Examining the Role of Carbonation and Temperature on Water Swallowing Performance: A Swallowing Reaction-Time Study

Emilia Michou, Aliya Mastan, Saira Ahmed, Satish Mistry and Shaheen Hamdy

School of Translational Medicine—Inflammation Sciences, University of Manchester (part of the Manchester Academic Health Sciences Centre (MAHSC)), Salford Royal Hospital, Eccles Old Road, Salford M6 8HD, UK

Correspondence to be sent to: Shaheen Hamdy, School of Translational Medicine—Inflammation Sciences, Faculty of Medical and Human Sciences, University of Manchester (part of the Manchester Academic Health Sciences Centre (MAHSC)), Salford Royal Hospital, Eccles Old Road, Salford M6 8HD, UK. e-mail: Shaheen.hamdy@manchester.ac.uk

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Abstract

Various therapeutic approaches for dysphagia management are based on modifications of bolus properties to change swallowing biomechanics and increase swallowing safety. Limited evidence exists for the effects of carbonation and bolus temperature on swallowing behavior. Here, we investigated the effects of carbonation and temperature on swallowing behavior using a novel automated and complex swallowing reaction time task via pressure signal recordings in the hypopharynx. Healthy participants (\(n = 39\), 27.7 ± 5 years old) were randomized in two different experiments and asked to perform 10 normal-paced swallows, 10 fast-paced swallows, and 10 challenged swallows within a predetermined time-window of carbonated versus still water (experiment 1) and of cold (4 °C) versus hot (45 °C) versus room temperature (21 °C) water (experiment 2). Quantitative measurements of latencies and percentage of successful challenged swallows were collected and analyzed nonparametrically. An increase in successfully performed challenged swallowing task was observed with carbonated water versus still water (\(P = 0.021\)), whereas only cold water shortened the latencies of normally paced swallows compared with room (\(P = 0.001\)) and hot (\(P = 0.004\)) temperatures. Therefore, it appears that chemothermal stimulation with carbonation and cold are most effective at modulating water swallowing, which in part is likely to be driven by central swallowing afferent activity.

Key words: carbonation, reaction time task, swallowing, temperature

Introduction

Peripheral sensory information from the oropharynx is important for the timely execution of voluntary swallowing (Jean 1984; Martin and Sessle 1993; Steele and Miller 2010). The afferent inputs from sensory receptors in the oral cavity, epiglottis, laryngeal, and pharyngeal areas, mediated by the trigeminal, glossopharyngeal, and vagus nerves, converge to Nucleus Tractus Solitarius of central pattern generator and higher cortical centers in the brain. This ensures that swallowing is directly modulated through peripheral feedback whereas cortical centers provide the motor plan for any adaptation required to accommodate different boluses’ parameters via stimuli from the periphery for the safe and successful swallowing performance.

Altering the properties of peripheral stimuli has been one of the impetuses for the formulation of various rehabilitation techniques in rehabilitation regimes for the dysphagic patient (cold mechanical stimulation at faucial pillars [Lazzara et al. 1986; Rosenbek et al. 1998], modified bolus viscosity [Dantas et al. 1990; Perlman et al. 1993], carbonation [Bulow et al. 2003; Miura et al. 2009], usage of different tastants [Hamdy et al. 2003; Leow et al. 2007; Yahagi et al. 2008; Humbert and Joel 2011]). Various physiological and neuroimaging techniques have also been applied to study how different bolus parameters affect swallowing, such as bolus volume, viscosity, taste, temperature, and repetition. However, bolus parameters such as carbonation and temperature have not been systematically investigated.

Earlier evidence showed that carbonation may increase the somatosensory perception by adding chemesthetic stimulation to the flavour/texture experience during water swallowing (Dessirier et al. 2000).
Various outcome measures have been used to investigate the effects of carbonation and temperature on swallowing mechanism, such as videofluoroscopy (Bisch et al. 1994; Cola et al. 2010), EMG applied on neck musculature (Ding et al. 2003; Selekou et al. 2007), and assessments of swallowing efficiency (Bove et al. 1998; Hamdy et al. 2003). More recently, some studies have investigated the effects of carbonation on swallowing biomechanics and safety in dysphagic patients (Bulow et al. 2003; Sdavou et al. 2011).

