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Challenges to assumptions regarding oral shear rate during oral processing and swallowing based on sensory testing with thickened liquids

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Abstract

For people with dysphagia, or difficulty swallowing, thickened liquids are used to slow bolus flow to make them easier to control. For these liquids, the oral shear rate of 50 s^{-1} has been adopted as the standard at which viscosity measurements are taken. However, there is evidence to suggest that other shear rates may be more appropriate to model the processes in the mouth and throat. This research compared the sensory and rheological properties of xanthan gum, guar gum, and carboxymethyl cellulose thickened liquids that had been matched for apparent viscosity at 50 s^{-1} to assess the validity of the current shear rate standard. Properties of gums were observed at various viscosity levels based on the International Dysphagia Diet Standardisation Initiative (IDDSI) framework. Textural sensory characteristics of samples were quantified using magnitude estimation scaling and a trained descriptive panel, while rheological measurements were taken at shear rates of 1 to 1000 s^{-1}. Perceived slipperiness of the gums was found to be driven by thickness level at low viscosity levels, but affected by the shear thinning behavior of the gums at higher viscosity levels. Although the liquids had been matched for apparent viscosity at 50 s^{-1}, panelists could distinguish both the perceived viscosities of the gums and their ease of swallowing, suggesting that 50 s^{-1} is neither appropriate to model the oral nor pharyngeal shear rates. A single oral shear rate could not be predicted from the data, and it is proposed that panelists evaluated oral viscosity using different methods at different viscosity levels. Based on the sensory data, the pharyngeal shear rate during swallowing appears to lie above 50 s^{-1}.

Graphical abstract

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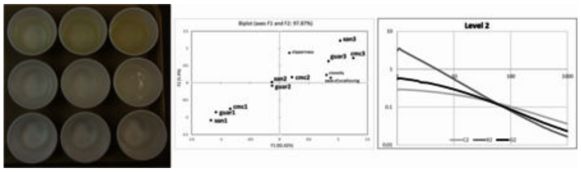

Keywords

Oral shear rate; thickened liquids; sensory evaluation; IDDSI; viscosity

1. Introduction

During the process of swallowing, liquid boluses are first held in a chamber on the upper surface of the tongue (Macqueen, Taubert, Cotter, Stevens, & Frost, 2003). A rostrocaudal pressure wave generated by the tongue then squeezes the liquid backwards through the mouth and through the pharynx towards the esophagus (Mackley et al., 2013). For people with dysphagia (difficulty swallowing), thin liquids often flow too fast into the pharynx, and may be aspirated (enter the airway) before airway protection mechanisms are initiated (Cichero et al., 2013; Gallegos, Brito-de la Fuente, Clavé, Costa, & Assegehegn, 2017). In these cases, thicker fluids have been found to reduce the risk of aspiration, due to their slower flow (Clavé et al., 2006). However, to date the literature does not provide guidance regarding the viscosity values that define effective thickening (Steele et al., 2015).

One of the barriers to defining the properties of optimally thick liquids for dysphagia management is the fact that the shear rates that operate both in the mouth and pharynx during swallowing are unknown. Furthermore, textural attributes such as perceived viscosity, ease of swallowing, and slipperiness are probably affected by shear rate, particularly for non-Newtonian shear-thinning liquids (Macosko, 1994). These properties are not only important for the acceptance of thickened liquids used in dysphagia management (Engelen, Van Der Bilt, Schipper, & Bosman, 2005; Vickers et al., 2015), but they also impact the effectiveness of thickened liquids for improving swallowing safety (Horwarth, Ball, & Smith, 2005; Macqueen et al., 2003; Sura, Madhavan, Carnaby, & Crary, 2012; Vallons, Helmens, & Oudhuis, 2015).

The current convention when describing the viscosity of liquids used in dysphagia management is to quote apparent viscosity at a shear rate of 50 s^{-1} and a temperature of 25°C (Cichero et al., 2013; National Dysphagia Diet Task Force & American Dietetic Association, 2002). This is based on a perceptual viscosity discrimination study reported by Wood (1968). However, there is limited scientific evidence for this standard (Brito, Sheth, Mukherjea, Rybak, & Ramkumar, 2014; Quinchia et al., 2011), and oral shear rates have been suggested to range from 10 to 1000 s^{-1} (Shama & Sherman, 1973).

In fact, the nature of the oral shear rate is highly contested, and some researchers have proposed that liquid foods do not operate under a single oral shear rate. Shama and Sherman (1973) suggested that food is evaluated under constant shear stress, while Christensen (1979) proposed that oral perceived viscosity is determined by an averaged viscosity over a range of shear rates rather than a single shear rate. On the other hand, there is still evidence for a single oral shear rate, and Cutler et al. (1984) found that 10 s^{-1} was a better indicator of oral shear rates than 50 s^{-1}, with the caveat that this shear rate was not representative of highly shear thinning liquids. Not only is the perceived viscosity of liquids affected by shear rate, but it is also affected by the viscosity level of the liquid. Studies conducted on Newtonian fluids found that the perceived viscosity of thickened liquids at the extremes of the spectrum (i.e. very thin or very thick) were more easily distinguished than the middle viscosities (Smith, Logemann, Burghardt, Carrell, & Zecker, 1997). Similarly in non-Newtonian fluids, small differences in viscosity were more detectable at low viscosities than at higher viscosities (Steele, James, Hori, Polacco, & Yee, 2014).

Swallowing may also provide important cues to differentiate viscosity. Smith et al. (2006) found that panellists were better able to discriminate viscosity when they evaluated viscosity by swallowing as compared to just oral evaluation, but the differences were not significant. Nevertheless, this suggests that liquid flow through the pharynx during swallowing operates at a different shear rate from that seen during bolus transport through the mouth; researchers have proposed that pharyngeal shear rate varies between 120 and 990 s^{-1} depending on bolus position in the pharynx (Meng, Rao, & Datta, 2005; Nishinari et al., 2016).

