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Original Research

Human Perception of Viscosity Is Decoupled from Sensitivity to Stress and Strain Rate

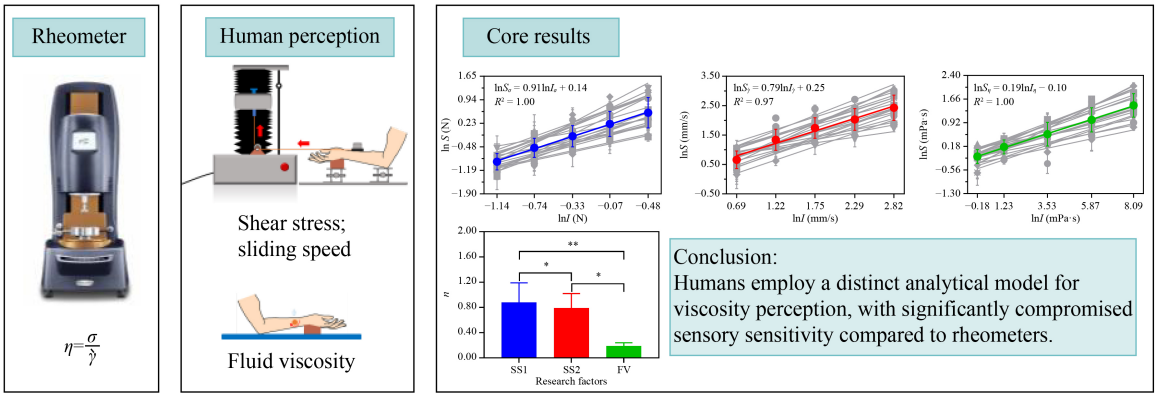
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GRAPHICAL ABSTRACT

Human vs. rheometer: distinct models for viscosity perception



HIGHLIGHTS

- Humans use a distinct analytical model for viscosity perception.
- Humans show good sensitivity in perceiving stress and rate of strain.
- Sensitivity of viscosity perception is significantly compromised, showing a strong compressive response distinct from primary tactile stimuli.
- Magnitude estimation combined with Stevens law reveals individual differences in sensory sensitivity, classifying subjects into three distinct categories.

ABSTRACT Viscosity is a key determinant of food texture and plays a central role in consumer perception of thickness and consistency. While viscosity can be precisely quantified using a rheometer, the psychophysical basis of human viscosity perception remains poorly understood. In this study, we investigated whether humans evaluate viscosity using an analytical model analogous to rheological measurement, namely the ratio of shear stress to shear rate. Human sensitivity to friction force (as a proxy for shear stress), sliding speed (as a proxy for shear rate), and apparent viscosity of near-Newtonian fluids was quantified using magnitude estimation and Stevens law. Participants showed moderate sensitivity to friction force (n = 0.91) and sliding speed (n = 0.79). In contrast, sensitivity to viscosity was markedly reduced (n = 0.19), indicating strong perceptual compression. These findings demonstrate a clear dissociation between sensitivity to primary mechanical stimuli and to viscosity, suggesting that humans do not combine stress and strain rate in a manner consistent with classical rheological models. Instead, viscosity perception likely arises from non-ratiometric integration of sensory inputs. This reduced sensitivity estimation has important implications for food design, suggesting that relatively large changes in physical viscosity may be required to produce perceptible differences in texture and mouthfeel.

KEYWORDS Sensory perception; Human sensation; Psychophysics; Viscosity perception; Food texture; Stevens law

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1 Introduction

Viscosity is a fundamental physical (or rheological) property of fluid that strongly influences the perception of texture, thickness, and mouthfeel in food systems. Viscosity can be precisely quantified using a rheometer or viscometer. The magnitude of viscosity is then used as an indicator of the ease of fluid flow. The higher the viscosity of a fluid, the bigger effort (i.e., larger external stress) it will need to maintain a flow or the slower the flow under an applied stress (or the gravity) [1]. Accurate measurement of viscosity is essential to food design and manufacturing, including the formulation and the use of functional ingredients, the choice of operational conditions and devices. From a sensory perspective, understanding viscosity perception is highly relevant to oral strategy of eating and swallowing and also to sensory experience, influencing satiety and product preference. This raises the possibility that perceptual constraints, rather than physical differences alone, govern how texture is experienced.

According to theory of rheology, viscosity of a fluid originates from the internal friction of fluid elements under a flow. Viscosity, η (Pa·s), is then defined as the ratio of the applied stress, σ (Pa or N/m^2), to the strain rate, $\dot{\gamma}$(s^{-1}), and can be calculated using the following equation:

$$\eta = \frac{\sigma}{\dot{\gamma}}. \tag{1}$$

According to this equation, force (stress), distance (displacement), and time are the three primary parameters for viscosity measurement. In a rotational rheometer setup, force is usually measured via a torque which is then converted to stress, as the total surface area of the rotation probe is already known. On the other hand, distance is usually measured by the angle of probe rotation and is converted into strain with the known gap size setup between the two measuring plates. This was then further converted into strain rate taken into consideration of time. For a Newtonian fluid, viscosity remains constant at a certain temperature and is independent of strain rate. In contrast, non-Newtonian liquids exhibit shear-dependent viscosity, often described using apparent viscosity. Fluids may exhibit shear-thinning or shear-thickening behaviour depending on how their microstructure evolves under deformation [2,3].

