Electrogastrography for psychophysiological research: Practical considerations, analysis pipeline, and normative data in a large sample

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Abstract
Electrogastrography (EGG) is the noninvasive electrophysiological technique used to record gastric electrical activity by means of cutaneous electrodes placed on the abdomen. EGG has been so far mostly used in clinical studies in gastroenterology, but it represents an attractive method to study brain-viscera interactions in psychophysiology. Compared to the literature on electrocardiography for instance, where practical recommendations and normative data are abundant, the literature on EGG in humans remains scarce. The aim of this article is threefold. First, we review the existing literature on the physiological basis of the EGG, pathways of brain-stomach interactions, and experimental findings in the cognitive neuroscience and psychophysiology literature. We then describe practical issues faced when recording the EGG in young healthy participants, from data acquisition to data analysis, and propose a semi-automated analysis pipeline together with associated MATLAB code. The analysis pipeline aims at identifying a regular rhythm that can be safely attributed to the stomach, through multiple steps. Finally, we apply these recording and analysis procedures in a large sample \( (N = 117) \) of healthy young adult male and female participants in a moderate \(<5\) hr) to prolonged \(>10\) hr) fasting state to establish the normative distribution of several EGG parameters. Our results are overall congruent with the clinical gastroenterology literature, but suggest using an electrode coverage extending to lower abdominal locations than current clinical guidelines. Our results indicate a marginal difference in EGG peak frequency between male and female participants, and that the gastric rhythm becomes more irregular after prolonged fasting.

KEYWORDS
electrogastrography, gastric rhythm, normative data, power and phase analysis, processing pipeline
1 AN INTRODUCTION TO ELECTROGASTROGRAPHY

1.1 The electrogastrogram and its usage

“Electrogastrography” refers to the monitoring technique of gastric myoelectrical activity from cutaneous electrodes placed on the abdomen (Figure 1a), which generates the electrogastrogram (EGG). The EGG has so far mostly been used for clinical purposes in gastroenterology (Koch & Stern, 2004; Parkman, Hasler, Barnett, & Eaker, 2003; Riezzo, Russo, & Indrio, 2013; Yin & Chen, 2013), but represents an interesting tool in psychophysiology (Stern, Koch, Levine, & Muth, 2007; Stern, Koch, Stewart, & Vasey, 1987). The EGG reflects the combination of the slow electrical gastric rhythm, constantly generated in the stomach wall, and of the more transient smooth muscle activity generating gastric peristaltic contractions. The main function of the stomach is to mix and grind food during digestion. The gastric rhythm sets the frequency of smooth muscle contractions and controls their propagation. The gastric rhythm is constantly generated in the stomach wall, even in the absence of muscular contraction (Bozler, 1945), or when the stomach is completely disconnected from the central nervous system (Suzuki, Prosser, & Dahms, 1986). Its normal frequency in healthy humans is around 0.05 Hz or three cycles per minute, that is, one cycle every 20 s. EGG frequency differs in other species (Mice: 2–5 cpm [Hou, Yin, Liu, Pasricha, & Chen, 2005]; Pigs: ~3.3 cpm [ Květina et al., 2010; Varayil et al., 2009]; dogs: 4–6.5 cpm [Andreis et al., 2008; Mintchev, Otto, & Bowes, 1997]; macaque monkeys: ~3.6 cpm [Linsong, HuaLiu, Xitai, Xiaojin, & Pingan, 1989]).

The definition of normogastria, or normal frequency range of the gastric rhythm in humans, varies depending on authors (for review, Chang, 2005; Parkman et al., 2003). Along with a number of studies (e.g., Chen & McCallum, 1992; Chen, Zou, Lin, Ouyang, & Liang, 1999; Lin, 1999; Parkman, Harris, Miller, & Fisher, 1996; Parkman et al., 2003; Pfaffenbach, Adamek, Kuhn, & Wegener, 1995; Riezzo, Chiloiro, & Guerra, 1998) and guidelines (e.g., Yin & Chen, 2013), we adopted the 2–4 cpm cycles per minute (cpm) range. A narrower range has also been advocated (e.g., 2.5 to 3.6 cpm in

FIGURE 1 (a) Recording setup. Cutaneous electrodes are placed on the left abdomen of the participant in a grid-like arrangement and connected to DC amplifiers. Ref. and Gnd correspond to Reference and Ground, respectively. (b) Example of raw data in one participant, where the gastric rhythm is visible as cycles of ~20 s length. Respiratory cycles are much faster (typically 3 to 5 s length). Heartbeats appear as transients every ~0.8 s (inset). EGG amplitude in this participant is close the median value observed in 100 participants. (c) Power spectrum at each of the seven recording electrodes. Peak frequency is indicated by a star on the channel with the largest power (black line). The white area corresponds to the normal frequency range of the EGG, also known as normogastria (2 to 4 cpm or 0.033 to 0.066 Hz). Inset: Electrode layout with the location of the electrode displaying the largest spectral power marked with a blue star. (d) Spectral density over a wider frequency range at the selected channel, revealing the spectral signatures of the respiratory (~0.3 Hz) and cardiac rhythms (~1.5 Hz)
Koch & Stern, 2004), and a number of studies used ranges closer to this definition (e.g., Abell & Malagelada, 1988; Gianaros, Quigley, & Mordkoff, 2001; Homma et al., 1999; Koch, Bingaman, Tan, & Stern, 1998; Koch, Hong, & Xu, 2000; Meissner, Muth, & Herbert, 2011; Muth, Koch, Stern, & Thayer, 1999; Stern, Vasey, Senqi, & Koch, 1991; Vianna, Weinstock, Elliott, Summers, & Tanel, 2006).

An example of a raw signal obtained from cutaneous abdominal electrodes is shown in Figure 1b. In this good quality recording, the gastric rhythm is visible to the naked eye. In the same raw data, the faster rhythms of respiration (typically around 0.2–0.4 Hz) (Kaiho, Shimoyama, Nakajima, & Ochiai, 2000) and heartbeats (1–1.7 Hz) can be observed, superimposed on the gastric rhythm (Abell & Malagelada, 1988; Stern et al., 1987). The spectral analysis of the EGG reveals a sharp peak around 0.05 Hz (Figure 1c). The EGG spectral signature is markedly distinct from those of respiration and heart rate, that peak at much higher frequencies (Figure 1d). Note that a harmonic of the gastric rhythm can sometimes be observed (Figure 1d) when the EGG departs from a perfect sine wave (Verhagen, Van Schelven, Samsom, & Smout, 1999).

Historically, the EGG was independently discovered by Alvarez, 1922; Davis, Garafolo, & Kveim, 1959; Tumpeer & Blitsten, 1926. While this recording technique received little attention for decades, computerized analysis rekindled interest in the 1990s in the field of gastroenterology (Koch & Stern, 2004). EGG recording and analysis has been first and mostly performed in the clinical domain, where it represents an appealing method since it is noninvasive, cheap, and relatively easy to install and acquire. In gastroenterology, the EGG is typically acquired before and after a meal, called the pre- and postprandial period, respectively. The EGG amplitude normally increases in the postprandial period in healthy participants, while EGG frequency remains relatively unaffected (for review see Koch & Stern, 2004; Riezzo et al., 2013; Stern et al., 1987). Gastroenterologists have been interested in characterizing EGG abnormalities in patients by describing changes in power and frequency. For instance, postprandial increases in EGG amplitude are altered in gastric motility disorders (Cucchiara et al., 1997; Parkman & Orr, 2007) and Parkinson’s disease (Kaneko et al., 1995). Other studies analyzed changes in EGG frequency. The gastric rhythm tends to get faster (tachygastria) in patients with nausea (Geldof et al., 1989), depression (Ruhland et al., 2008), and schizophrenia (Puepelmann et al., 2009). Note that different approaches have been used to characterize departure from normogastria, either by analyzing the percentage distribution of EGG power in different frequency bands or by analyzing the shifts of EGG peak frequency over time (Stern et al., 2007). Here, we will focus on preprandial EGG recordings in healthy participants.

