotion- and stressed-related eating (ESRE) report a difficulty using self-monitoring health information technology such as calorie intake and expenditure applications, i.e. MyFitnessPal. A GBCI could be used with or without eating detection devices to analyze signals after meals for an increase in normal gastric power. If this increase is inhibited, the GBCI could guide a wearer through a biofeedback-assisted diaphragmatic breathing exercise or other personalized calming response so that stress does not continue to interfere with normal digestive activity.

5.4.2 Meauring Nausea in VR. Tachygastria, or increased frequency and dysrhythmic gastric activity, has been associated with nausea. Participants in a optokinetic rotating drum who experienced motion sickness had an increased level of tachygastria [14]. Motion sickness is also commonly reported in VR. A GBCI wearable could detect the onset of motion sickness and subsequently change the visual feedback associated with the motion sickness, provide vestibular stimulation [25], or provide gastric stimulation that may help ease motion sickness and regulate gastric activity.

5.4.3 Monitoring Gastrointestinal Disorders. Vianna et al. demonstrated that those who suffer from active Chron's disease, a form of IBD, reported greater sadness, fear, and disgust when presented with stimuli that elicited these emotions [27]. Mental health issues such as depression are present in Crohn's patients. In addition, depressive symptoms in IBD patients have been reported to predict gastrointestinal disease symptoms, which then increase the likelihood of depressive symptoms, contributing to a vicious cycle. Providing Chron's patients with EGG feedback and a guided breathing exercise similar to the one shown to be effective by Li et. al. [19] may help them regulate negative emotions that are intensified by the increased sensitivity and lowered pain threshold of the inflamed gastrointestinal tract.

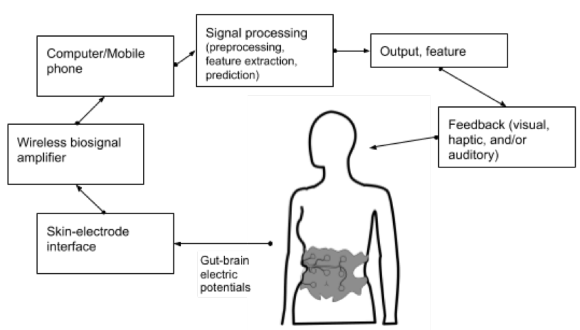

Figure 8: A gut-brain computer interface (GBCI) [29], a closed-loop biofeedback interface using gut signals.

6 LIMITATIONS AND FUTURE WORK

In-laboratory affect elicitation studies present known difficulties. In line with previous literature and our hypothesis, positive films did not have a statistically significant effect on EGG signal. The "happy" film also received below a 3 valence rating from participants, suggesting it was considered neutral or slightly negative (Table 4). Further, the analysis of results was made to compare to previous literature by using a single recording electrode and a normalized EGG and EDA response. Other methods of analysis of signals should be explored, particularly the analysis of multiple electrodes. In addition, a more expanded set of stimuli should be used in future studies.

In addition, research in non-invasive "gut" recordings such as EGG is a challenging area. Though EGG was first published in 1922 by WC Alvarez in the Journal of the American Medical Association (JAMA) [1], two years before the first reported EEG recording by Hans Berger in 1924, it has received substantially less research attention compared to EEG and other electro-physiological methods. EGG has between 1% to 10.6% of the publications and patents in pairwise comparisons and makes up 0.5% of the pool after a Google Scholar Search for similar methods. Compared to other methods, the following challenges exist for the future of EGG:

No standardized montage. There exist recording guidelines for single-channel analysis, and HR-EGG was recently introduced. However, no standard comparable to those of the International 10-20 System in EEG [31] or to the Einthoven's Triangle for ECG [30] yet exists.

Few off-the-shelf research-grade and consumer-grade recording devices. Companies are now beginning to be formed for medical devices to record EGG and some software and hardware for recording EGG exists; however, the equivalent of an ECG chest band, EDA wristband, and EEG cap does not exist for the EGG signal. It might be desirable to have a 64-channel high-resolution EGG 'waistband' that would record both gastric and intestinal signals in a standardized grid. Given increasing research in this area and overlapping hardware requirements with other signals, an off-the-shelf high-density recording apparatus may become available in the next decade.

7 CONCLUSION

For many decades now, AC researchers have investigated the relationship between data and models of human emotion to integrate emotions into HCI, and perhaps even contribute new data to the understanding of emotion. In this paper we explored a promising new method to capture "gut-brain" electrical changes related to positive and negative affect, and to levels of emotional arousal. As research in the gut-brain further expands the inextricable link between human cognition, emotion, and the gut, an increased interest in non-invasive electrophysiology of the gut may follow. We investigated affect detection using electrogastrography (EGG) and found that in line with previous literature, negative stimuli inhibited its activation. From our understanding of EGG, we propose gut-brain computer interfacing (GBCI) and its potential applications. By combining EGG with other physiological channels such as ECG or EDA, we may be able to get a more complete understanding of affective physiology. Devices may now understand us a little better, by understanding gut feelings.

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