Finally, perceived viscosity is affected by slipperiness. Slipperiness affects the perception of texture of thickened liquids, mainly decreasing viscosity perception (Vickers et al., 2015). Unlike perceived viscosity and ease of swallowing, slipperiness is affected by the inherent properties of the gums, and not shear rate. Slipperiness, or lubrication of the samples, is a result of an immobile layer between the tongue and palate surfaces that does not flow with the rest of the food (Malone, Appelqvist, & Norton, 2003; Prakash, Tan, & Chen, 2013). Slipperiness can be measured with tribological techniques which quantify lubrication, but the cost associated with procuring such instruments is prohibitive (Chen, Liu, & Prakash, 2014). As such, other studies have attempted to find correlations with rheological measures, and some researchers have proposed a relation between slipperiness and the shear-thinning behaviour of gums (Ong, Steele, & Duizer, 2018; Richardson, Morris, Ross-Murphy, Taylor, & Dea, 1989; Szczesniak & Farkas, 1962; Vickers et al., 2015).

Clearly, there is a lack of consensus surrounding the relation of sensory textural attributes to rheological measurements. In this paper, we sought to provide further information on oral shear rates during liquid swallowing, and to show how these are affected by the shear-thinning behavior of gums. To do this, we compared rheological measurements of viscosity across a shear rate range from 1 to 1000 s^{-1} to perceived viscosity ratings of the liquids obtained via magnitude estimation scaling, as well as ratings of textural attributes of the liquids analyzed in a trained descriptive panel. Because perceived textural attributes may differ at different viscosity levels, we studied liquids of several different consistencies as defined by the International Dysphagia Diet Standardisation Initiative, or IDDSI, which is the most recently established system for classifying liquids used in dysphagia management. The IDDSI framework defines categories of liquid flow based on how much liquid remains in a 10 mL Becton Dickinson slip tip syringe after 10 s of flow under gravity: level 0 - thin (<1 mL), level 1 - slightly thick (1–4 mL), level 2 - mildly thick (4–8 mL), level 3 - moderately thick (8–10 mL), and level 4 - extremely thick (no flow or drip within 10 s)

(IDDSI, 2016). Notably, the IDDSI framework uses a visual scale instead of viscosity to classify liquids, as flow rate may be affected by factors other than viscosity (IDDSI, 2016). The IDDSI system was chosen as there is currently no universally accepted system for classifying viscosity levels used in dysphagia management (Cichero et al., 2013; Newman, Vilardell, Clavé, & Speyer, 2016), and IDDSI has proven successful as an accessible system to caretakers and end users of thickened liquid products (Lam, Stanschus, Zaman, & Cichero, 2017; Su et al., 2018). Nevertheless, the rheology of the liquids was also measured as another basis for comparing the liquids.

The liquids studied in this experiment were thickened to the first three IDDSI levels using different gums with varying shear thinning behavior but matched for apparent viscosity at 50 s^{-1}. It was hypothesized that these thickened liquids would have different perceived viscosities at this shear rate, and that this relationship would change at different viscosity levels. In addition, perceived viscosity and ease of swallowing ratings were predicted to be different from each other as the processes were expected to occur at different shear rates. Finally, it was expected that slipperiness ratings would be related to the shear-thinning behaviour of the gums.

2. Materials and Methods

2.1. Preparation of thickened liquids

Nine samples of thickened liquids were prepared using three different gums at three viscosity levels. All samples were prepared at the University of Guelph, Canada. The gums used were carboxymethyl cellulose, or CMC, (Pre-Hydrated Ticalose CMC 2500 Powder, TIC Gums), xanthan gum (Pre-Hydrated Ticaxan Rapid-3 Powder, TIC Gums), and guar gum (Pre-Hydrated Guar Gum 8/24 Powder, TIC Gums). These gums were chosen for their different shear-thinning behavior (Phillips & Williams, 2009) as well as their resistance to degradation by salivary alpha-amylase (Ferry et al., 2006; Newman et al., 2016; Weber, Clerici, Collares-Queiroz, & Chang, 2009). They were added to a base of Vegetable Glycerine (Now solutions) to aid in dispersion of the thickener and this mixture was then added to Natural Spring Water (President’s Choice®) in levels shown in Table 1.

Samples were formulated so that at each of the three IDDSI levels tested, all samples had the same apparent viscosity at 50 s^{-1}, and if the IDDSI flow test was conducted on the samples, the results would still fall within the correct IDDSI level. This led to concentrations of gums that matched apparent viscosity levels of 50 cP, 135 cP, and 325 cP for IDDSI levels 1, 2, and 3 respectively when taken at 50 s^{-1}. Note that these levels fall within thin (1–50 cP) and nectar-thick (51–350 cP) when using the National Dysphagia Diet Task Force viscosity classification and moderately thick (50–150 cP) and extremely thick (300–500 cP) when using the Japanese Society of Dysphagia Rehabilitation scheme (National Dysphagia Diet Task Force & American Diatetic Association, 2002; Funami, 2016).

Samples were made by first whisking the weighed thickener into the glycerol by hand to disperse the thickener and prevent clumping (Francis, 1961; I. H. Smith et al., 2014). Then, 22°C water was whisked into the slurry by hand. Glycerol was chosen as the solvent due to its negligible impact on the viscosity of water at the concentrations used (Segur & Oberstar, 1951). Once the mixture was well incorporated, it was mixed with a stand mixer (Bosch Compact MUM4405) for 5 minutes, and then samples were left to rest for 2 hours prior to serving or taking viscosity measurements. Samples were always kept at room temperature (22°C).