1.2 | The EGG in psychophysiology

The potential relevance of visceral signals for understanding brain and behavior has long been underlined for emotions (Cannon, 1927; Damasio, 1996; James, 1890; Lange, 1885), but also in a relationship with self and consciousness (Azzalini, Rebollo, & Tallon-Baudry, 2019; Christoff, Cosmelli, Legrand, & Thompson, 2011; Craig, 2002; Critchley & Harrison, 2013; Thompson & Varela, 2001), as well as in physical and mental health (Khalsa et al., 2018; Quadt, Critchley, & Garfinkel, 2018). Note that brain-viscera interplay ranges from the implicit nonconscious signaling of bodily afferents to the brain and/or automatic descending modulation of stomach activity by the brain to explicit or consciously accessible visceral perception (Azzalini et al., 2019; Quadt et al., 2018).

Despite the potential relevance of brain-viscera relationships, empirical studies investigating the electrical activity of the gastrointestinal system remain scarce and provided mixed results. Initial studies on shock/noise avoidance reported mixed results on EGG amplitude (Davis & Berry, 1963; Fedor & Russell, 1965; Stern, 1966, 1983; White, 1964). Different physical and psychological stressors were found to increase spectral power in the tachygastric range (Gianaros et al., 2001; Muth et al., 1999; for conflicting results see Riezzo, Porcelli, Guerra, & Giorgio, 1996; Stern et al., 1991), while the effects on amplitude have been mixed (Riezzo et al., 1996; Stern et al., 1991). In line with the results of stressors, videos evoking disgust were found to evoke tachygastria (Harrison, Gray, Gianaros, & Critchley, 2010) but this result was not replicated (Meissner et al., 2011). Emotions induced by movie clips (or music) most often do not alter the EGG frequency (Baldaro et al., 1996, 2001; Baldaro, Battacchi, Trombini, Palomba, & Stegagno, 1990; Chen, Xu, Wang, & Chen, 2005; Chen et al., 2008; Lin et al., 2007), while results on amplitude are inconsistent (Baldaro et al., 1996, 2001; Chen et al., 2005, 2008; Lin et al., 2007; Vianna et al., 2006). Several studies found increased mean EGG power during the performance of tasks of mental arithmetic (Davis, Berry, & Paden, 1969; Holzl, Schroder, & Kiefer, 1979; Riezzo et al., 1996; for conflicting null finding see Walker & Sandman, 1977), but other studies on mental arithmetic and puzzle-solving reported fewer episodes of large amplitude gastric activity (Ercolani et al., 1982; Ercolani, Baldaro, & Trombini, 1989; Martin, Nicolov, Ormieres, Beloncle, & Murat, 1982). Different factors, like the type of task, or fed versus fasted state of participants, number of participants as well as interindividual variability (Riezzo et al., 1996) might account for discrepancies between different studies. The absence of standardized procedures in psychophysiology for recording and analyzing the EGG might play an additional role (but see e.g., Koch et al., 2000 for reproducibility in the water load test).
In addition to a potential modulation of EGG parameters by descending cognitive influences, ascending influences arising from the stomach were recently shown to influence brain dynamics at rest, with a modulation of the amplitude of the alpha rhythm by the phase of the EGG (Richter, Babo-Rebelo, Schwartz, & Tallon-Baudry, 2017) in the parieto-occipital region. fMRI data reveal that the brain at rest is coupled with the gastric rhythm in an extended cortical network (Rebollo, Devauchelle, Béranger, & Tallon-Baudry, 2018), including known viscerosensitive regions such as primary and secondary somatosensory cortices, as well as the parieto-occipital region where gastric-alpha coupling was observed. Gastric-brain coupling thus appears to play a role in the large-scale organization of brain dynamics at rest. Although little employed so far, the EGG thus appears as an attractive method to study brain-viscera interactions.

1.3  Physiological basis of the EGG

1.3.1  Pacemaker cells and smooth muscles

The stomach mixes ingested food with secretions and grinds it into particles that can be emptied into the duodenum through the pylorus (Figure 2a). The stomach is classically divided into two parts (Koch & Stern, 2004). The proximal stomach consists of the fundus (upper curved part) and the corpus (or body, the main central part of the stomach), which acts as a reservoir and controls intragastric pressure (Tack, 2012). The distal stomach consists of the lower part of the corpus, the antrum, and the pylorus, and is responsible for the mixing, grinding, and emptying of solid food (Kelly, 1980; Rayner, Hebbard, & Horowitz, 2012). The gastrointestinal tract contains two muscular layers that control gut peristalsis: a thin outer longitudinal layer and a thick inner circular layer. Unlike the rest of the organs of the gastrointestinal tract, the stomach has an additional innermost oblique layer of smooth muscles, which allows more refined control of motility patterns (Birmingham, 1898; Christensen & Torres, 1975; Fritsch & Kühnel, 2008).

The stomach wall contains a distinctive type of cells, the Interstitial Cells of Cajal (ICCs), located between the circular and longitudinal muscular layer (myenteric Interstitial Cells of Cajal, ICC-MY) or within the muscular layers (intramuscular Interstitial Cells of Cajal, ICC-IM) (O’Grady, 2012; Sanders, Ward, & Koh, 2014) (Figure 2b). Although ICCs are not neurons (Klüppel, Huizinga, Malysz, & Bernstein, 1998), they display neuron-like properties. Both types of ICCs continuously and intrinsically generate and propagate slow pacemaker currents (for review see Huizinga & Chen, 2014), constituting the basis of the gastric rhythm (Hirst & Edwards, 2006; Sanders, Koh, & Ward, 2006; Sanders et al., 2014). During digestion, the gastric rhythm generated by ICCs triggers smooth muscle contraction with additional inputs from excitatory enteric motor neurons (Sanders et al., 2014) and vagal efferent neurons (Chang, Mashimo, & Goyal, 2003). In addition to their role in slow wave generation, ICC-IM is involved in the transduction of inputs from enteric motor neurons (Hirst & Edwards, 2006; Sanders et al., 2006, 2014). While ICCs control the pace of gastric contractions, enteric motor neurons and vagal efferent neurons regulate the amplitude of contractions. It follows that the frequency of the surface EGG is likely to be related to the intrinsic pacemaker activity of ICCs, while EGG amplitude is related to a combination of currents generated in ICCs, enteric motor neurons, and smooth muscles.

ICCs generate the gastric rhythm and actively propagate the slow waves through the ICC network as well as to

**FIGURE 2** The stomach and the generation of the gastric slow rhythm. (a) Anatomical regions of the stomach, with the main divisions into fundus, corpus, and antrum. The gastric rhythm originates from the pacemaker region (orange) near the greater curvature of the mid/upper corpus. From here, it entrains other pacemaker cells, resulting in traveling rings of electrical wavefronts in the direction of the antrum (O’Grady et al., 2010). (b) The Interstitial Cells of Cajal (ICC, blue) are the generators of the gastric rhythm. They lay in the stomach wall, between and within the circular and longitudinal muscle layers. An additional thin oblique muscle layer located in the innermost part of the stomach, adjacent to the circular layer, is not represented here. The electrical activity of the pacemaker is passed through the entire ICC network and is also passively conducted into coupled muscle cells. ICCs make synapse-like contact with vagal sensory neurons (Powley et al., 2008), presented in green, in a structure known as intramuscular arrays, that can detect mechanical changes in smooth muscles. Adapted from Koch & Stern, 2004.
electrically coupled smooth muscle cells. Rings of electrical wavefronts travel circumferentially in a proximal to distal gradient along the stomach (Koch & Stern, 2004), pushing food toward the pylorus when accompanied by muscular contractions. How wave propagation is orchestrated is not known with certainty. It has since long been assumed that the stomach contains a “dominant pacemaker” area in the greater curvature of the mid/upper corpus, entraining slow waves at other sites, possibly with a gradient in frequency (Hinder & Kelly, 1977; Kelly, Code, & Elveback, 1969; Koch & Stern, 2004; O’Grady et al., 2010; Riezzo et al., 2013).