Although viscosity is a material property which can be measured precisely by instruments, it is also perceptually accessible. Humans can assess viscosity through visual cues or tactile interactions (mostly using fingers, or using mouth in cases of eating and drinking) [4–6]. For example, by looking at a fluid flowing inside a tilted container or out of a pipe, one can give an approximate estimate of its viscosity. Fingers rubbing or tongue moving against the hard palate during an eating/drinking process can also give a good assessment of fluid viscosity [7]. However, in sensory context, viscosity appears a little too academic and, therefore, terms such as thickness or consistency are more commonly used instead [8].

Even though humans are fully capable of perceiving viscosity, the underlying mechanism of this perception remains unclear. We speculate that viscosity cannot be directly encoded from tactile sensation, but is a derived sensory attribute inferred from more fundamental stimuli [9]. The rise of this hypothesis is based on two main considerations. Firstly, it is common knowledge that humans' tactile systems contain sensors only for detecting pressure, displacement, stretch, and vibration [10,11]. Therefore, we assume that viscosity is derived from more basic tactile inputs, particularly force (stress) and movement speed (strain rate). This raises the possibility that humans may internally reconstruct viscosity using a transformation analogous to that employed in rheological measurements.

Secondly, empirical studies have shown correlations between perceived viscosity and instrumentally measured viscosity [6,12–14]. Perceived viscosity by humans can thus be interpreted as a sensory representation of physical property. The inherent link between the two can be described by the well-known psychophysical law, the Stevens law, which shows that the perceived intensity of a sensory attribute (S) shall be in a power law relationship to the intensity of the sensory stimulus (I), i.e., the material property:

$$S = kI^n, \tag{2}$$

where the power law index n characterizes perceptual sensitivity, and k represents the scaling constant of Stevens law. The Stevens law has been proved widely applicable, and successes have been observed for many sensory attributes, including acoustic, visual, taste, and tactile [15,16].

In this investigation, a set of experiments were designed to address whether humans use a rheometer-like model for viscosity evaluation (i.e., Equation 1). Shear stress (represented by friction force) and shear rate (represented by sliding speed) were both measured instrumentally and evaluated perceptually by human subjects. A set of near Newtonian fluids (Golden syrup) was used for viscosity analysis. By comparing sensitivities to primary mechanical cues and to viscosity

itself, we aim to determine whether human perception of viscosity is consistent with, or deviate from, classical rheological models. Our results seem to indicate that humans' viscosity perception is probably decoupled from that to shear stress and shear rate, or humans probably use a different analytical model from the one applied in rheological analysis.

2 Experimental Design

2.1 Subjects

Twenty subjects (50% female; mean age ± SD = 23.16 ± 0.89 years; mean BMI ± SD = 20.19 ± 1.60 kg/m^2) with no reported skin problems were recruited and screened on the campus of Zhejiang Gongshang University. Consent was obtained from each subject before the experiment. The experiment followed all ethical requirements set by Zhejiang Gongshang University (No. 21133589).

2.2 Magnitude estimation

The Magnitude Estimation Method was used for sensory analysis of the perception of stress (friction force), sliding speed, and viscosity. Procedures follow ISO standard [17]. An initial reference stimulus was assigned a value of 10. The perceived intensity of the following samples was then given by the subject as times of reference. For example, if it is 2.00 times of the reference sample, the perceived intensity of the sample is then 10.00 × 2.00 = 20.00; if it is 5.50 times of the reference sample, the perceived intensity is then 10.00 × 5.50 = 55.00 [18]. No upper or lower limit was given, and subjects can make any estimation based on their instant sensation. Subjects were trained prior to the experiment to ensure that they fully understood the assignment rules and the experimental procedure. The order of presentation of the sensory attributes for all subjects was in a balanced order.

2.3 Experimental setup

The instrument used for the shear stress and sliding speed experiments was a texture instrument (TA.XT Plus, Stable Micro Systems, UK) with an additional pulley setup (Caliper Technology Ltd., China) [19] (Fig. 1A).

This device was composed of a probe, a limiting pulley, a connecting thread, a wrist pad and an arm support frame. Structurally, the probe was divided into two functional parts from top to bottom: the upper part was a stainless steel (#304) cylindrical block for applying pressure, with a diameter range of 20.0–30.0 mm and a height range of 8.0–27.1 mm. The lower part was a nylon fiber board equipped with a photosensitive resin slider, which moves in a horizontal direction and in direct contact with the skin; the slider had a length of 29.0 mm, a width of 20.0 mm, a thickness of 3.5 mm and a fillet radius of 5.0 mm. In addition, two concentric cylindrical grooves were machined on the upper surface of the nylon fiber board, both with a depth of 5.0 mm and diameters of 20.0 mm and 30.0 mm, respectively. The fixed pulley was made of polyoxymethylene (POM) plastic; the connecting line was a 40-count cotton thread, which featured flexibility and bending resistance to achieve stable connection between the probe and the load cell of texture analyzer.