In the absence of definitive evidence for the exact underlying mechanism responsible for the effects of carbonation and/or different effects of hot and cold temperature on water swallowing behavior, it would be of interest to investigate the effects of these parameters on swallowing performance using a robust and reliable measure of swallow function. One such method is the timed swallowing reaction task.

Reaction time tasks have been utilized for more than a century in psychological experiments and lately in motor-training experiments (Miller and Low 2001). With regard to volitional swallowing, one has to consider the fact that it is a complicated sensorimotor task requiring the recognition of the stimuli, the processing and planning of the motor action, the volitional coordination of respiration and swallowing, and the immediate reaction of musculature to peripheral stimuli at a specific time. The swallowing reaction time paradigm, described initially by Mistry and colleagues (Mistry et al. 2007), incorporates all above characteristics of the reaction task. It has also been used in various studies (Jefferson et al. 2009; Jayasekeran et al. 2010; Michou et al. 2012) in order to observe changes in swallowing performance following rehabilitative neurostimulation paradigms and has been shown to have excellent intraindividual reliability (Murphy et al. 2009).

Aims

Using a swallowing reaction time paradigm, we aimed to systematically investigate whether carbonated liquids can affect swallowing performance compared with still water and to test further whether water temperature plays a role in the execution of swallowing response in young healthy participants.

We hypothesized that the increased somatosensory input of carbonated water would provoke changes in swallowing reaction tasks compared with still water. In addition, cold and hot water boluses would differentially modify swallowing latencies compared with room temperature water, with the cold water resulting in quicker swallows and an increase in the number of successful challenged swallows.

Materials and methods

Participants

No significant illnesses were reported by the healthy participants, whereas their general practitioners were informed of their participation prior to the commencement of the study. Written informed consent was obtained from all participants before the experiments. The exclusion criteria included any history of swallowing problems, significant medical disorders, pregnancy, or use of medication that acts on the central nervous system. The research protocols were approved by Wrightington, Wigan and Leigh Research Ethics Committee, and all experiments were undertaken in the clinical laboratories of the Gastrointestinal Sciences at Salford Royal Hospital NHS Trust, England, in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). A total of 39 healthy participants were investigated, all of whom consented to participate in the experiments, and assigned to the two different protocols in a random order, with no cross-overlap in participation.

Swallowing reaction time paradigm

Participants were requested to swallow a 3-mm intraluminal catheter with built-in pressure transducer between a pair of platinum ring electrodes (Gaeltic Ltd). The manometric catheter was inserted according to the established pull-through technique, which allows for direct assessment for the upper esophageal sphincter’s resting pressure when passed in the oropharynx. The catheter then was pulled 2.5–3 cm aborally, so that it lay in the midpharyngeal region. The catheter was inserted either orally (13–15 cm) or nasally (15–17 cm) depending on the subject’s preference. Additional care was taken to have the pressure transducer with a posterior orientation of the sensors and then the catheter was securely taped to the lip of the nose of the participant to minimize catheter displacement during swallows. Similar to previous studies (Mistry et al. 2007), the catheter was connected to a desktop computer running the Visual Basic software, via a pressure measurement interface (Department of Medical Physics, Salford Royal Hospital NHS Trust). Signals were digitally converted, monitored, and stored in a laboratory desktop. Solid gel, cloth-backed disposable skin electrodes (H69P, Tyco Healthcare) were placed, 2 cm apart, to the dorsum of each volunteer’s hand and used to deliver an electrical pulse (cue) to the subjects. The subjects were asked to perform swallows of 5-mL boluses of the liquids delivered into the mouth via a plastic catheter connected to a hand-held syringe.

Swallowing reaction time (SRT) was calculated as the latency between the delivery time of the electrical cue to the onset of the pharyngeal swallow, registered via the pressure signal crossing a predefined pressure threshold (~50% of the pressure amplitude to six single calibration swallows). The subjects had to swallow the different boluses following electrical cues delivered to the thanar muscle as follows: (a) at their own pace (termed normal swallows), (b) predetermined 150-ms time-window (challenged swallows), calculated from the difference in the latencies of the normal and fast swallows according to the formula:
Challenge Time Window = Fast SRT + \{[\text{Normal SRT} − \text{Fast SRT}]\} + 75 ms.

If the subjects performed a swallow prior to the electrical cue, then these data were discarded.