2.2. Viscosity measurements

Viscosity measurements were taken with a Physica MCR 301 Rheometer (Anton Paar, Benelux) using concentric cylinder geometry. Viscosity was measured with a logarithmic shear ramp test with controlled shear rate from 1 to 1000 s^{-1} at 25°C, and three replicates were taken of separate batches of all samples.

2.3. Panelists

All panels were approved by the University of Guelph Research Ethics Board (REB#16SE020). Potential participants were recruited from the University of Guelph by email, and written consent was obtained from each panelist prior to their participation in the study. All panelists were given monetary remuneration for their time. For the magnitude estimation scaling panel, 29 healthy untrained panelists were recruited for the experiments, and 16 panelists took part in all three sessions. Each viscosity level was tested separately. For each level, three sessions of eight panelists each were conducted, and there were 24, 22, and 24 panelists for IDDSI levels 1, 2, and 3 respectively. This sample size was chosen in accordance with other studies using the same method (Kokini, Kadane, & Cussler, 1977; Moskowitz & Sidel, 1971). For the trained descriptive analysis panel, 10 panelists were recruited to evaluate the samples, and the number of panelists was chosen as per a previous study by Ross et al. in 2012.

2.4. Magnitude Estimation Scaling

One sensory panel was held for each IDDSI level, leading to three separate panels in total. All panels were held in the Human Nutraceutical Research Unit of the University of Guelph. For each IDDSI level, panelists evaluated three samples that had been matched for viscosity at a shear rate of 50 s^{-1}, as described previously. Before each session, panelists were presented with two examples of magnitude estimation scaling, the first as a general description on the whiteboard, and the second on a worksheet to ensure that each panelist understood the instructions before evaluating the samples. During the training, panelists were given three samples. They were asked to choose one as a reference sample and to quantify the intensity of the desired attribute (e.g. volume, size) by assigning a number to it. They were then asked to rate the intensity of the attribute for the subsequent samples in proportion to the reference sample (Kokini et al., 1977; Meilgaard, Civille, & Carr, 1991). In the actual test, panelists were asked to rate the perceived viscosity of the samples. No other definitions were given for perceived viscosity.

Samples were served in 30 mL portions in white Styrofoam sample cups labelled with random three-digit blinding codes. Unsalted soda crackers (Premium Plus®) and filtered water were provided for oral cleansing between samples, and panelists were instructed to drink the samples from the cups. During the evaluation, panelists were required to wear nose plugs, and samples were served under red light to mask the odor and color differences between the samples.

2.5. Trained Descriptive Analysis Panel

A trained descriptive analysis panel was held to evaluate the sensory attributes of the thickened liquids. Attributes to be analyzed were selected based on a previous study, and the attributes chosen were perceived viscosity, slipperiness, and ease of swallowing. The techniques and definitions of these attributes are shown in Table 3. As with the magnitude estimation scaling, samples were provided in 30 mL portions in white Styrofoam sample cups labelled with random three-digit blinding codes. Unsalted soda crackers (Premium Plus®, Mondelez International, Toronto, ON, Canada) and filtered water were provided for oral cleansing between samples. Panelists were instructed to taste all samples with the provided teaspoons, and as with the previous panel, panelists were required to wear nose plugs, and samples.

Each panelist completed 11 h of training according to a procedure modified from Meilgaard et al. in 1991. Nevertheless, because all panelists completed less than 60 h of training, they were considered minimally trained (Chambers, Allison, Iv, & Hall, 2004). During training, panelists were given references for each attribute, and they were taught to evaluate the intensity of each attribute against the reference. References included thickened liquid solutions made with sodium alginate, Thicken Up Clear® (Nestle Resource®), and pectin (Table 4). Panelists were taught to evaluate one new attribute per session, and panelists practiced rating the sample attributes with increasing numbers of samples and attributes as sessions progressed. At the beginning of the training, panelists recorded their ratings on papers with 15 cm line scales, but after they had learned all the attributes, panelists evaluated the samples in sensory booths using computers. At the end of training, panelists could evaluate the three attributes and the nine samples in a single session without using references.

During data collection, panelists evaluated the attribute intensities of each sample on a continuous 15 cm line scale labelled with appropriate anchors. Panelists were given the products in a randomized complete block design, and each panelist conducted four replicates of each product. All responses were recorded on a computer using Compusense 5.8 software (Guelph, ON, Canada)

2.6. Statistical Analyses

All analyses were performed with SAS 9.4 (Cary, NC, USA), and a type I error rate of $\alpha=0.05$ was chosen for all tests. Viscosity measurements were analyzed using the MEANS procedure to calculate means and standard deviation for all the samples.

Before analyzing the data from the magnitude estimation scaling, they were first standardized so that the geometric mean of the ratings for each panelist was equal to one (Moskowitz & Sidel, 1971), and then the data was converted to the log scale (Butler, Poste, Wolynetz, Agar, & Larmond, 1987). The data were then analyzed with a mixed model ANOVA using the GLIMMIX procedure, with the type of gum as a fixed factor and panelists as a random factor to see if the type of gum had a significant effect on the perceived viscosity of the samples. Gums at each level were all analyzed separately, with four separate analyses run. Least squared means and standard errors of the gums were generated, and Tukey's multiple means comparison test was used to compare the means to determine significant differences in effect.