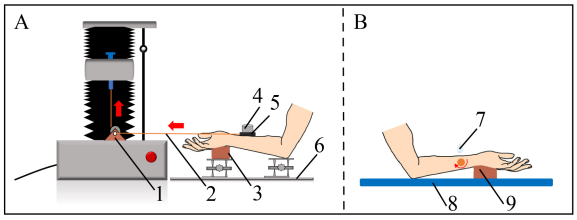


Fig. 1 Schematic diagrams of (A) shear stress and sliding speed sensing experiment and (B) fluid viscosity sensing experiment (1: limiting pulley, 2: 40-count cotton thread, 3: sponge pad for wrist supporting, 4: 304 stainless steel cylindrical block, 5: photosensitive resin slider, 6: arm support frame, 7: fluid sample, 8: towel, 9: sponge pad for wrist supporting).
Note: in the shear stress and sliding speed perception experiments, the TA.XT Plus was connected to a computer, and the movement of the probe was controlled by a computer programme so as to achieve sliding friction on the skin of the inner side of the right arm. For the fluid viscosity perception experiments, the sample was carefully deposited on the inner side of the left arm, and the right index finger was used to make a clockwise uniform circular movement to sense viscosity. A Minimal Metronome via mobile phone app was used to regulate the speed of finger mobbing. The laboratory temperature was 21.00 ± 1.00 °C and the relative humidity was (50.00 ± 10.00)%.

Before experiments, PS6630 soft silicone (Yipin Art Model Material Company, China) was used to verify the reliability and stability of the device. Fluid viscosity was determined using a rotational rheometer.

2.3.1 Experiments on the perception of shear stress and sliding speed

In setting the values of the independent variables, it is necessary to satisfy both the suprathreshold range in which the difference lies in the subject and the realistic condition constraints (stable sliding and not exceeding the upper speed limit of 20.00 mm/s). The shear stress when the skin and the contact object slide relative to each other is the product of the normal force and the

coefficient of friction of the contact surface, i.e., the shear stress could be seen as equivalent to the kinetic friction [20], so different weights of stainless steel blocks formed different shear stresses, with the applied values of 0.32, 0.48, 0.72, 1.08 and 1.61 N; and the programmed parameters were set to different sliding velocities, with the applied values of 2.00, 3.40, 5.78, 9.83 and 16.70 mm/s.

In the shear stress perception experiments, 0.32 N was used as the reference sample, and the sliding speed was constant at 5.78 mm/s; the sliding speed perception experiments were conducted similarly. The shear stress was assigned based on the degree of skin pulling, and the sliding speed was assigned based on the speed of the object moving on the skin; the greater the degree of pulling and the faster the speed, the greater the value. All tests were conducted in tension model set by the texture analyzer and data (force and distance) were recorded by the instrument.

The proximal joint of the radial ulna on the palmar surface of the right forearm was taken as the starting point, and the extended centre line was measured 80.00 mm towards the distal joint, extending 35.00 mm wide on both sides, marking the experimental area. Subjects were asked to rest for at least 10 minutes on their arrival to ensure they are in relaxed condition. Before experiment, a disposable alcohol pad was used to wipe and clean the skin of the testing area. After resting quietly for 10.00 min, the subjects first wiped the skin with a disposable alcohol pad. Throughout the experiment, subjects wore eye masks to avoid visual interference. Experiment was conducted in three sessions, each consisting of 5 tests against the reference. A short break was given between sessions.

2.3.2 Viscosity perception experiments for near-Newtonian fluids

Golden syrup (Taikoo Sugar, China) was used as near-Newtonian fluid for viscosity analysis. A set of golden syrup solutions was obtained by mixing it with ultrapure water (filtered by Direct-Q®5UV, Merck Millipore, Germany). Apparent viscosity of the fluids was measured using a rheometer (Discovery Hybrid Rheometer-2, TA Instruments, USA) equipped with a cone-and-plate geometry (diameter: 40.00 mm, angle: 2.017 degrees, operating gap: 55.00 μm) with a constant shear rate of 50.00 s^{-1}, at temperature of 28.00 ºC. This was repeated three times and average value was obtained as the value of instrumental measurement.

The proximal joint of the radial ulna on the palm surface of the left forearm was taken for viscosity assessment, and a circle with a diameter of 30.0 mm was drawn as the experimental area by extending the centre line to the distal joint of the radial (Fig. 1B). A test fluid of 0.05 mL was placed onto the experimental site of the forearm and subjects were asked to use their right-hand index finger to touch the liquid and move clockwise circular motion. A Minimal Metronome via mobile phone app was used to regulate the speed of finger mobbing. Rotational speeds of 40.00, 60.00, 80.00, 100.00 and 120.00 BPM (beats per minute) were also applied to test its effect on viscosity perception. Before the experiment, the skin was wiped with a disposable alcohol pad; an eye mask was worn throughout the experiment; after the experiment, the arm was cleaned with wet and dry paper towels; and the experiment was repeated three times.