1.3.2 | Relating cutaneous EGG to gastric physiology

Because the frequency of the gastric rhythm is determined by ICCs’ intrinsic pacemaker activity, cutaneous EGG frequency directly reflects the frequency of the gastric basal rhythm, as revealed by simultaneous cutaneous EGG and inversive recordings in humans (Brown, Smallwood, Dutchie, & Stoddard, 1975; Chen, Schirmer, & McCallum, 1994; Coleski & Hasler, 2004; Familoni, Kingma, & Bowes, 1987; Hamilton, Bellahsene, Reichelderfer, Webster, & Bass, 1986; Lin, Chen, Schirmer, & McCallum, 2000; Mintchev, Kingma, & Bowes, 1993).

The relative contribution of ICCs and smooth muscle contractions to cutaneous EGG amplitude is more difficult to estimate (Angeli et al., 2013; Bayguinov, Hennig, & Sanders, 2011; Hocke et al., 2009; O’Grady, 2012; Stern et al., 2007; Xing, Qian, & Chen, 2006), for two main reasons: First, the electrophysiological signature of smooth muscle contraction is filtered out in cutaneous EGG (Verhagen et al., 1999), and more generally how electrical signals of gastric origin are combined in surface recordings remains to be fully understood (Cheng, Du, & O’Grady, 2013; Du, O’Grady, Cheng, & Pullan, 2010). Second, the amplitude of the gastric rhythm is dependent on the fasting/fed state of the stomach. As a first approximation, one could consider that during digestion the EGG corresponds to a combination of muscle contractions and ICC intrinsic activity, whereas in the fasting state, the stomach is empty and surface EGG mostly corresponds to ICC activity (Smout, Van Der Schee, & Grashuis, 1980). This is the rationale underlying the clinical test comparing pre- and postprandial EGG amplitude. However, even when the stomach is resting as in moderate fasting, a few muscular contractions may occur (O’Grady et al., 2010; Sanders et al., 2014), and occasional intense muscular activity can be observed in prolonged (i.e., overnight) fasting (Koch & Stern, 2004).

Because ICCs are present all along the gastrointestinal tract, cutaneous electrodes might capture the myoelectrical activity of other organs of the GI tract, raising the question of the organ-specificity of the signal. The small intestine displays frequencies that are much higher than the stomach, usually above 0.16 Hz (Christensen, Schedl, & Clifton, 1966; Riezzo et al., 2013; Waldhausen, Shaffrey, Skenderis, Jones, & Schirmer, 1990). The frequency range of the colon is broader, ranging from 2 to 12 cycles per minute in humans (Erickson et al., 2019; Homma et al., 1995; Pezzolla, Riezzo, Maselli, & Giorgio, 1989; Riezzo, Pezzolla, Maselli, & Giorgio, 1994; Taylor, Dutchie, Smallwood, & Linkens, 1975), that is, potentially overlapping in frequency with the gastric rhythm (Amaris, Sanmiguel, Sadowski, Bowes, & Mintchev, 2002; Erickson et al., 2019). Still, numerous studies found that the 3 cpm rhythm disappeared, or was largely reduced, following surgical removal of the stomach but not of the colon (Homma et al., 1995; Imai & Sakita, 2005; Kaiho et al., 2000; Pezzolla et al., 1989).

1.4 | Pathways of gut-brain signaling

There is evidence in the cognitive neuroscience literature that stress or emotions can alter cutaneous EGG frequency or amplitude (Baldaro et al., 1996; Gianaros et al., 2001; Lin et al., 2007; Muth et al., 1999; Stern et al., 1991; Vianna et al., 2006), indicating descending influences from brain to stomach, and that ascending influences, from stomach to brain, influence brain dynamics (Richter et al., 2017). What are the currently known anatomical pathways supporting those interactions? In this section, we present the mechanisms of sensory transduction of the gastric rhythm and ascending pathways up to cortical targets, followed by an overview of descending projections from brain to stomach. Note that much remains to be determined, from signal transduction (Umans & Liberles, 2018) to anatomofunctional pathways (Azzalini et al., 2019). Only very few stomach-specific anatomical tracing studies exist in animals (for a recent example in rodents see Han et al., 2018). Besides, it is tempting to extrapolate from anatomical tracing and/or electrophysiological studies in animals (rodents, cats and monkeys) to humans, on the assumption that visceral pathways are probably ancient and conserved through evolution. However, differences between species have been reported (Bishop, Malliani, & Thorèn, 1983; Pritchard, Hamilton, & Norgren, 2000; Shipley & Sanders, 1982). The overall description presented in this section is drawn from studies in rodents, cats and monkeys, and some pathways may differ in humans.

1.4.1 | Detection of the gastric rhythm and mechanical changes in sensory neurons

The EGG reflects a combination of gastric smooth muscle contractions and of the gastric rhythm generated by ICCs. Both types of signals might be detected in the stomach by
sensory neurons. ICCs make direct synapse-like contact with vagal afferent neurons, also known as intramuscular arrays (Powley & Phillips, 2011; Powley et al., 2008). The gastric rhythm might thus be directly relayed to the brain through vagal afferent neurons, although this has not been directly tested. Experimental work has mostly been devoted to the signaling of gastric smooth muscle contractions. Multiple cell types, including ICCs, are grouped in arborized structures that run along the smooth muscle and act as mechanoreceptors across the gastrointestinal tract, with different sensitivity thresholds and adaptation profiles (Berthoud, Blackshaw, Brookes, & Grundy, 2004; Blackshaw, Brookes, Grundy, & Schemann, 2007; Umans & Liberles, 2018). Those mechanosensory structures continuously sense the contractile state of the stomach and can transmit changes in smooth muscles to the brainstem through vagal and spinal afferent fibers. It is worth underlining that in the vagus nerve, around 80% of the fibers are ascending, indicating the brain is probably more of a listener than a sender of vagal information (Agostoni, Chinnock, De Daly, & Murray, 1957). In contrast, the ratio between efferents and afferents in the spinal splanchnic nerve is closer to 50:50 (Foley, 1948; Leek, 1972).

1.4.2 Vagal and spinal pathways relay gastric information to the brainstem, thalamus, and cortex

Vagal sensory neurons project to the nucleus of the solitary tract in the brainstem, an important relay center for visceral information, that is also involved in the initiation of gastric control reflexes (Azpiroz & Malagelada, 1990). The nucleus of the solitary tract displays a rough viscerotopic organization (Altschuler, Bao, Bieger, Hopkins, & Miselis, 1989), but with local overlap between inputs from the heart and the gastrointestinal tract (Paton & Kasparov, 2000). Visceral afferents are relayed to the parabrachial nucleus (Figure 3, right panel), which integrates vagal and spinal information and is the main relay of visceral information to subcortical and cortical structures (Hylden, Hayashi, Bennett, & Dubner, 1985; Norgren, 1978; Pritchard et al., 2000).

The nucleus of the solitary tract and parabrachial nucleus directly targets the main neuromodulatory centers (Figure 3): the serotoninergic dorsal raphe nucleus, the noradrenergic locus coeruleus, and the dopaminergic substantia nigra and ventral tegmental area (Coizet, Dommett, Klop, Redgrave, & Overton, 2010; Pritchard et al., 2000; Saper & Loewy, 1980). The functional relevance of gastric vagal signaling on the dopaminergic reward pathway has been recently elegantly demonstrated in mice (Han et al., 2018), where stimulation of the vagal sensory ganglion activated self-stimulation behavior, conditioned place preferences, and induced dopamine-release from substantia nigra. The parabrachial nucleus also targets the amygdala, the hypothalamus, and the striatum (Bester, Besson, & Bernard, 1997; Fulwiler & Saper, 1984; Saper, 2002).

Gastrointestinal inputs can reach the thalamus through parabrachial projections or direct spinothalamic pathways. Parabrachial outputs target the ventromedial, reticular, intralaminar, and ventroposterior thalamic nuclei (Coen, Hobson,}
& Aziz, 2012). Spinal and vagal inputs are already combined in the parabrachial nucleus and further convergence takes place in the thalamus. Unexpectedly, the lateral geniculate nucleus, a visual thalamic relay, receives massive inputs from the parabrachial region (Erişir, Van Horn, & Sherman, 1997; Uhlich, Cucchiaro, & Sherman, 1988), and parabrachial activation affects visual responses in the lateral geniculate nucleus (Lu, Guido, & Sherman, 1993; Uhlich, Tamamaki, Murphy, & Sherman, 1995) and cortex (Munk, Roelfsema, König, Engel, & Singer, 1996).