The electrical cue on the hand was delivered by an electronic pulse generator (Digitimer model DS7) set to trigger at 7-s intervals. Data recording took place within 3 s after the electrical cue and this was followed by a rest period (2 s). Afterward and within 1 s, the 5-mL boluses were delivered and the participants had to hold the bolus in their mouth for 1 s prior to the trigger electrical cue. The SRT and the successful and unsuccessful challenged swallows were recorded by “Swallow Splash” Software (Department of Medical Physics, Salford Royal Hospital NHS Trust) for further off-line analysis.

Liquid preparation

Carbonated water

Carbonated water was prepared by the investigators prior to each study, by adding 8 mg of CO₂ from a canister in 1-L water in a commercially available soda maker (iSi, Siphon Soda-Seltzer maker), which keeps the water under constant temperature (4°C), pH (4.1), and pressure (~60 bars/900 psi, resulting in 9 bars working pressure in a 1-L bottle). Therefore, the product of carbonated water was free of additional elements existing in commercially purchased soda beverages.

Temperature of water solutions

Three different glass containers of 1-L water were prepared prior to the study at three different temperatures: (a) room (21°C), (b) cold (4°C), and (c) hot (45°C) temperature. These temperatures were chosen based on the existing literature. The temperatures in the glass containers were constantly checked with lab thermometers throughout the study. If the temperature changed during an ongoing trial, another member of the research team who was present during the study immediately changed the water with another identical container with solution at the correct temperature.

Experimental protocols

Protocol 1: Investigating the effects of carbonation on swallowing performance

Twenty healthy participants (13 male; mean age 25.7 ± 5.87 years [± standard error of the mean ±SEM]) were asked to attend the laboratory for a single visit. The participants sat comfortably in a reclining chair with the catheter in situ. The subjects were asked to perform 10 normal swallows (normally paced swallowing), 10 fast swallows (swallowing as fast as possible), and 10 challenged swallows (swallowing within a challenging time-window) for two sessions each of carbonated (condition A) and still water (condition B) presented in a pseudorandomized order (ABAB, BABA, etc.). There was a 5-min rest period between each block of swallows to avoid washout effects. All the measurements for the swallowing reaction times paradigm were recorded as described in the “experimental procedures.”

Protocol 2: Investigating the effects of temperature on swallowing performance

Nineteen healthy participants (9 male, mean age 29.7 ± 3 years, ± SEM) were asked to attend the laboratory for a single visit. The participants sat comfortably in a reclining chair with the catheter in situ. The subjects were asked to swallow 5-mL boluses of either cold (4°C), hot (45°C), or room temperature (21°C) water, whereas performing 10 normal swallows, 10 fast swallows, and 10 challenged swallows. Each block of (total 30) swallows in each temperature was repeated twice in a pseudorandomized manner for all temperatures within the same visit. Participants were instructed to rest for 5 min between each block of 30 swallows to allow for normalization of mouth temperature back to body temperature.

Figure 1 shows the two experimental protocols, whereas Figure 2 presents the experimental set-up procedures for the different swallowing tasks (identical for protocols 1 and 2).

Randomization and data analysis

Pseudorandomization was carried out for the delivery of all boluses for both protocols for all subjects’ visits using the block randomization option of the statistical software StatsDirect (Version 2.7, StatsDirect Ltd). Two members of the team performed the recordings (baseline and follow-up) and the intervention. All research data sets were anonymized.

Nonparametric tests and intraclass correlation (ICC, single measures) for the different groups of data in each protocol were used to investigate variability and agreement across the measurements of the different study runs. The grand mean for each condition (carbonation vs. still water in protocol 1 and cold vs. hot vs. room water temperature in protocol 2) were calculated. The effects of the familiarity, practice, variability associated with fatigue, and carryover effects of respiratory cycle were controlled because each subject served as their own control and an average value for each of 10 trials on each condition was calculated. The statistical analyses were performed using SPSS 16 (SPSS Inc.). Nonparametric Friedman’s tests were performed for each of the “normal,” “fast,” and for a percentage of the successful “challenged” (correctly timed) swallows. Where comparisons were made between single data points, this was performed using nonparametric Wilcoxon’s test. \( P \) values of less than 0.05 were taken as a measure of statistical significance and data are expressed as mean (±SD) unless stated otherwise.
Figure 1  Protocols 1 and 2 of the study (SRT: swallowing reaction time).