Data from the trained descriptive analysis panel were analyzed with mixed model ANOVA using the GLIMMIX procedure, with the level, type of gum, and panelists as fixed factors, and sessions as a random factor to see if the level and type of gum had a significant effect on the perceived sensory attribute. Least squared means and standard errors were generated for each attribute and sample to compare samples. A separate covariance structure was fitted with different errors for panelists and level of gum because their variance was found to be heterogenous, and this was chosen based on AICC fit statistics. Kendall Tau's test of concordance was used to test the sample and panelist interaction for any cross-over effects. All means were compared using Tukey's multiple means comparison to determine significant differences in effect. Finally, principal component analysis was used to analyze the data from the trained panel using the FACTOR procedure to see the effect of different samples on sample attributes.

3. Results

3.1. Viscosity Measurements

Viscosity measurements for the gums matched for apparent viscosity at 50 s^{-1} at the different IDDSI levels are shown in Table 2. The IDDSI classification was used as a guide for selecting concentrations of gums, but IDDSI itself is not based on specific viscosity levels, rather it is based on the gravity flow of liquids through syringes. The viscosity curves of the gums measured at shear rates of 1 to 1000 s^{-1} are shown in Figures 1a-1c. At shear rates below 50 s^{-1}, xanthan gum had the highest apparent viscosity, followed by guar gum then CMC. At shear rates above 50 s^{-1}, CMC had the highest apparent viscosity, followed by guar gum then xanthan gum. At all IDDSI levels, xanthan gum displayed the most shear-thinning behaviour, followed by guar gum and then CMC.

3.2. Magnitude Estimation Scaling Panels

Results of the magnitude estimation scaling of perceived viscosity of the samples matched for viscosity at 50 s^{-1} are shown in Table 5. Based on the analysis of variance results, the type of gum had a significant effect on perceived viscosity at all IDDSI levels. At IDDSI levels 1 and 2, guar gum was perceived to be significantly lower in perceived viscosity than both xanthan gum and CMC. At IDDSI level 3, the perceived viscosity of guar gum was significantly lower than xanthan gum, and the perceived viscosity of CMC was not significantly different from guar or xanthan gum. For the concentrations of gum tested, the rank order of perceived viscosity of xanthan gum, guar gum, and CMC was comparable to the results of the IDDSI flow test.

3.3. Trained Descriptive Analysis Panel

Mixed model ANOVA of the effect of level of thickener and type of gum on sensory attributes found that the level of thickener had a significant effect ($P<.0001$), with F values of 1136.48, 639.64, and 1116.42 for the attributes of ease of swallowing, slipperiness, and viscosity respectively. Although the type of gum was also found to be significant ($P<0.05$), the F values were much lower at 23.2, 4.72, and 15.4 for ease of swallowing, slipperiness, and viscosity respectively. The F value represents the ratio between the effect and the error, so a low F value signifies either a small effect or a high error (Paule & Powers, 1989). Thus, panellists were more adept at differentiating between the samples based on their level of thickness rather than the type of gum. Significant interactions were also found between panellists and samples, but the Kendall Tau's test of concordance found that panellists were concordant ($P<.0001$), and there were no crossover effects.

Mean ratings of sensory attributes assessed in the trained panel are reported in Table 6. For the attribute of slipperiness, at IDDSI level 1, xanthan gum had the lowest slipperiness, followed by guar gum, then CMC, which was rated as significantly more slippery than xanthan gum. At IDDSI level 2, the slipperiness ratings of the samples were not significantly different, but guar gum had the lowest slipperiness, followed by xanthan gum and then CMC. At IDDSI level 3, the rating for slipperiness for xanthan gum was significantly higher than that of guar gum and CMC.

Like slipperiness, for perceived viscosity at IDDSI level 1, xanthan gum and guar gum had significantly lower perceived viscosity than CMC. At IDDSI level 2, the three gums did not differ significantly in perceived viscosity, but guar gum had the lowest perceived viscosity, followed by xanthan gum and CMC. At IDDSI level 3, guar gum had significantly lower perceived viscosity than both xanthan gum and CMC.

For ease of swallowing ratings at IDDSI levels 1 and 2, the rating for xanthan gum was significantly lower than CMC, with guar gum ranked in the middle and not differing significantly from the other two gums. At level 3, CMC was again rated the most difficult to swallow, followed by xanthan gum, and guar gum was rated significantly lower than CMC.

The principal component analysis, shown in Figure 2, gave further information about the relationship between the attributes, the types of gums, and their viscosity levels. Factor 1 of the biplot accounted for 92.42% of the variance, and this was influenced primarily by sample viscosity. On the other hand, factor 2 only accounted for 5.4% of the variance, and this was likely influenced by type of gum. The biplot showed that slipperiness was mostly influenced by the type of gum, while perceived viscosity and ease of swallowing were influenced by the viscosity of the samples.

4. Discussion

The purpose of this research was to identify connections between slipperiness, perceived viscosity, and ease of swallowing, and instrumental measurements for thickened liquid samples thickened to different IDDSI levels and matched for apparent viscosity at 50 s^{-1}. For all three attributes, the differences observed between the samples were driven by thickness level. Although samples were matched to the same apparent viscosity, some of the ratings of the attributes differed significantly within the same IDDSI level. It should be noted that the mean apparent viscosities at each of the IDDSI levels differed slightly, but the samples at each level had overlapping confidence intervals (Table 2). Regardless, based on previous studies on perceived viscosity discrimination of thickened liquids (Smith et al., 1997, 2006; Steele, James, et al., 2014), it is unlikely that the differences in the sample apparent viscosity were significant enough to drive the differences observed in the rating of the attributes.