2.4 Data analysis

Linear regression analyses were performed using the logarithm of physical stimulus intensity as the horizontal coordinate and the logarithm of sensory intensity assignment as the vertical coordinate. The slope of the regression line is taken as the *n*-value of Stevens law and the *y*-axis intercept is the lnk-value. Stevens' *n* and *k* were first estimated separately for every participant and modality, followed by group summaries and cross-modality analysis. Correlation, significance and multiple linear regression analyses were performed using the software Microsoft Excel 2019 and IBM SPSS Statistics 25. Plotting was performed using the software GraphPad Prism 9.5 and Microsoft PowerPoint.

3 Results and Discussion

3.1 Psychophysics of humans' perception of friction force and sliding speed

To measure apparent viscosity, a rheometer primarily measures only two parameters: shear stress and strain under a controlled temperature condition. Taking experimental time into consideration, strain is then converted into strain rate or shear rate. The apparent viscosity is then calculated according to rheological definition as the ratio of the shear stress against shear rate. We speculate that humans probably do the same, by sensing the stress (force) and rate of deformation for viscosity evaluation. The first part of this investigation was designed to assess humans' sensitivity to the two parameters using Stevens law. Altogether 20 subjects were recruited for sensory analysis by dragging a specially designed probe on their forearms. Real friction force between a moving probe and skin was measured using instrumental reading and perception of the intensity of the friction force was reported by the subject using

magnitude estimation method. Since the friction force acts on the direction parallel to the skin and the contacting area between the moving probe and skin is fixed, we assume that this scenario represents humans' response to shear stress. Also based on similar considerations, perception of the moving/sliding speed of the probe against skin was used as an indicator for the perception of the shear rate.

Fig. 2 shows humans' perception of the friction force perceived between the moving probe and skin (Fig. 2A) and its moving speed (Fig. 2B) against instrumental measured values, both expressed in Stevens law for individual subjects. Overall, human perception shows a positive relationship with instrumental measured values. The Stevens law for shear stress for the 20 subjects was $\ln S = 0.91\ln I + 0.14$, with a mean n-value of 0.91, and that for sliding speed was $\ln S = 0.79\ln I + 0.25$, with a mean n-value of 0.79. Humans' perceptual sensitivities were all less than 1.0 for both friction force and moving speed, suggesting that humans' sensitivity in perceiving these two sensory stimuli lags behind their intensity changes measured by instrument. However, it should be noted that large variations exist among subjects. The n-values for friction force were distributed between 0.51 and 1.48 among all subjects, with 6 (or 30%) subjects having n-values greater than 1.00, 3 (or 15%) subjects close to 1.00, and 11 (or 55%) subjects smaller than 1.00 (Fig. 2C). The n-values for sliding speed were distributed between 0.36 and 1.19, with only 2 (10%) subjects having n-values greater than 1.00, and most of the subjects (90%) were shown to be less sensitive ($n < 1.00$) to perceive the speed of surface sliding (Fig. 2D).