Figure 2  Schematic illustration of the methodology of swallowing reaction time tasks for the normal, fast and challenged swallows. For the latter swallows the individuals had to swallow with the predetermined 150 ms target window for the swallow to be successful.
Results

The effects of carbonation on swallowing performance

The mean values of each run of different boluses (carbonated and still water) in each condition (normal, fast, and challenged swallows) are presented in Table 1.

Normal swallowing reaction times

ICC between the two identical still water swallowing trials indicated almost perfect agreement (0.936, 95% confidence interval [CI]: 0.909–0.985), whereas for the trials with carbonated water the identical repetitions were in excellent agreement as well, ICC reaching 0.938 (95% CI: 0.849–0.975). For still water boluses, the grand mean of SRT for the latencies of normal swallows was 1995 ± 483.7 ms (mean ± SD) and 2026.8 ± 472 ms (mean ± SD) for carbonated boluses. Nonparametric test (Wilcoxon’s test) showed no significant difference between carbonated and still water latencies of the normal swallows (z = 0.672, P = 0.50).

Fast swallowing reaction times

ICCs between the two fast-swallowing trials indicated almost excellent agreement between the measurements for both still water (0.872, 95% CI: 0.705–0.947) and carbonated solutions (0.831, 95% CI: 0.621–0.929), whereas the grand mean values were 886.45 ± 64.76 (±SD) and 879.46 ± 65.62 (±SD), respectively. Similar to the results for the normal swallows, there was no statistical difference between carbonated and still water fast swallows (z = 0.033, P = 0.737).

Challenged reaction swallowing tasks

Figure 3 shows the difference in grand mean successful challenged swallows between still and carbonated water. The number of successful trials achieved out of 10 swallows was used to calculate the percentage of successful challenged swallows. ICCs calculated between the repeated trials with still water reached good agreement (ICC: 0.583, 95% CI: 0.088–0.768) with a grand mean success rate of 31.25 ± 15.88% (±SD). Success rate was improved with carbonated water and reached 39.5 ± 16.38% (mean ± SD), with the values showing a strong agreement between the two identical trials (ICC: 0.651, 95% CI: 0.375–0.867). The increase in the number of successful challenged swallows for carbonated water was statistically significant (z = 2.308, P = 0.021).

The effects of temperature on swallowing performance

The grand mean values of each run with still water boluses of different temperature (cold, room, and hot temperature) in each condition (normal, fast, and challenged swallows) are presented in Table 2.

Normal swallowing reaction times

Agreement between the repeated trials with boluses of different temperatures (cold, room, and hot temperature) was

Carbonated water increased the number of successful challenged swallows compared with still water (*z = 2.308, P = 0.021).

Table 1  Mean and grand mean latencies (mean ± SEM) for repeated trials for normal and fast swallows and successful challenged swallows (%) with carbonated and still water swallows by young healthy adults

<table>
<thead>
<tr>
<th>Swallow type</th>
<th>Water swallow condition</th>
<th>Study 1</th>
<th>Study 2</th>
<th>Grand means</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Carbonated</td>
<td>2031±110</td>
<td>2022±108</td>
<td>2026.8±8472</td>
</tr>
<tr>
<td>Fast (ms)</td>
<td>Still</td>
<td>933±65</td>
<td>839±69</td>
<td>886.45±64.29</td>
</tr>
<tr>
<td></td>
<td>Carbonated</td>
<td>902±75</td>
<td>855±62</td>
<td>879±65.62</td>
</tr>
<tr>
<td>Challenged swallows (%)</td>
<td>Still</td>
<td>28.5±3.27</td>
<td>34±4.99</td>
<td>31.25±15.88</td>
</tr>
<tr>
<td></td>
<td>Carbonated</td>
<td>33.5±3.93</td>
<td>45.5±4.32</td>
<td>39.5±16.38</td>
</tr>
</tbody>
</table>

Carbonated water increased the number of successful challenged swallows compared with still water (*z = 2.308, P = 0.021).
excellent. For the room temperature, ICC was 0.766 (95% CI: 0.492–0.903), whereas for the hot water bolus, ICC was 0.65 (95% CI: 0.683–0.946) and for cold water boluses 0.834 (95% CI: 0.626–0.932). Compared with the latencies of normal swallows with room temperature water (grand mean: 1594 ± 79 ms, ±SD) and hot water (1545 ± 87 ms, ±SD), the latencies of normal swallows with cold water (1390 ± 80, ±SD) appeared shortened. The three bolus temperatures were thus compared with Friedman’s nonparametric test. Friedman’s chi-square was 15.1 and a P value of 0.001 suggested that the distributions of the latencies with the different temperatures were different. Nonparametric Wilcoxon’s test revealed a significant difference between the latencies of cold and room temperature water swallows (z = −3.4, P = 0.001) and cold and hot water swallows (z = −2.9, P = 0.004), but no significant difference between room and hot temperature swallows latencies (z = −0.523, P = 0.601).