From the thalamus, numerous cortical areas receive visceral inputs (Figure 3), including primary and secondary somatosensory cortex (Amassian, 1951; Downman, 1951), insula (Cechetto & Saper, 1987), ventromedial prefrontal cortex (Vogt & Derbyshire, 2009) and cingulate motor regions (Dum, Levinthal, & Strick, 2009). In rodents, viscerotopy is present in the ventrobasal nucleus of the thalamus and in the insula (Cechetto & Saper, 1987). Although it is known that in humans the somatosensory cortex is coupled with the stomach (Rebollo et al., 2018) and that it responds to heartbeats (Kern, Aertsen, Schulze-Bonhage, & Ball, 2013), whether the somatosensory cortex shows a viscerotopic organization, and how viscerotopy is integrated with somatotopy, has not between investigated since the 50’s (Downman, 1951).

1.4.3 | Descending influences

As reviewed in Section 1.2, gastric amplitude and/or frequency can be modified by cognitive and emotional factors. Indeed, gastrointestinal functioning is regulated by both vagal (Hall, el-Sharkawy, & Diamant, 1986; Stern, Crawford, Stewart, Vasey, & Koch, 1989), or parasympathetic, and spinal, or sympathetic, centers. The main parasympathetic center is the dorsal motor nucleus of the vagus (Gillis, Quest, Pagani, & Norman, 1989), that has descending projections to smooth muscle cells as well as to Interstitial Cells of Cajal (Schemann & Grundy, 1992; Travagli, Hermann, Browning, & Rogers, 2006). The vagal innervation from the dorsal nucleus of the vagus modulates the amplitude of the gastric rhythm and can have either an activating or inhibiting effect (Andrews & Scratcherd, 1980; Pagani, Norman, Kasbekar, & Gillis, 1985; Travagli et al., 2006). The sympathetic efferent nuclei controlling the stomach are located in the intermediotraverse cell column of the thoracic-lumbar spine, and project to prevertebral and paravertebral ganglia located outside the spine (Furness, 2006). In turn, spinal projections innervate enteric neurons, arterioles of the gut wall and striate muscles of sphincters to control vasoconstriction, liquid balance, secretion, blood flow, and motility (Furness, 2012; Holzer, 2006; Sveshnikov, Smirnov, Myasnikov, & Kuchuk, 2012). Sympathetic projections can induce either an inhibition or a stimulation of stomach contractions (Smirnov & Lychkova, 2003; Sveshnikov et al., 2012). Sympathetic projections are modulated by higher level structures, including parabrachial nucleus, nucleus of the solitary tract (Saper & Loewy, 1980), rostroventrolateral medulla (Deuchars & Lall, 2015), raphe nucleus (Morrison, Sved, & Passerini, 1999), locus coeruleus (Bruinsteijn et al., 2012) as well as several hypothalamic nuclei (Deuchars & Lall, 2015).

1.4.4 | Brain-stomach coupling in humans

In humans, pioneering studies identified brain regions coupled with the stomach using gastric distension, induced by inserting and inflating a balloon in the stomach of participants, or, alternatively, by asking participants to drink a specific amount of liquid. Water ingestion can also be used to measure explicit gastric interoception, as recently proposed by van Dyck et al., 2016. Gastric distension activates somatomotor regions, insula, vmPFC and mid-cingulate, and deactivates occipital regions (Ladabaum et al., 2001; Lu et al., 2004; van Oudenhove et al., 2009; Vandenbergh et al., 2005; Wang et al., 2008). More recently, stomach-brain coupling was investigated during the resting state, without gastric stimulation. Rebollo et al., 2018, recorded the EGG in healthy participants during quiet rest, while simultaneously recording brain activity with functional magnetic resonance imaging. They then identified the regions where spontaneous fluctuations in the BOLD signal were phase-synchronized with the gastric rhythm. This revealed an extended network including primary and secondary somato-sensory cortices, mid-cingulate areas, and extended portions of the occipital lobe, indicating that gastric–brain coupling contributes to the large-scale organization of brain activity at rest.

2 | THE EGG: RECORDING, PREPROCESSING, AND DATA QUALITY ASSESSMENT

The aim of this section is to propose practical suggestions to record the EGG in the typical young and healthy population sampled in psychophysical research, as well as a semi-automatized procedure to assess data quality and to extract the gastric rhythm characteristics in terms of amplitude, frequency, and phase. The procedure aims at identifying the gastric rhythm, that is, a regular oscillation in the normogastric range (2–4 cpm). Such a signal can safely be attributed to the stomach, whereas artifacts are likely to disrupt the regularity of the rhythm. It follows that the procedure as it currently stands is not appropriate to investigate departure from normogastria. The procedure reported here is also not designed to analyze the spatial propagation of the gastric waves along the stomach, and we refer the interested reader to Angeli
et al., 2015; Bradshaw et al., 2016; Gharibans, Coleman, Mousa, & Kunkel, 2019; O’Grady et al., 2010, 2012.

### 2.1 Recording apparatus

The EGG is recorded with standard cutaneous electrodes, similar to electrocardiogram electrodes, and standard skin preparation (e.g., slight abrasion of the skin for optimal skin-to-electrode interface contact). EGG amplitude lies typically between 50 and 500 microVolt, commensurate with electroencephalography (EEG). Standard EEG acquisition systems can thus adequately amplify EGG signals, but several additional conditions must be met, due to the very slow pace (~0.05 Hz) of the gastric rhythm. First, DC amplifiers are best suited to record the EGG since even a very low high-pass filter might distort the data. Most recent EEG acquisition systems have the large analog-digital conversion range required for DC recordings without amplifier saturation. Second, recordings have to be long enough to collect a sufficient number of gastric cycles. As a rule of thumb, one minute contains about three gastric cycles, and 15 min correspond to only 45 cycles. Note that it can be useful to acquire some extra data (about 40 s) before and after the period of interest to facilitate off-line filtering at the very low frequency of the gastric rhythm. Last, sources of very slow fluctuations in the recordings have to be minimized. In particular, hanging wires might swing around and induce slow drifts in the recordings and should thus be taped to a fixed support. Wrapping the wires in a shield can limit wire swinging as well as reduce electromagnetic artifacts. Because EGG frequency is around 0.05 Hz, sampling frequency could in principle be very low (below 1 Hz). However, a higher sampling frequency is required for proper artifact identification, in particular, participant’s movements that are accompanied by muscle artifacts.

Participants should obviously have no gastric or digestive disorder. Several medications might influence the EGG, including prokinetic anti-emetic agents, narcotic analgesics, anticholinergic drugs, and anti-inflammatory agents, as well as probiotics and prebiotics (Américo, Miranda, Corá, & Romeiro, 2009; Chiba et al., 2007; Indrio et al., 2009; Walläden, Lindberg, Sandin, Thörn, & Wattwil, 2008). Different recommendations exist in the gastroenterology literature with regards to the inclusion of participants taking these medications (Murakami et al., 2013; Riezzo et al., 2013; Yin & Chen, 2013). A practical solution for psychophysiological studies in healthy participants is to include only subjects without medication.

Another inclusion/exclusion criterion that might prove useful is the body mass index (BMI, Weight (kg)/(Height (m))^2). Participants with a high BMI typically display a lower EGG amplitude (Riezzo, Pezzolla, & Giorgio, 1991; Simonian et al., 2004; Somarajan, Cassilly, Obioha, Richards, & Bradshaw, 2014), potentially because a thicker abdominal wall increases the distance between the electrical source and the recording electrodes and hence results in a lower amplitude recording (Liang & Chen, 1997; Obioha et al., 2016). In addition, people with high BMI show more activity outside the 2–4 cpm range (McCallum, Jones, Lin, Sarosiek, & Moncure, 2001; Simonian et al., 2004; Tolj, 2007), and in morbid conditions, altered gastric emptying (McCallum et al., 2001; Tosetti et al., 1996). In sum, it thus might prove advantageous to include only rather lean participants. In practice, we include subjects with a BMI comprised between 18 and 26. Note that the phase of the menstrual cycle might impact EGG frequency (Parkman et al., 1996; Tolj, 2007) and should thus be documented if the absolute EGG frequency is a parameter of interest.