Slipperiness was originally hypothesized to be related to the shear-thinning behaviour of the gums, as this has been reported in other similar research (Ong et al., 2018; Richardson et al., 1989; Szczesniak & Farkas, 1962; Vickers et al., 2015). However, this pattern was only the case for IDDSI level 3, where xanthan gum, which has the most shear-thinning behaviour, also had the highest slipperiness. At the other two levels, the slipperiness rating for xanthan gum was lower than the other gums. From the principal component analysis, it was seen that slipperiness was not only influenced by the type of gum, which reflects the shear-thinning behaviour of the gums, but also the viscosity of the liquids. For IDDSI levels 1 and 2, CMC, which was perceived as most viscous, was also perceived as the most slippery. However, at IDDSI level 3, xanthan gum was perceived significantly more slippery than CMC and guar gum even though it was not significantly different from CMC in perceived viscosity.

The relationship between slipperiness and viscosity level has been noted by other researchers. Kokini et al. (1977) described slipperiness as a mixture of frictional and viscous components. Therefore, because slipperiness is related to lubrication in the mouth, there is a reduction in friction with more viscous fluids. Further confirming this theory, Malone et al. (2003) suggested that the immobile lubrication layer stops the surfaces from contacting, so more viscous products would have a greater effect at reducing turbulent flow in the contact zone, thus reducing drag. This phenomenon was also seen in this research, where the ratings for slipperiness in IDDSI level 1 were lower than those in level 2, which were likewise lower than those in level 3. From the data, it is suggested that below a certain viscosity level, perceived slipperiness is dependent on viscosity of the liquids, but above that threshold, the slipperiness of the samples becomes dependent on the shear-thinning behaviour of the liquids.

Unlike slipperiness which was influenced primarily by the type of gum, both perceived viscosity and ease of swallowing were highly related to the viscosity levels of the gums. For these attributes, ratings of the gums at each level were always significantly higher than those of a previous level. However, within the same IDDSI level, panellists were still able to distinguish between some of the gums.

For perceived viscosity, both the magnitude estimation scaling and trained descriptive panels found differences between gums in the same IDDSI level. The purpose of magnitude estimation scaling was to gain a preliminary understanding of the viscosities of the gums, based on panellists' own understanding of viscosity. In addition, during magnitude estimation scaling, panellists evaluated the samples from sample cups, while the trained panellists evaluated the products with spoons, so the data from the two tests were not expected to correspond exactly. Nevertheless, panellists in both sensory tests rated CMC as significantly more viscous than guar gum in levels 1 and 2, and they rated xanthan gum as significantly more viscous than guar gum in level 3. However, the individual rankings for the gums at each IDDSI level were different, and they did not correspond well to instrumental apparent viscosities at any shear rate.

In fact, only perceived viscosity ratings for IDDSI level 1 could be related to instrumental apparent viscosity. At IDDSI level 1, CMC was evaluated to be the most viscous, followed by guar gum, and then xanthan gum. This pattern corresponded to the apparent viscosities of the gums at shear rates higher than 50 s^{-1}, which suggests that a more appropriate oral shear rate estimate for liquids thickened to IDDSI level 1 would lie above 50 s^{-1}. On the other hand, the gums at IDDSI levels 2 and 3 did not follow any definable pattern. At level 2, the gums were not perceived to be significantly different from each other. At level 3, both CMC and xanthan gum were rated significantly higher than guar gum, and this did not follow patterns from the apparent viscosity measurements.

As evidenced by the different patterns in the ranking of the gums at each of the IDDSI levels, panellists appear to have been using different mechanisms to evaluate the samples at each IDDSI level. During training, panellists were asked to evaluate sample viscosity both by slurping from a spoon and by how it flowed in the mouth, and the discrepancy between the levels could be a result of the evaluation methods that panellists used. Houska et al. (1998) found that the shear rates predicted for viscosity perception by manipulating samples orally was higher than that of slurping the products. Thus, panellists could have been relying more on oral manipulation for the lower viscosity products, and then a mixture of the two tests with the higher viscosity levels. Another explanation for the difference could be different thickness levels of the products, which has been shown to affect oral shear rate (Parkinson & Sherman, 1971; Shama & Sherman, 1973). Nevertheless, what can be concluded is that perceived viscosity could not be related to a single oral shear rate, and this is likely because there are many factors that play a role in determining the perceived viscosity of a product.

Unlike perceived viscosity, ratings of ease of swallowing maintained a constant pattern across all three IDDSI levels, where CMC was always rated as the most difficult to swallow, and at levels 1 and 2, xanthan gum was rated as easier to swallow than guar gum. However, at IDDSI level 3, xanthan gum was rated as more difficult to swallow than guar gum. Nevertheless, the ratings of ease of swallowing for guar gum and xanthan gum were not significantly different for level 3.

Based on the rheological data of the samples, CMC displayed less shear-thinning behaviour as compared to xanthan gum and guar gum. Thus, at higher shear rates, the rate of decrease in the viscosity of the gum was not as prominent as that of xanthan gum and guar gum. This translates to CMC having a higher viscosity than xanthan gum and guar gum at higher shear rates, and since CMC had a higher viscosity than the other gums at shear rates above 50 s^{-1}, this suggests that the pharyngeal shear rate during swallowing is also higher than 50 s^{-1}. Such a shear rate corresponds with other research on the pharyngeal shear rate during swallowing. Yamagata et al. (2012) proposed that 100 s^{-1} was the optimal shear rate for measuring swallowing in elderly patients, and this was corroborated by Zhu et al. (2014) who found that 120 s^{-1} was the shear rate dominant in the upper pharynx. Other researchers have suggested pharyngeal shear rates up to 400 s^{-1} for thin liquids with viscosity similar to water, but this is likely to decrease for liquids at higher viscosities (Brito-de la Fuente, Ekberg, & Gallegos, 2012; Meng et al., 2005).