Fast swallowing reaction times

The ICCs of the two runs within the specific conditions (cold, room, and hot temperature) again indicated excellent agreement (cold: ICC: 0.836, 95% CI: 0.627–0.933; hot: ICC: 0.715, 95% CI: 0.398–0.879; room: ICC: 0.779, 95% CI: 0.518–0.908). Similarly to normal swallows, shorter latencies were numerically apparent for cold water (1058 ± 61 ms) compared with hot (1112 ± 59 ms) and room temperature water (1125 ± 57 ms) for the fast-paced swallows. However, the distributions of the latencies of the fast different temperatures boluses were not different (Chi-square: 2.427, P = 0.297, Friedman’s nonparametric test).

Challenged reaction swallowing tasks

The agreement between the success rate of the two trials for the different temperatures was less good compared with normal and fast swallow and showed only a fair agreement for room temperature (ICC: 0.427, 95% CI: −0.021 to −0.732) and hot water (ICC: 0.364, 95% CI: −0.733 to −0.122) but poor agreement for cold water (ICC: 0.231, 95% CI: −0.232 to 0.622). Cold bolus challenged swallows appeared to be less accurately performed (29.5 ± 3%, ±SD) compared with challenged swallows with room temperature boluses (38.9 ± 3%, ±SD) and hot temperature boluses (38.2 ± 3%, ±SD). However a Friedman’s chi-square showed no evidence that the distributions of the successful swallows of three different temperatures were different (chi-square: 3.5, P = 0.171).

Discussion

This study set out to investigate the effects of carbonation and different temperatures on swallowing performance with the use of a swallowing reaction times paradigm. In both experiments, the agreement between the repeated trials for the same boluses was generally strong. Partially supporting our hypothesis, carbonated water increased the number of successful swallows in the challenged swallowing tasks, whereas no difference was observed for the latencies of the normal and fast swallows between carbonated and still water. Moreover, for both carbonated and still water swallowing, there was an absolute increase in the number of successful swallows in the repeated trial for each solution (Table 1); however, this increase was not significantly different compared with the absolute individual values from the initial trials, because both trials showed good agreement. Thus, any concurrent habituation of the experimental procedures did not play a role in the results. With regard to temperature, swallowing latency to normal swallows was decreased with cold boluses, but there was no effect on fast or challenged swallows, whereas hot water did not affect the responses on
swallowing reaction time tasks. Our results merit further discussion.

The effects of carbonation on swallowing performance

Taking into consideration that swallowing latencies for the normal and fast swallows did not differ between carbonated and still water, yet carbonation increased the ability to score successfully in the challenged swallowing tasks, it seems reasonable to assume that the effects of carbonation are more noticeable when the swallowing system is stressed in an experiment featuring a challenge.

In the literature, beneficial effects of carbonation were observed only in dysphagic population (Jennings et al. 1992; Bulow et al. 2003; Sdravou et al. 2011) examined with videofluoroscopy for penetration/aspiration scores and specific transition stage bolus timings, that is pharyngeal transit times. Studies performed with healthy subjects for the effects of carbonation did not show any significant effects (Ding et al. 2003; Plonk et al. 2011). Ding et al. (2003) did not find any significant effect of 5-mL carbonated boluses on the amplitude and duration of the submental EMG, whereas no change on swallowing apnea duration was noted with chemesthetic perception in women (Plonk et al. 2011). It is therefore not surprising that we failed to observe any difference for the latencies of the normal and fast swallows between the carbonated and still water swallows in our healthy young population.