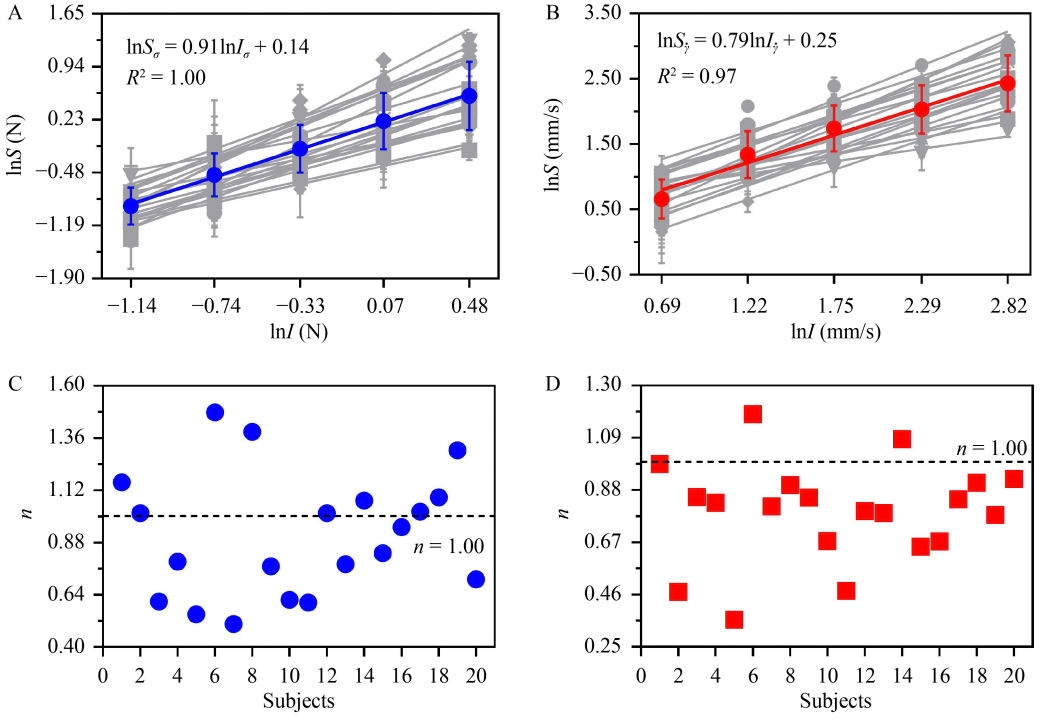


Fig. 2 Linear regression results (A, B) and power index n scatter plots (C, D) of the perception of shear stress and sliding speed by the skin of the medial right forearm (SS1: shear stress; SS2: sliding speed; $N = 20$).

Note: in Figs. 2A and 2B, the logarithm of physical stimulus intensity was the horizontal coordinate, the logarithm of sensory perception intensity was the vertical coordinate, the gray data were the perceptions of each subject, the blue and red data were the mean values of perceptions, and the linear regression resulted in the equation, and the slope of the equation represented the n value of Stevens law, i.e., sensory perception sensitivity, and the R^2 expressed the degree of fit of the data of the linear regression; Figs. 2C and 2D were the scatter plots of the slope n-value of the linear regression line of shear stress and sliding speed for each subject, $n = 1.00$ dashed line indicated that the sensory perception sensitivity was the same as the physical stimulus change.

3.2 Humans psychophysics of viscosity perception of near-Newtonian fluids

A set of near-Newtonian fluids was used for viscosity evaluation. Instrumental viscosity of each sample was quantified using a rotational rheometer, while perceived viscosity data were collected from 20 participants via forearm tactile evaluation: participants rubbed the test fluid against their forearm skin with the index finger for a minimum of 30 s to complete sensory ratings. This

extended rubbing duration allowed participants sufficient time to fully engage in the complex multisensory cognitive process underlying liquid perception [21]. The perceived viscosity is then plotted against the instrumental viscosity using Stevens law, and relationships are shown in Fig. 3. To our surprise, humans' sensitivity in detecting viscosity is much lower than that in perceiving friction force (presumably shear stress) and the sliding speed (presumably shear rate), with a mean n-value of only 0.19, with $\ln S = 0.19\ln I - 0.10$ (Fig. 3A). The distribution of n-values for the 20 subjects ranged from 0.11 to 0.30 (Fig. 3B), which were significantly lower than that for the friction force and the sliding speed, as shown in Fig. 2.

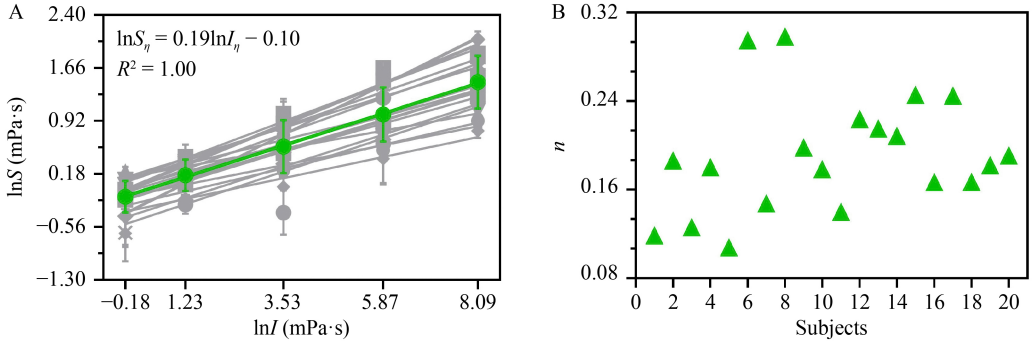


Fig. 3 Linear regression results for fluid viscosity perception (A) and power index n scatter plot (B) (FV: fluid viscosity; $N = 20$).
Note: in Fig. 3A, the logarithm of physical stimulus intensity was the horizontal coordinate, the logarithm of sensory perception intensity was the vertical coordinate, the gray data were the perceptions of each subject, the green data were the perceptions of the average value, the linear regression equation was obtained, and the slope of the equation indicated the n-value of Stevens law which was the sensitivity of the sensory perception, and the R^2 indicated the degree of fit of data of linear regression; Fig. 3B showed a scatter plot of the slope n values of the linear regression line for fluid viscosity for each subject, $n = 1.00$ dashed line indicated that the sensory perception sensitivity and physical stimulus changes were the same.

Humans' low sensitivity in viscosity perception has already been reported by a number of literature studies. Steele et al. [22] demonstrated that healthy adults exhibit limited percept liquid viscosity in the oral cavity, a finding that aligns with the general compressive response ($n < 1$) of rheological perception. This limited perceptual sensitivity to liquid viscosity is further supported by Camacho et al. [23], who reported a Weber fraction of $K = 0.26$ for oral thickness perception of Newtonian model beverages, indicating that a substantial change in physical viscosity (≈ 26%) is required for a discriminable perceptual difference in the oral cavity. This compressive perceptual response for shear viscosity has also been confirmed in haptic (non-oral) assessments, where Lv et al. [6] reported a power law index of 0.54 for finger-based shear viscosity perception, further validating that rheological perception via tactile modalities is characterized by reduced sensitivity relative to physical stimulus changes.