It had also been suggested that there is unlikely to be a single oropharyngeal shear rate, as both bolus viscosity and lubrication of samples could affect the shear rate (Nicosia, 2013). This could explain why xanthan gum was more difficult to swallow than guar gum at level 3, as xanthan gum had the highest perceived viscosity at this level, and higher viscosity products are more difficult to swallow (Seo, Hwang, Han, & Kim, 2007; Steele, Molfenter, Péladeau-Pigeon, Polacco, & Yee, 2014). Finally, although this research only measured the steady shear viscosity of the liquids as this is most relevant to viscosity during swallowing (Hadde, Nicholson, & Cichero, 2015), other research has reported that viscoelastic behaviour of fluids may also affect ease of swallowing (Brito-de la Fuente, Turcanu, Ekberg, & Gallegos, 2017; Syahariza & Yong, 2017), and this could help quantify the differences seen in the ease of swallowing not accounted for by the apparent viscosity measurements.

5. Conclusions

This study evaluated the sensory properties of gums of different shear thinning behaviour that were matched for apparent viscosity at 50 s^{-1} in an attempt to further the understanding on the connections between sensory characteristics and instrumental measures. Slipperiness was found to be affected at low viscosity levels, but at higher levels, the type of gum drove the sensation of lubrication. It is proposed that product characteristics become more important at higher viscosity levels, but the threshold at which they become dominant will need to be determined with further research.

Although samples were matched for apparent viscosity at 50 s^{-1}, panellists could still perceive significant differences between the gums within a thickness level for the attributes of perceived viscosity and ease of swallowing. This suggests that 50 s^{-1} may not be an appropriate estimation of either of those shear rates. A single oral shear rate could not be determined to predict perceived viscosity, and it is hypothesized that panellists may use different methods for evaluating oral perceived viscosity at different viscosity levels. As such, a single rheological measurement may not be sufficient to predict perceived viscosity. This study also showed that 50 s^{-1} is too low of an estimation for the pharyngeal shear rate during swallowing, and this was seen at all three IDDSI levels tested. Although a shear rate above 50 s^{-1} is suggested to represent the pharyngeal shear rate during swallowing, this will likely be affected by sample viscosity, and it is unlikely that a single shear rate can be applicable for products of all viscosities.

There has been an ongoing discussion regarding the use of 50 s^{-1} as the oral shear rate standard for use in dysphagia management, and this research suggests that another shear rate standard be found. Furthermore, there is evidence to show that oral and pharyngeal shear rates differ significantly, and it is recommended that the latter be used as it is more relevant for swallowing safety. However, this research only tested three types of hydrocolloids at three viscosity levels, and further research can expand upon these parameters. In particular, corn starch, which was excluded due to its degradation by salivary alpha amylase, should be studied as it is a commonly used thickener with different textural and shear thinning properties to the hydrocolloids tested. In addition, this research did not consider the viscoelastic properties of the fluids, and future work on oscillational rheology of the liquids may be useful in establishing a safe swallowing standard.

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Highlights

- Slipperiness was affected by both the type of gum and level of thickness

- Perceived viscosities of the samples were different even when liquids were matched for apparent viscosity at 50 s^{-1}, but they could not be related to rheological measurements

- Pharyngeal shear rate during swallowing likely occurs above 50 s^{-1}

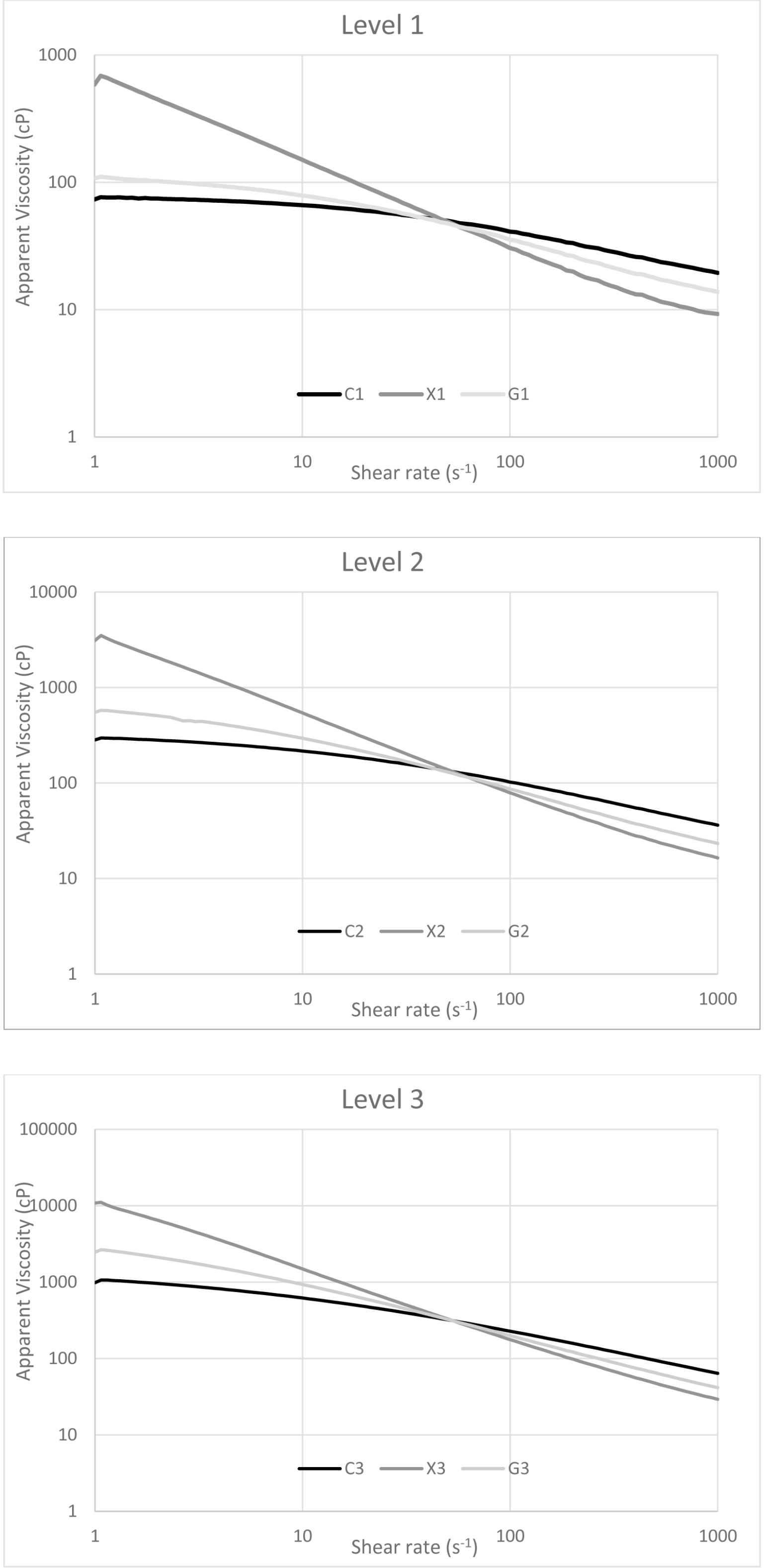
Level 1
Apparent Viscosity (cP)
1000
100
10
1
1
10
100
1000
Shear rate (s^{-1})
C1
X1
G1
Level 2
Apparent Viscosity (cP)
10000
1000
100
10
1
1
10
100
1000
Shear rate (s^{-1})
C2
X2
G2
Level 3
Apparent Viscosity (cP)
100000
10000
1000
100
10
1
1
10
100
1000
Shear rate (s^{-1})
C3
X3
G3