Mechanistically, there is evidence that multiple systems are responsive to CO₂, such as chemoreception for respiration regulation (Lahiri et al. 2001), olfaction (Hu et al. 2007), and nociception (Simons et al. 1999; Dessirier et al. 2001). More importantly, recent literature findings show that the taste system is responsive to carbonation (Chandrashekar et al. 2009). The conversion of CO₂ to carbonic acid in carbonated water, a reaction catalyzed by carbonic anhydrase, leads to activation of lingual nonciceptors which excite trigeminal neurons, involved in signaling oral irritation to higher centers (Cowart 1998; Dessirier et al. 2000). The recent animal studies (Chandrashekar et al. 2009) showed that sour cells on the tongue provide the cellular sensors for carbonation. It has therefore been postulated that carbonation seems to act not only on the taste system but also in other orosensory pathways (Komai and Bryant 1993; Simons et al. 1999). If this assertion is correct, then carbonation may be in part producing its effects through changes in higher centers involved in swallowing and taste, and given the central brain regions overlap (Small et al. 1999; O’Doherty et al. 2001), such cortical involvement might help explain why only challenged swallows were affected.

Indeed, similar changes in challenged swallows with the same swallowing reaction time paradigm have been observed following the excitatory peripheral pharyngeal electrical stimulation (Jayasekeran et al., 2010) and following the combination of the peripheral and cortical stimulation (Michou et al. 2012). Thus, our data support the notion that like pharyngeal stimulation and cortical stimulation, carbonation is altering (complex) swallowing through a centrally mediated mechanism that is likely to be driven by afferent stimulation.

The effects of temperature on swallowing performance

Interestingly, normal swallows with cold water were performed more quickly (shorter latencies) compared with the latencies of hot and room temperature water. The documented effects of temperature on oropharyngeal swallowing in humans are somewhat heterogeneous (Lazzara et al. 1986; Bisch et al. 1994; Shaker et al. 1994). Physiologically, it has been observed that the cold receptors have a receptive field of 1 mm or less and are within 200 microns of the tongue surface, whereas innervated by the smallest myelinated fibers (Hensel and Zotterman 1951; Zotterman 1953; Hensel and Boman 1960). However, the receptive fields for both warm and cold stimulus in the oral cavity, pharynx, and larynx are not equally efficacious in evoking pharyngeal swallowing (Storey 1968a, 1968b). It is also documented that in the CNS, cold temperature neurons predominate in the medulla (Hutchison et al. 1997). Further evidence has shown that in discriminative sensation testing, the laminar-I neurons carry temperature signals to the final insular cortex “with one or two relays” (Romanovsky 2007).

Therefore, it is reasonable to contend that oral sensory information could be altered by different temperatures. It seems that cold boluses have probably increased oral awareness for the normal swallows. Support to our results is the electrophysiological evidence with EMG of oropharyngeal musculature externally showing that cold boluses (3 mL) shortened the time to trigger pharyngeal phase of swallow in healthy subjects, whereas cold (8–10 °C) and hot water (58–60 °C) shortened the time of completion of the pharyngeal phase compared with normal temperature water (23–25 °C) (Selcuk et al. 2007).

We did not observe any change in fast-swallowing latencies of hot or cold water swallows. In the literature, in mildly dysphagic stroke patients, shortened pharyngeal response times were observed with 1-mL cold boluses with videofluoroscopy, but in nondysphagic subjects, cold boluses resulted in longer pharyngeal response times and laryngeal elevation (Bisch et al. 1994). It may be that in the dysphagic population, cold boluses increased sensory input but for the healthy population, the duration and the coordination of the swallowing sequence is optimal and cannot change for the number of swallows in this study (n = 10) or even bolus volumes used (5 mL). This might explain the fact that we did not observe any changes in the fast-paced swallows in our sample.
Considering the above results, it seems that the low number of successful swallows in the challenge swallowing task could be partially due to the fact that cold may have influenced participants' sensory evaluation in order to perform the task.

Limitations to this study include the fact that our findings are only generalizable to the young healthy adults who participated. Future studies should include participants of different age groups with both genders equally represented. Moreover, it would be important to clarify if acidity of the carbonated bolus (pH 4.1) played a role on the physiological effects observed on swallowing either with or in addition to increased somatosensory input. Further investigation for the effects of carbonation with neurostimulation and neuroimaging techniques would probably provide further insight into the importance of somatosensory input with carbonated water, prior to the use of the latter in patient studies.

In conclusion, an increase in success rates of the challenged swallowing tasks was observed with carbonated water compared with still water, whereas cold water shortened only the latencies of normal swallows. Given the fact that carbonated water was delivered at a constant cold temperature (4 °C), increased somatosensory input with chemesthetic stimulation from carbonation appears to account for the increased success rate in the challenged swallowing tasks, requiring complex and quick planning and response from swallowing neural network.

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