Significance analysis and correlation analysis demonstrate that the n-values of friction force and sliding speed, sliding speed and fluid viscosity showed significant differences ($P < 0.05$); n-values of friction force (n_{SS1}) and n-values of fluid viscosity (n_{FV}) show highly significant differences ($P < 0.01$) (Fig. 4). Correlation analysis results among n- and k-values are given in Table 1.

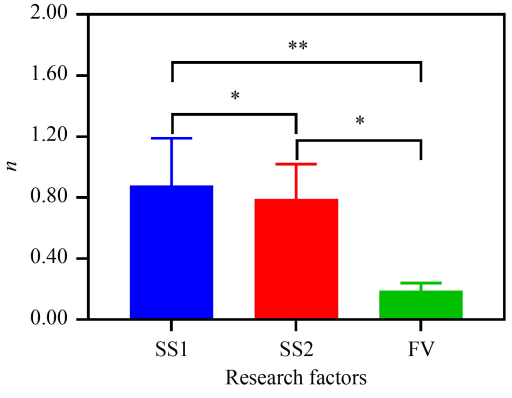


Fig. 4 Significance analysis of n values for shear stress (SS1), sliding speed (SS2) and fluid viscosity (FV) ($N = 20$).
Note: * indicated that there was a significant difference ($P < 0.05$) between the two groups of data, ** indicated that there was a highly significant difference ($P < 0.01$) between the two groups of data; the analysis of significance was performed using one-way analysis of variance (ANOVA).

The calculated n-values for all participating subjects are summarized in Table 2. Based on the significance of the n-value of the three parameters, subjects can be roughly grouped into three categories. Category I represents the cases of a significant difference ($P < 0.05$) between n-values of any two parameters (9 subjects).

Table 1 Correlation analysis of power index n and constant k derived from Stevens law for shear stress, sliding speed and fluid viscosity (N = 20).

	n_{SS1}	k_{SS1}	n_{SS2}	k_{SS2}	n_{FV}	k_{FV}
n_{SS1}	1.000	0.799**	0.545*	−0.031	0.612**	−0.129
k_{SS1}		1.000	0.535*	0.048	0.396	0.143
n_{SS2}			1.000	−0.623**	0.446*	−0.355
k_{SS2}				1.000	−0.208	0.595**
n_{FV}					1.000	−0.188
k_{FV}						1.000

Note: in Table 1, SS1 denotes shear stress, SS2 represents sliding speed, and FV stands for fluid viscosity. * indicates a significant difference ($P < 0.05$) between the corresponding row and column data, ** indicated a highly significant difference ($P < 0.01$) between the corresponding row and column data; correlation analyses were performed using Pearson Correlation.

Table 2 Classification of subjects according to power index n of friction force, sliding speed and fluid viscosity (N = 20).

Category	Subject	n_{SS1}	n_{SS2}	n_{FV}
Category I	2	1.02 ± 0.09^a	0.47 ± 0.19^b	0.19 ± 0.00^c
	5	0.55 ± 0.03^a	0.36 ± 0.05^b	0.11 ± 0.02^c
	6	1.48 ± 0.11^a	1.19 ± 0.21^b	0.30 ± 0.02^c
	7	0.51 ± 0.17^a	0.81 ± 0.06^b	0.15 ± 0.03^c
	8	1.39 ± 0.09^a	0.90 ± 0.15^b	0.30 ± 0.02^c
	12	1.02 ± 0.10^a	0.80 ± 0.09^b	0.22 ± 0.02^c
	16	0.95 ± 0.16^a	0.67 ± 0.05^b	0.17 ± 0.04^c
	18	1.09 ± 0.09^a	0.91 ± 0.05^b	0.17 ± 0.03^c
	19	1.30 ± 0.12^a	0.78 ± 0.03^b	0.18 ± 0.00^c
Category II	1	1.16 ± 0.27^a	0.98 ± 0.02^a	0.12 ± 0.02^b
	3	0.61 ± 0.01^a	0.85 ± 0.20^a	0.13 ± 0.02^b
	4	0.79 ± 0.11^a	0.83 ± 0.05^a	0.18 ± 0.04^b
	9	0.77 ± 0.17^a	0.85 ± 0.06^a	0.20 ± 0.02^b
	11	0.60 ± 0.09^a	0.47 ± 0.12^a	0.14 ± 0.03^b
	13	0.78 ± 0.28^a	0.79 ± 0.06^a	0.22 ± 0.01^b
	14	1.07 ± 0.02^a	1.09 ± 0.13^a	0.21 ± 0.03^b
	15	0.83 ± 0.16^a	0.65 ± 0.05^a	0.25 ± 0.01^b
	17	1.02 ± 0.15^a	0.84 ± 0.30^a	0.25 ± 0.02^b
	20	0.71 ± 0.14^a	0.92 ± 0.24^a	0.19 ± 0.06^b
Category III	10	0.62 ± 0.30^{ab}	0.68 ± 0.22^a	0.18 ± 0.02^b

Note: different letter superscripts in the same row indicated that there was a significant difference ($P < 0.05$) in the perceived sensitivity of the subjects for the three variables, while the same letter superscripts for the perceived sensitivity of the variables in the same row indicated that there was no significant difference ($P > 0.05$); significance analyses were performed using one-way analysis of variance (ANOVA), and subjects were classified according to the significance results.