Figure 1a.

Viscosity measurements of xanthan gum (X), guar gum (G), and carboxymethyl cellulose (C) at IDDSI level 1, when matched for apparent viscosity at 50 s^{-1}

Figure 1b. Viscosity measurements of xanthan gum (X), guar gum (G), and carboxymethyl cellulose (C) at IDDSI level 2, when matched for apparent viscosity at 50 s^{-1}

Figure 1c. Viscosity measurements of xanthan gum (X), guar gum (G), and carboxymethyl cellulose (C) at IDDSI level 3, when matched for apparent viscosity at 50 s^{-1}

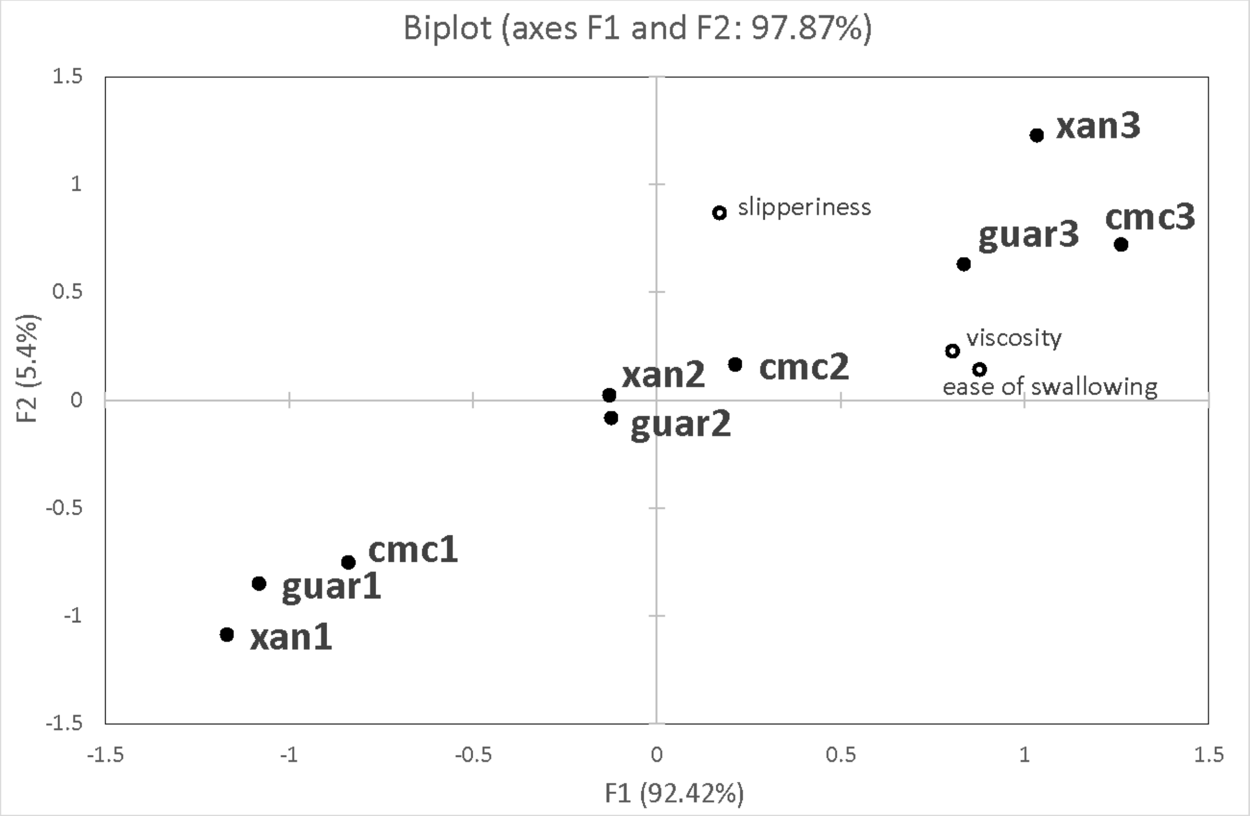

Figure 2.