Studies in gastroenterology focus on the typical EGG amplitude increase following food ingestion, reflecting muscle contractions and gastric motility and other parameters (Stern, Jokerst, Livine, & Koch, 2001; Stern et al., 1989). Another option for psychophysiology is to ask participants to fast for at least 2 hr preceding their appointment (i.e., about 3 hr before the actual beginning of the recording) to focus the analysis on the basal gastric rhythm in an almost empty stomach with little muscular contractions. Only about 10% of a solid meal remains in the stomach 2 to 3 hr after meal ingestion (Vasavid et al., 2014). In any case, the time elapsed since the last meal should be documented and taken into account in the experimental design. Note that details on the contents of pre-fast meal and feeling of hunger at the time of recordings are potentially relevant parameters but were not recorded in this data set.

### 2.2 Participants

#### 2.2.1 Participants’ information and inclusion

Participants are informed early in the inclusion process of electrode location, which implies that their shirt is raised, their skin exposed between navel and sternum, and shaved if too hairy. Participants feeling uncomfortable with the procedure can thus withdraw at that early stage, and are informed that they can withdraw at any time later on. Participants might also feel more comfortable if the experimenter placing the electrodes is of the same gender as the participant. Last, participants are asked to avoid tight-fitting clothes that might potentially touch the electrodes and hence compromise recording quality.

#### 2.2.2 Participants’ position

Most studies in gastroenterology record EGG with the patient in a lying position, which reduces voluntary movements,
although ambulatory EGG recordings are currently being developed (Gharibans et al., 2018). Another advantage of a lying position is that the electrodes rest on the abdominal surface and not in fatty folds (Koch & Stern, 2004). However, a good EGG can also be obtained in a sitting position, although the amplitude is typically a bit lower, most likely due to the distance of the stomach to the skin surface (Jonderko, Kasicka-Jonderko, & Blonska-Fajfrowska, 2005). In practice, we place the electrodes while subjects are in a standing or lying position, thus allowing easier access to anatomical landmarks. After electrodes are placed, we record from participants in a semi-reclined sitting position, as is customary for MEG or EEG recordings, and ask participants to avoid any voluntary movement. Movements induce large artifacts in the recording, and artifacted data segments should be identified and excluded from further analysis (Verhagen et al., 1999).

2.3 | Electrode placement

Unlike electrocardiography, electrode placement in electro-gastrography is not standardized. The stomach is located in the upper left abdomen but the precise location with respect to external landmarks varies (Gharibans et al., 2019). Many clinical studies used between 2 and 4 electrodes. We initially used a 17 electrode grid (Richter et al., 2017), which proved too large, and after some trials and errors found that a grid of seven electrodes provided sufficient coverage to detect a good quality EGG in most participants. The coverage we propose is sufficient to detect a good quality signal in at least one recording location; if the aim of the study is to analyze the propagation of the gastric rhythm along the stomach, a higher density of electrodes and a wider coverage is recommended (Gharibans et al., 2019). Recording locations are illustrated in Figure 4a. The electrode location proposed here deviates from the electrode location reported in the clinical literature (see for instance the review of Riezzo et al., 2013) in that it covers lower portions of the abdomen. In clinical settings, electrodes are most often located in the vicinity of electrodes 2, 3, 5, and 7 in Figure 4 (Chen et al., 1999; Geldof et al., 1989; Koch & Stern, 2004; Mintchev et al., 1993; Parkman et al., 2003; Simonian et al., 2004).

In the proposed setup (Figure 4a) the first electrode (1) is placed 2 cm above the umbilicus. Electrodes 2 and 3 are placed above electrode 1 on the midline, at, respectively, one-third and two-thirds of the distance between electrode 1 and the xiphoid process. The locations of two other electrodes (6, 7) are determined by a vertical line crossing the midpoint of the left clavicle, and horizontally by the locations of electrodes 1 and 2. Note that the electrode 7 location might fall above the rib cage, in which case it is advisable to shift it toward the midline to improve the signal to noise ratio. Finally, electrodes 4 and 5 are placed in between the two columns.

**FIGURE 4** Localization of electrodes with respect to anatomical landmarks (umbilicus, xiphoid process, mid-clavicular line, and coastal margin). (a) Setup for a unipolar montage. The circle area and color code at each electrode location indicate how often this electrode was found to display the largest gastric rhythm, in a sample of 100 healthy participants with a good spectral signature of the gastric rhythm. (b) Setup for a bipolar montage, better suited for fMRI recordings. See text for detailed explanations. REF: Reference. GND: Ground
The EGG can also be recorded in an MRI environment, but it might require the use of bipolar electrodes to avoid amplifier saturation. We used the following scheme (Figure 4b; Rebollo et al., 2018): Four bipolar electrodes are placed in three rows over the abdomen, with the negative derivation placed 4 cm to the left of the positive one. The midpoint between the xiphoid process and umbilicus is identified, and the first electrode pair is set 2 cm below this area, with the negative derivation (1−) set at the point below the rib cage closest to the left mid-clavicular line. The second electrode pair (2+, 2−) is set 2 cm above the umbilicus and aligned with the first electrode pair. The positive derivation of the third pair (3+) is set in the center of the square formed by electrode pairs one and two. The positive derivation of the fourth electrode pair (4+) is centered on the line traversing the xiphoid process and umbilicus at the same level as the third electrode. The ground electrode is placed above the iliac crest (Figure 4b). Note that scanner artifacts are much faster than the gastric rhythm and can easily be filtered out, at least with a standard echo-planar imaging sequence and that the B0 magnetic field of the scanner does not affect EGG frequency (Rebollo et al., 2018).

2.4 | Power spectrum and channel selection

The first step in data analysis is to extract the gastric rhythm. We first present processing steps for a good quality recording and come back to noisy data and artifacts in section 2.6. Spectral power at each electrode is computed to identify the location with the largest activity in the normogastric 0.033–0.066 Hz (2–4 cpm) range and to determine the peak frequency of each participant. Several methods for spectral power estimation can be used. Here, we used a Fast Fourier Transform (FFT) as implemented in the Fieldtrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011) with a Hanning taper to reduce spectral leakage and control frequency smoothing. We provide the relevant code for spectral estimation and other analyses at https://github.com/niwolpert/EGG_Scripts (for computing the power spectrum, see function “compute_FFT_EGG”). As illustrated in Figure 1c, a good quality recording shows a distinctive spectral signature in the normogastric range, with a peak frequency similar at most, if not all, recording sites. The channel with the largest power at peak frequency is selected for further analysis. Note that the spectral signature of the EGG is clearly different from the spectral signatures of either respiration or heartbeats (Figure 1d), and that a harmonic at twice peak frequency might be observed. Peak frequency is usually fairly stable over a couple of hours but might vary over longer recording times (Lindberg, Iwarzon, & Hammarlund, 1996). Power and amplitude might also be extracted from the spectral analysis.

2.5 | Phase and amplitude of the filtered signal

For a more refined, time-resolved analysis of the EGG, the next step is to filter the raw EGG from the selected channel around the participant’s peak frequency to better isolate the gastric rhythm. Several types of filters might be considered, bearing in mind that the very low frequency of the EGG imposes additional constraints on filter design and filter stability. We opted for a finite impulse response filter, known to be more stable and less likely to introduce nonlinear phase distortions (Cohen, 2014), and more precisely a third-order frequency sampling designed finite impulse response filter (MATLAB: FIR2), with a bandwidth of ±0.015 Hz around the participant’s peak EGG frequency (function “compute_filter_EGG”). For instance, if peak frequency is exactly 0.05 Hz (3 cpm), the filter covers the range between 0.035 and 0.065 Hz (2.1 and 3.9 cpm). If peak frequency is 0.035 Hz (2.1 cpm), close to the lower limit of the normogastric range, the filter range is 0.02–0.05 Hz (1.2–3 cpm) and therefore also includes signal outside the normogastric range. Of note, filtering, especially at low frequencies, is difficult, and the actual filter deviates from the ideal filter, with smoother transitions, extending at higher and lower frequencies, as illustrated in Figure 6a. Filter width is designed to be wide enough to capture physiological fluctuations in the duration of the gastric cycle, but narrow enough to exclude not only respiration, but also the harmonic of the gastric rhythm (Verhagen et al., 1999).