Category Ⅱ represents the cases of no significant difference ($P > 0.05$) between n-values for friction force and sliding speed, but significantly different ($P < 0.05$) from that of fluid viscosity (10 subjects). Category Ⅲ consists of only one subject who showed no significant difference ($P > 0.05$) between n-values of any two parameters.

Human perception of viscosity has also been evaluated at different rubbing speeds regulated by a metronome. Since the fluid samples are near-Newtonian and their apparent viscosity should remain the same, one would not expect significant change of the n-values of viscosity perception in this case. As shown in Table 3, one can see that the n-value for viscosity perception remains relatively stable, with the increase of the finger rubbing speed from 40 to 120 BPM. Only the n-value obtained at 40 BPM shows some statistical difference from those obtained at other speeds. These results more or less confirm that subjects perform consistently in perceiving viscosity despite changing experimental conditions.

Table 3 Summary of logarithmic linear regression results for five golden syrup fluid samples at 5 BPMs (N = 20).

BPM	$\ln S = n\ln I + \ln k$		
	n	k	R^2
40.00	0.23 ± 0.07^b	1.26 ± 0.30	0.94 ± 0.04
60.00	0.26 ± 0.07^a	1.27 ± 0.28	0.94 ± 0.05
80.00	0.28 ± 0.05^a	1.21 ± 0.19	0.97 ± 0.03
100.00	0.27 ± 0.06^a	1.24 ± 0.25	0.95 ± 0.03
120.00	0.29 ± 0.07^a	1.24 ± 0.37	0.95 ± 0.05

Note: a linear regression of the fluid viscosity assignment at each BPM yielded the equation $\ln S = n\ln I + \ln k$. The slope indicated the perceived sensitivity n, the higher the value of n the more sensitive it was; k was lnk taking the exponent; and R^2 denoted the degree of fit of the data to the linear regression. Different letter superscripts in the same column indicated that there was a significant difference ($P < 0.05$) in the perceived sensitivity of viscosity of fluid samples at the corresponding BPM; the same letter superscripts in the same column indicated that there was no significant difference ($P > 0.05$) in the perceived sensitivity of viscosity of fluid samples at the corresponding BPM.

3.3 Further discussion

The key findings of this study show a clear dissociation between the sensitivity to primary mechanical cues (force and speed) and the sensitivity of viscosity, a derived sensory attribute.

Our results (Fig. 2) show that human's perception of friction force and the speed of surface movement follow the general psychophysical principle as described by the Stevens law relationship, with a power law index n of 0.91 and 0.79 respectively. Since friction force is a force acting in horizontal direction and the contacting area between the moving probe and skin is known, one can assume that this n-value should also represent humans' sensitivity to shear stress. Similarly, power law index for sliding speed can also be used to indicate humans' sensitivity to shear rate. We can then infer that humans' sensation of the two rheological variables, shear stress

and strain rate, is slightly lower than linear relationship, meaning that humans are slightly less sensitive in tactically detecting the intensity change of these two parameters. This is not surprising since literature studies already show that humans are not as sensitive as instruments in detecting changes in sensory intensity [24–26].

If humans were applying a rheometer-like computation (i.e., viscosity as the ratio of stress to shear rate), then perceptual sensitivity to viscosity should be predictable from the sensitivities of these primary variables. Strikingly, our observation shows a large discrepancy between humans' sensitivity to viscosity (n = 0.19) and sensitivities to shear stress (n = 0.91) and strain rate (n = 0.79), suggesting that this is not the case. Instead, these results indicate that human perception does not reconstruct viscosity via an explicit ratio-based computation. Rather, viscosity perception likely emerges from a non-ratiometric and possibly heuristic integration of sensory inputs. It is still too early to speculate the real analytical model for sensory perception of viscosity. However, one possible speculation could be that the sensation of shear rate (sliding speed) plays a more dominating role in the internal analysis of viscosity, which causes distortion of viscosity perception. This of course requires further experimental investigation.