Principal component analysis of trained panel data looking at the effect of samples on attributes of slipperiness, viscosity, and ease of swallowing (n=40, 10 panelists, 4 sessions)

Table 1.

Sample formulation for liquids thickened with xanthan gum, guar gum, and carboxymethyl cellulose, when matched for apparent viscosity at 50 s^{-1}

IDDSI Level	Thickness	Water (g)	Xanthan gum (g)	Guar gum (g)	Carboxymethyl cellulose (g)
1	Slightly-Thick	200	0.45	0.70	0.70
2	Mildly-Thick	200	0.90	1.05	1.15
3	Moderately-Thick	200	1.80	1.55	1.70

Table 2.

Viscosity measurements and IDDSI flow test results of samples matched for apparent viscosity at 50 s^{-1} and conducted at 25°C

IDDSI Level	Gum	Viscosity (cP)	Standard Deviation	95% Confidence Interval		IDDSI Flow Test (mL)
				Lower Limit	Upper Limit	
1	Xanthan	49.4	1.59	45.4	53.3	1.3
	Guar	47.8	2.97	40.4	55.1	1.0
	CMC	50.0	0.61	48.4	51.5	1.5
2	Xanthan	139	4.0	129	149	5.0
	Guar	131	4.9	118	143	4.0
	CMC	135	1.5	131	138	4.6
3	Xanthan	331	3.0	324	338	9.1
	Guar	326	3.8	316	335	8.0
	CMC	322	2.6	315	328	8.0

Table 3.

Sensory attributes, techniques, and definitions used by trained panelists to evaluate liquids thickened with xanthan gum, guar gum, and carboxymethyl cellulose

Attribute[a]	Technique	Definition
Ease of Swallowing	Place ½ tsp of product at the back of mouth, swallow the entire bolus, measure the force required to pass the liquid completely from the mouth to the throat	The effort required for the throat muscles to swallow
Slipperiness	Place ½ tsp of product in the mouth, with product in the mouth, move tongue horizontally just under the palate, measure how the tongue slides through product	The amount in which the product slides across the tongue and elicits a slippery sensation when moving the tongue horizontally in the mouth
Viscosity	Place a spoonful of product close to lips, slurp gently to measure the flow of liquid, measure the force required; once the product is in mouth, allow to flow across tongue, measure the rate of flow	The force to draw between lips and spoon and the rate of flow across the tongue

[a] Attributes evaluated on a 15 cm line scale, 0 represents low level of an attribute while 15 represents a high level of that attribute

Table 4.

Product brands and quantities used as references to represent the minimum and maximum intensities for each of the attributes evaluated by the trained panel

Attribute	Product	Brand	Quantity (g)	Water (mL)
Swallow 0	Thicken Up Clear	Nestlé Resource®	0.70	200
Swallow 15	TICA Algin HG400TG02904	Caldic	3.00	200
Slippery 0	TICA Algin HG400TG02904	Caldic	0.70	200
Slippery 15	Thicken Up Clear	Nestlé Resource®	4.50	200
Viscosity 0	Pre-Hydrated Pectin 1694 Powder	TIC Gums	1.50	200
Viscosity 15	Pre-Hydrated Pectin 1694 Powder	TIC Gums	6.00	200

Table 5.

Mixed model variance analysis of the effect of type of gum on perceived viscosity measured by magnitude estimation scaling (*n*=24, 22, 24, 23 for IDDSI levels 1, 2, 3, and 4 respectively)

IDDSI	Level	Xanthan Gum	Guar Gum	Carboxymethyl Cellulose	F Value	Pr > F
1	Mean	2.03^{a}	1.93^{b}	2.04^{a}	5.72	0.0061
	SE	0.025	0.025	0.025		
2	Mean	2.02^{a}	1.89^{b}	2.10^{a}	11.76	<.0001
	SE	0.030	0.030	0.030		
3	Mean	2.11^{a}	1.90^{b}	1.99^{ab}	8.98	0.0005
	SE	0.035	0.035	0.035		

[a-b] Means in the same row sharing a letter are not significantly different according to a Tukey’s multiple range test (P≥0.05).

Table 6.

Means, standard errors, and mean comparisons of sensory attributes in thickened liquids, as evaluated by trained panelists (n=40; 10 panelists, 4 sessions)

Attribute		IDDSI Level 1			IDDSI Level 2			IDDSI Level 3		
		Xan	Guar	CMC	Xan	Guar	CMC	Xan	Guar	CMC
Ease of Swallowing	Mean	1.3^{f}	2.0^{ef}	3.0^{e}	6.5^{d}	6.8^{cd}	8.6^{c}	12.5^{ab}	11.4^{b}	13.5^{a}
	SE	0.24	0.24	0.24	0.44	0.44	0.44	0.29	0.29	0.29
Slipperiness	Mean	2.0^{e}	3.0^{de}	3.6^{d}	7.3^{c}	6.9^{c}	8.2^{c}	13.1^{a}	10.5^{b}	11.2^{b}
	SE	0.33	0.33	0.33	0.49	0.49	0.49	0.27	0.27	0.27
Viscosity	Mean	1.6^{e}	2.1^{e}	3.3^{d}	7.1^{c}	6.6^{c}	8.0^{c}	13.0^{a}	11.2^{b}	12.9^{a}
	SE	0.25	0.25	0.25	0.40	0.40	0.40	0.27	0.27	0.27

[a-f] Means in the same row sharing a letter are not significantly different according to a Tukey’s multiple range test (P≥0.05).