By applying the Hilbert transform to the filtered data, we retrieve the instantaneous phase and amplitude envelope of the gastric rhythm. Figure 5 shows two examples of the filtered signal, and amplitude and phase obtained after applying the Hilbert transform. The distribution of cycle duration is usually Gaussian (Figure 5b), with sometimes outliers (Figure 5d), defined as exceeding mean ± 3 SDs. We observed that cycles with abnormally long or short duration also often presented a nonmonotonous phase evolution (inset in Figure 5c).

2.6 | Identification of noisy recordings

We have presented so far good quality recordings. Identifying noisy recordings, or noisy segments of data, is of course
critical. In the following, we suggest some criteria to guide decisions.

2.6.1 | Power spectra

The power spectrum is a good indicator of data quality. As shown in Figure 6a, a high-quality recording shows a clear spectral peak in normogastric range with a peak frequency that is congruent across several channels. We systematically discarded power spectra with variability in peak frequency between electrodes (Figure 6b-e). We also discarded cases where a clear spectral signature is observed, but at only one location, as in Figure 6f. As detailed in Section 3, the power at peak frequency (between 26 and 8,800 µV^2 in our data) does not appear as a reliable indicator of signal quality.

2.6.2 | Identification of participants with highly variable gastric cycle duration

Once the EGG is filtered at the selected channel around peak frequency, we do a second quality check based on the regularity of the cycle durations. We estimated, in each participant, cycle duration from the phase of the Hilbert transform and computed the SD of cycle duration (see function “compute_std_cycle_duration”). The distribution of the SD of cycle duration in the 100 participants we recorded is shown
We retained a criterion of the SD of cycle duration smaller than $6$ to include participants in further analysis. We compared this data-driven procedure with a procedure based on the clinical EGG literature (see function “show_prop_normogastria”), where it is held that EGG recordings in a healthy subject should be composed of at least $70\%$ cycles in the normogastric range ($2–4$ cpm, or cycle duration between $15$ and $30$ s) (Parkman et al., 2003; Riezzo et al., 2013). Bradygastria refers to slow cycles ranging between $30$ and $60$ s ($1–2$ cpm) and tachygastria to short cycles between $6$ and $15$ s ($4–10$ cpm) (Riezzo et al., 2013). We found that those four participants identified as outliers in the distribution of SD of cycle duration (Figure 7a) are also outliers in the percentage of cycles in normogastria and exhibit less than $70\%$ cycles in the normogastric range (Figure 7b). The two criteria thus appear equivalent in this data set.

Note that this processing step is dependent on the filter width (ideal and best fit) used. It is not suited for studies attempting to induce shifts in gastric peak frequency, resulting in a larger variability of gastric cycle duration or even in a shift of gastric peak frequency outside the normogastric range, as when eliciting nausea or disgust (Geldof et al., 1989; Harrison et al., 2010; Meissner et al., 2011; Stern et al., 1985).

### 2.7 Identification of artifacted data segments

Once recordings of overall good quality have been selected, artifacts transiently affecting the data have to be identified. Any type of artifact which involves a movement of the wires or of the abdominal wall might contaminate the signal. This includes for example movement of the legs, abdomen or torso, touching of the electrodes or wires, talking or coughing. Artifacts perturb the signal not only at the exact time of their occurrence, but spread over time given the very low frequency of the filter used.

The procedure we propose to identify artifacted data segments is based on two criteria: a cycle whose length exceeds the mean $\pm 3$ SDs of the cycle length distributions (Figure 5b, d), and a cycle that displays a nonmonotonic change in phase (inset in Figure 5c). This procedure is implemented in the function “detect_EGG_artifacts.” Any cycle meeting at least one of those criteria is considered as artifacted. Note that whether cycles tagged as artifacted by this procedure represent

![FIGURE 6](image-url) Explanations of power spectra of data included in further analysis (a) or discarded (b-f). Each line corresponds to a recording channel, and the spectral region highlighted in white corresponds to normogastria. (a) Power spectrum with a well-defined spectral peak in the normogastric range, occurring in several channels at the same frequency. The star indicates peak frequency and the black line corresponds to the channel with the largest power at peak frequency. The red line represents the ideal filter, and the green line the best fit for the ideal filter. (b) Power spectrum with peaks at different frequencies in different channels. (c) Power spectrum with spectral peaks at two different frequencies. (d) Power spectrum with a broad peak, well defined in only one channel. (e) Several channels display a spectral peak but at different frequencies. (f) A well-defined spectral peak is present, but only in one channel.
real artifacts or truly irregular gastric activity remains an open question.

It is advisable to complement the semi-automated procedure we propose by a visual inspection to confirm artifact detection (Verhagen et al., 1999), but also to verify that the filtering, which can get unstable at very low frequencies, did not induce signal distortion.

2.8 | Conclusion on preprocessing steps

We propose a preprocessing procedure of the EGG consisting of different steps with associated quality checks. All steps aim at identifying a regular rhythm, with a progression in the refinement of the analysis level. This procedure is summarized in Figure 8: In a first step, we decide whether the peak in the power spectrum is clear enough, with a peak frequency consistent between recording sites, to allow for the selection of a channel and a peak frequency. In a second step, the data are filtered and the phase computed, together with the distribution of cycle length. If at least 70% of the cycles lie in the normogastric range, and/or if the SD of cycle length is smaller than 6, the recording is considered to be of sufficient quality, else it is discarded. The last step consists of identifying artificiated data segments, based on cycle duration and phase monotonicity within a cycle.

3 | Normative data and interindividual variability in young, healthy volunteers

Here, we apply the procedures described in Section 2 in a large data set of EGG recordings (N = 117) obtained in
our group, from which normative parameters of the gastric rhythm in a healthy, young, and rather lean population can be derived.

### 3.1 Material

We used the data from 117 healthy participants (52 male, 65 female) sitting in a reclining chair. Participants were aged between 18 and 30 years (mean: 24, $SD = 3.1$) and had a BMI comprised between 16 and 26 (mean: 21.3, $SD = 2.03$). We aimed at recording participants in a moderate fasting state, where stomach contractions are scarce, and thus asked participants to fast for at least two hours before their appointment. One data set ($N = 17$) corresponds to the re-analysis of published data (Richter et al., 2017), the rest corresponds to various unpublished pilot studies. Most participants ($N = 75$, including the participants from Richter et al., 2017) were recorded for 12–15 min at rest with eyes open using the MEG acquisition system of Elekta Neuromag® with a sampling frequency of 1,000 Hz, DC to 330 Hz. EGG data were also recorded in 25 participants performing an experiment on visual perception at a threshold for 12 min, and 17 subjects viewed a short movie (“Bang! You’re Dead” from Alfred Hitchcock, 1961) during 15 min, using a BioSemi acquisition system with a sampling frequency of 2048 Hz, DC to 400 Hz. A subset of 66 participants filled out the Trait Anxiety Inventory (Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983). All participants signed a written informed consent and were paid for participation. The procedures were approved by the Ethics Committee CPP Ile de France III and were in accordance with the Helsinki declaration.

EGG was recorded as described earlier. We used the montage of seven electrodes described above, except in the 17 participants of Richter et al., 2017. Here, we had used a bilateral grid of 19 EGG electrodes (17 active, 1 reference, and 1 ground) placed over four regularly spaced rows, that we subsampled to match the current seven active electrodes schema.

### 3.2 Results

#### 3.2.1 EGG identification in 117 recordings

We applied the procedures described above to the 117 EGG recordings (Figure 8). A well-defined spectral peak within the normogastric range could be observed in 100 participants out of 117 (85%). The BMI of the 100 participants with an identifiable spectral peak ($M = 21.2$, $SD = 2$) was slightly, but significantly, lower than the BMI of the 17 participants where the peak could not be found ($M = 22.3$, $SD = 2$; $t(115) = -1.99$, $p = .049$). We then discarded participants whose gastric rhythm was irregular. Two different criteria could be considered, either a $SD$ of gastric cycle duration larger than 6 (Figure 7a), or less than 70% of cycles in normogastria (Parkman et al., 2003; Riezzo et al., 2013). Those two criteria converged on the same four participants. Overall, our procedure was successful at recording and identifying the gastric rhythm.
rhythm in 82% (96/117) of the participants. Within the 96 remaining participants, 16 come from the study of Richter et al., 2017, and 80 from the new, unpublished data sets. Within the 96 recordings selected, 2.5% of the cycles were identified as artifacted, that is, as having an excessively long or short duration, or as displaying a nonmonotonous change in phase.