Our research findings may also have important implications to the perception of many sensory attributes which are not directly perceived but are internally derived from primary sensations. For example, toughness can be both a material property and also a sensory attribute of a food material, resembling the ease of a food against chewing. With the help of a texture analyzer, toughness can be estimated via the amount of work of deformation per amount of food sample (i.e., per unit volume). Sensorially, toughness perception relies on perceived force, deformation distance, sample size and duration, serving as a typical derived sensory attribute [9]. It remains unconfirmed whether toughness perception aligns with instrumental measurements from texture analyzers. Creaminess represents a far more complex textural percept jointly governed by bulk viscosity and interfacial friction [27]. Our results demonstrate that rheometers exhibit higher detection sensitivity than human tactile discrimination for viscosity, shear stress and shear rate. However, Laguna et al. [28] provided contradictory experimental evidence: untrained panelists successfully distinguished thickness, creaminess and watery mouthfeel between skim and full-fat milk via triangle tests, while rheological and tribological characterisations captured no significant physical discrepancies between the two samples. This contrast implies the existence of a critical rheometric sensitivity or torque threshold. We hypothesize that Stevens law loses validity for ultra-low-viscosity fluids, where human touch can resolve subtle differences undetectable by instruments; stable scaling between instrumental outputs and perceived viscosity is only established above a certain critical viscosity magnitude. Overall, the psychophysical mechanisms underlying such multi-factorial sensory attributes are complex, so any *in vitro* evaluation model requires rigorous cross-validation against human sensory data. Beyond the forearm tactile test adopted in this experiment, the present results also deliver brief but valuable implications for oral texture perception research. Distinct from forearm skin, the oral cavity involves continuous saliva secretion that alters fluid rheology and interfacial lubrication during mastication, and oral mucosa possesses inherently different tactile sensitivity. Future research is warranted to examine whether the decoupling pattern between viscosity perception and shear stress/strain rate sensitivity discovered on forearm skin persists under actual oral processing conditions.

3.4 Limitations

Of course, this investigation involves some assumptions and limitations of experimental design. Firstly, during the sensation of friction force, different loads were added to the slider on skin surface. While the friction force is changing, the same is the compression force. Even though subjects were asked to focus on friction in the horizontal direction, it may be inevitable that increased compression may also contribute to friction sensation. Secondly, it should be acknowledged that the effective interfacial shear rate during active tactile exploration is a human movement and therefore need not be identical to the shear rate imposed during rheometry. The assumption of using friction force as an indication of shear stress is made based on the assumption that friction force acts in the horizontal direction and causes shearing action on skin surface. However, the magnitude of friction could also be complicated due to an edge effect of the dragging probe. Thirdly, while all experiments were conducted in a laboratory of controlled temperature and stable relative humidity and all experimental devices (including the moving probe) were fully thermally equilibrated before experiment, possible effect of thermal sensation cannot be excluded, due to different thermal conductivity of the probe and skin. Finally, the sample size (N = 20) limits population-level generalization, particularly given the observed inter-individual variability in psychological exponents. Future studies with larger and more diverse cohorts are needed to establish the robustness and population distribution of these relationships.

On top of above listed limitations, sensation of time is a hugely important factor to viscosity evaluation, but this was not included in the current experimental design. The

sensation of time was an internal part of the sensation of speed or rate (distance and time). However, despite these limitations, the results from this investigation are still sufficiently convincing that the psychophysics of derived sensory attributes could be based on very different psychophysical rules from that of primary sensory attributes (i.e., stress and strain rate).

4 Conclusions

Humans are capable of perceiving viscosity (commonly described as thickness or consistency), despite lacking dedicated sensory receptors. It is therefore reasonable to assume that viscosity perception is derived from more fundamental mechanical cues, specifically stress and shear rate. A key question of this study was whether humans combine these inputs using an analytical model analogous to that employed by a rheometer.

To address this, we quantified human sensitivity to friction force (as a proxy for shear stress), sliding speed (as a proxy for shear rate), and apparent viscosity of near-Newtonian fluids. Psychophysical responses were analysed using Stevens law model. The results revealed a clear dissociation between sensitivity to primary mechanical stimuli and to viscosity. While participants showed moderate sensitivity to friction force (n = 0.91) and sliding speed (n = 0.79), sensitivity to viscosity was markedly reduced (n = 0.19).

These findings indicate that, although humans can reliably sense the primary variables underlying viscosity, they do not combine them in a manner consistent with classical rheological models. Instead, viscosity perception likely arises from a distinct, non-ratiometric integration of sensory inputs, resulting in substantial perceptual compression. Overall, this study demonstrates that the psychophysics of derived sensory attributes can differ fundamentally from that of their underlying physical variables, highlighting important differences between human perception and instrumental measurement. This could be particularly true for some complicated sensory attributes which cannot be directly perceived but must be derived from primary sensory stimuli.

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Competing interests The authors declare no conflicts of interest.

Compliance with ethics guidelines Altogether 20 subjects were recruited for this study. Informed consent was obtained from all participants. The study adhered to the Ethics Code and the Declaration of Helsinki principles, with approval from the Ethics Review Committee of Zhejiang Gongshang University (Approval No. 21133589). Participants were fully aware that they had the right to withdraw from the study at any time without providing a reason. Each participant received compensation of CNY 25 per session (no longer than one hour) for their participation. No personal identity was used for data analysis.

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