### 3.2.2 Electrode selection

For each participant, we identified, within the seven electrode grids, the electrode with the strongest peak in the 0.033–0.067 Hz range and selected it for all further analysis. The location of the selected electrode varied on a participant-by-participant basis, with electrode 1 selected in 14% of participants, electrode 2: 4%, electrode 3: 1%, electrode 4: 14%, electrode 5: 15%, electrode 6: 22%, electrode 7: 30%. Figure 4a shows, for each location in the grid, how often it was selected. The electrode showing the highest peak in the normogastric range was in the lower left abdominal region in more than half of the participants (electrodes 6 and 7) but all locations proved useful in at least one participant.

### 3.2.3 Analysis of gastric frequency, amplitude and cycle duration variability

We then analyzed several properties of the EGG in the 96 remaining participants. Mean dominant EGG frequency was 0.048 Hz (SD = 0.004) (Figure 7c). Female subjects had a slightly higher mean peak frequency than males, but this difference did not survive correction for multiple comparisons (Figure 7c; \( M_{\text{female}} = 0.0486 \) Hz, SD = 0.0044; \( M_{\text{male}} = 0.0467 \) Hz, SD = 0.0039; rank sum test \( z = -2.25 \), uncorrected \( p = .03 \); Bonferroni-corrected \( p = .15 \)). As detailed in Table 1, we found no link between EGG peak frequency and age, BMI, anxiety, time of recording (morning versus afternoon) or elapsed time since the last meal.

The mean average amplitude across participants was 97.3 µV (SD = 70.2) (Figure 7d). None of the demographical variables tested revealed any link with amplitude (Table 1), including BMI.

Last, we estimated fluctuations in EGG frequency by computing the SD of cycle duration. There was a significant positive correlation between longer fasting and higher variation in cycle length (Bonferroni-corrected \( p = .02 \), \( r^2 = 0.09 \); Figure 7e), mostly driven by subjects with an elapsed time since last meal greater than 10 hr. Participants with a large EGG amplitude had more regular cycles, as revealed by the negative correlation between amplitude and SD of cycle length (\( p = .002 \), \( r^2 = 0.1 \); Figure 7f). None of the other variables measured co-varied with the SD of cycle duration.

| Description | Gender (rank sum test) | Age (robust correlation) | BMI (robust correlation) | Anxiety (robust correlation) | Time of recording (rank sum test morning vs. afternoon) | Elapsed time since last meal (robust corr.) |
|-------------|------------------------|--------------------------|-------------------------|-----------------------------|--------------------------------------------------------|--------------------------------------------|
| Mean frequency (Hz) | \( M_{\text{gender}} = 0.0486 \) Hz, SD = 0.0044; \( M_{\text{age}} = 0.0467 \) Hz, SD = 0.0039; rank sum test \( z = -2.25 \), uncorrected \( p = .03 \); Bonferroni-corrected \( p = .15 \) | \( r = .05 \) | \( r = -.14 \) | \( r = -.1 \) | \( r = -.07 \) | \( r = -0.06 \) |
| Mean amplitude (µV) | 97.3 µV (SD = 70.2) | \( r = .05 \) | \( r = -.14 \) | \( r = -.1 \) | \( r = -.22 \) | \( r = .3 \) |
| %normogastria | 96% | \( r = .02 \) | \( r = -.1 \) | \( r = .05 \) | \( r = .05 \) | \( r = .02 \) |
| SD cycle duration | 2.5 | \( r = .002 \), \( r^2 = 0.09 \) | \( r = .02 \) | \( r = -.14 \) | \( r = -.06 \) | \( r = .02 \) |

Note: Bonferroni-corrected \( p < .05 \).
The data came from different experimental conditions (resting state, acquired with a BioSemi system, and various visual tasks, acquired with a BioMag system). No meaningful differences were found between experiments for any of the EGG parameters tested, apart from a difference in EGG amplitude, which might reflect more a difference in gain calibration between the two recording systems rather than on experimental conditions.

3.2.4 | Amplitude in clean versus artifacted data segments

We finally compared EGG amplitude in “clean” versus artifacted cycles, that is, cycles that were either of extreme duration or nonmonotonous. No significant difference in amplitude was found between clean cycles ($M = 96.6 \mu V$, $SD = 86.3$) and cycles of extreme duration ($M = 86 \mu V$, $SD = 51.2$; rank sum test $z = -4$, $p = .67$). Amplitude in nonmonotonous cycles ($M = 40.3 \mu V$, $SD = 39$) was significantly lower than in clean cycles ($M = 96.6 \mu V$, $SD = 86.3$; rank sum test $z = -8.5$, $p < .001$). However, as shown in Figure 9, only a small proportion (20%) of the cycles with very low amplitude were nonmonotonous, and a number of nonmonotonous cycles have a large amplitude.

4 | DISCUSSION

We propose here a procedure for recording and analyzing EGG data, and test this approach in 117 healthy, young, and rather lean male and female participants who had been fasting for at least two hours. The analysis pipeline aims at identifying a regular rhythm that can be safely attributed to the stomach, through multiple steps: by selecting only those participants who have a well-defined spectral signature, with a peak frequency in the normogastric range (2–4 cpm) and regular cycles, and by excluding cycles whose duration exceeds mean $\pm 3 SD$ or whose phase is irregular.

We could identify the spectral signature of the gastric rhythm in 85% of the participants, most often at lower left abdominal locations. The largest amplitude could often be observed at electrodes located lower than usually recorded in clinical settings (Chen et al., 1999; Riezzo et al., 2013). Peak frequency was centered around 0.05 Hz, consistent with the gastroenterology literature, with a marginal difference in peak frequency between female and male participants. The large majority (96%) of the recordings with a clear spectral signature were also regular, with a $SD$ of gastric cycle smaller than 6. The latter criterion proved equivalent to the criterion of 70% of cycles in the normogastric range (2–4 cycles per minute/0.033–0.067 Hz) employed in the clinical EGG literature. The parameter that most influenced the EGG was the time elapsed since last meal, with fasting longer than 10 hr leading to a more irregular rhythm. BMI, anxiety, and age had no noticeable relationship with EGG amplitude, frequency or regularity.

4.1 | Electrode montage

We found that the sharpest spectral signature of the gastric rhythm could most often be found over lower left abdominal regions, that is, locations that are lower than in standard clinical settings (Riezzo et al., 2013; Simonian et al., 2004; Yin & Chen, 2013). This result is in line with recent EGG studies, where electrodes also covered a lower portion of the abdomen, but that were additionally informed, via CT scan analysis, on the precise stomach location and geometry in both patients and healthy controls (Gharibans, Kim, Kunkel, & Coleman, 2017, 2019). Both in the Gharibans et al. studies, and in ours, participants were seated, slightly or half-reclined, thus differing from most clinical studies where a lying position is the norm (e.g., Geldof et al., 1989; Kaneoke et al., 1995; Lin, 1999), potentially leading to a different stomach position. In addition, we used here the reference electrode location commonly advocated in the clinical literature (Chen et al., 1999) over the upper right abdominal location, which might contribute to observing larger EGG amplitudes more often at the lower left location. While distance to reference electrode might contribute to EGG signal amplitude, it is unlikely to be the only determinant, for two reasons. In some participants, the largest EGG amplitude was detected close to the reference (i.e., electrodes 2 and 3). Conversely, the electrode where the largest EGG amplitude is most often detected (#7) is not the electrode the furthest away from the reference electrode. Note that reference-free EGG data can be obtained by a higher density coverage and the surface laplacian transform (Gharibans et al., 2017).
Still, it is important to bear in mind that electrodes at lower locations might be more likely to record not only from the stomach, but also from other organs of the GI tract (Amaris et al., 2002; Erickson et al., 2019). While the rhythmic activity of the small intestine is at higher frequencies, the frequency range of the colon is broader, covering the frequency range between 0.03 and 0.13 Hz (Amaris et al., 2002; Erickson et al., 2019; Homma et al., 1995; Pezzolla et al., 1989; Riezzo et al., 1998), or even up to 0.2 Hz (Taylor et al., 1975). The frequency range of the colon is broader, covering the frequency range between 0.03 and 0.13 Hz (Amaris et al., 2002; Erickson et al., 2019; Homma et al., 1995; Pezzolla et al., 1989; Riezzo et al., 1998), or even up to 0.2 Hz (Taylor et al., 1975). The frequency range of the colon and of the stomach might thus overlap, but the spectral signature of the stomach seems more narrow-band than the spectral signature of the colon. It is thus important to couple the use of the low electrode montage we advocate with strict criteria to identify the spectral signature of the stomach in the recordings.

4.2 Data set selection based on spectral analysis and percentage in normogastria

The best evidence for gastric activity is a sharp spectral signature with a peak within the normogastric range. We retained two criteria: the sharpness of the spectral peak, and its presence at several recording locations. Applying those criteria in a rather strict manner led to discarding 18% of the participants, which is quite a large proportion, but this conservative approach should guarantee a large contribution of the gastric rhythm to the recorded signal. This first processing step could, and should, be improved in the future by finding a more quantitative approach to characterize the spectral signature.

The absence of the spectral signature of the gastric rhythm in EGG spectra can be attributed to various reasons. The signal might be too small because the stomach is too far away from the selected recorded locations, either because of an unusual stomach position or because abdominal fat increases the distance between stomach and electrode (Chen et al., 1999; Liang & Chen, 1997). Although participants with high BMI (above 26) are more likely to have more abdominal fat and to display a lower EGG amplitude (Riezzo et al., 1991; Simonian et al., 2004; Somarajan et al., 2014), we do not observe a link between EGG amplitude and BMI. However, participants without an EGG spectral peak had a higher BMI than participants with a spectral peak. This might indicate that abdominal fat can decrease the signal-to-noise ratio to the point that the gastric rhythm can no longer be detected. However, if the gastric rhythm can be detected, its amplitude and frequency do not depend on BMI, at least in the restricted BMI range explored in our sample. Signal to noise ratio might also be compromised because of artifacts, in particular, due to movement of the abdominal wall or of wires. Additionally, the gastric rhythm might be disorganized and hence display a blurred spectral signature, even in healthy participants which were screened for gastrointestinal pathologies.

After assessing power spectra, we quantified the regularity of gastric cycles using two independent approaches (SD of gastric duration smaller than 6 or 70% of cycles in normogastria), that converged and identified the same four participants with irregular EGG, out of 100. Note that the criteria on spectral signature are somewhat redundant with the criteria on cycle regularity. Indeed, irregular cycles are likely to result in a wide spectral peak, while we selected recordings with a well-defined spectral signature.

4.3 Data segment selection

To the best of our knowledge, there is currently no standard for artifact rejection in EGG recordings, although some new methods are being developed for ambulatory recordings (Gharibans et al., 2018). Here, we chose to discard gastric cycles, that is, data segments of about 20 s, if the cycle was excessively long or short or if the phase displayed a nonmonotonous evolution within a cycle. Participants with a large EGG amplitude also had more regular cycles. At the single-subject level, nonmonotonous cycles were more numerous when amplitude was low, but could be also observed in data segments with large amplitude. In other words, while there is a link between amplitude and cycle regularity, there is no one-to-one correspondence. It is important to underline that we do not know whether the cycles we discard represent artifacts (motion, electrical noise, …) accompanied with signal loss or a true irregularity of the gastric rhythm. Our procedure aims at extracting a regular rhythm that can be safely assumed to reflect the gastric rhythm. It is obviously unsuitable for clinical studies or cognitive studies in which irregularities of the gastric rhythm are of interest (see, e.g., Harrison et al., 2010).

4.4 Factors affecting EGG peak frequency, amplitude, and cycle duration variability

We found that women showed on average a slightly higher peaking frequency than men, a difference that was small and not strong enough to survive correction for multiple comparisons. This is in line with two previous studies (Parkman et al., 1996; Tolj, 2007) in comparably large sample sizes ($N = 83$ and $N = 120$). No effect was detected in smaller samples of adults (Paffenbach et al., 1995; Simonian et al., 2004) or in children (Riezzo et al., 1998). We did not document the phase of the menstrual cycle, which might impact EGG activity, although different studies yielded contradictory results (Parkman et al., 1996; Paffenbach et al., 1995; Tolj, 2007). Age was not related to EGG peak frequency, amplitude or
cycle length variability, in line with previous studies investigating this age range (18–30 years) (Parkman et al., 1996; Pfaffenbach et al., 1995; Riezzo et al., 1991; Shimamoto et al., 2002; Simonian et al., 2004; Tolj, 2007). Note that our data set stems from a quite homogenous population: We did only include participants with a BMI range comprised between 18 and 26 and with an age between 18 and 30 years. EGG parameters are altered for higher values of BMI (Simonian et al., 2004; Tolj, 2007) or age (Parkman et al., 1996; Pfaffenbach et al., 1995; Riezzo et al., 1991; Shimamoto et al., 2002; Simonian et al., 2004; Tolj, 2007).

As time elapsed since the last meal increased, the EGG became more irregular. The correlation was mostly driven by participants having had their last meal more than 10 hr before the recording, that is, participants who had skipped breakfast. This suggests that in order to increase the chance of recording a regular signal, it might be recommended to ask participants to have a meal 2 to 4 hr before the recordings. This finding might potentially be linked to the observation that during very prolonged fasting (typically overnight), the stomach shows transient periods of strong contractions (also called the “phase III of the interdigestive complex”—Koch & Stern, 2004), which could impact the stability of the EGG. Combined with the classical finding that EGG amplitude increases right after a meal, these results emphasize the importance of taking into account the time elapsed since last meal in the experimental design (for instance by counterbalancing the order of presentation of different conditions between participants) and data analysis (for instance by adding time elapsed since last meal as a regressor).

Note that we restricted the analysis to a subset of EGG parameters (peak frequency, amplitude, cycle duration variability, percentage normogastria). Other parameters of interest, not studied here, are related to departure from normogastria (see e.g., Koch & Stern, 2004; Riezzo et al., 2013; Yin & Chen, 2013).

4.5 Conclusion: strengths and limitations

We propose here a full pipeline to record and analyze the EGG of young, healthy, and rather lean participants in a moderate fasting state, and validate it in a large data set. The pipeline aims at identifying a rhythm with a peak frequency between 0.033 and 0.067 Hz (2–4 cpm), and regular enough over time, so that it can safely be attributed to the stomach. It follows that we do not investigate lower or higher frequencies, for lack of criteria to discriminate signal from noise (Verhagen et al., 1999) and that the procedure we propose is not well suited for psychophysiological studies targeting large changes in gastric rhythm frequency, such as nausea, disgust, and stress. The procedure is also not suitable for investigating the spatial propagation of gastric slow wave along the stomach, and we refer the reader to other approaches (Angeli et al., 2015; Bradshaw et al., 2016; Gharibans et al., 2019; O’Grady et al., 2010, 2012).

The pipeline depends on the definition of the normal range of the gastric rhythm, an issue that is not fully resolved in the clinical literature (Chang, 2005; Parkman et al., 2003). This pipeline allows to estimate the duration of each gastric cycle, thereby providing a finer temporal resolution than approaches based on running spectral analysis (Stern et al., 2007). Gastric cycle duration estimation is dependent on the design and width of the filter used for analysis, which should be wide enough to capture physiological fluctuations of the gastric rhythm but narrow enough to exclude contaminating sources. Finally, the procedure is only semi-automatized. Visual inspection is still required to detect large artifacts before any processing, to select power spectra satisfying all criteria, and to verify the quality of the filtering process.

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CONFLICT OF INTEREST

The authors declare that no competing interests exist.

CUSTOM CODE

The custom code used for this article can be accessed online at the following address: https://github.com/niwolpert/EGG_Scripts

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