Haptic discrimination and matching of viscosity

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Abstract—In three experiments, viscosity perception of liquids using the sense of touch was studied. The first two were discrimination experiments in which Weber fractions were determined for a number of viscosities spanning the range of what is encountered in daily life, and for two ways of perceiving viscosity (stirring with a spatula or with the index finger). For high viscosities, Weber fractions were around 0.3, whereas they increased for lower viscosities. For low viscosities, discrimination performance was much worse with the finger than with the spatula. In the third experiment, subjects matched liquids perceived with these two methods, which resulted in biases of around 80 %. Control experiments and force measurements were performed to find an explanation for these results. It was concluded that the relationship between perceived and physical viscosity is steeper for stirring liquids with a spatula than stirring with the finger.

Index Terms—viscosity, liquid, psychophysics, haptic perception, touch

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1 INTRODUCTION

THE viscosity or ‘thickness’ of a liquid is a property that is encountered often in daily life, for instance when stirring soup or mixing paint. Viscosity can be perceived in many ways; visually by looking at the movement of the liquid when it is poured or when the container is shaken; haptically by shaking the container and feeling the movement of the liquid, or by stirring with the hand or a spoon. This last method makes use of a simple physical relationship: the higher the viscosity, the slower an object moves when pushed through the liquid with a certain force. By perceiving the applied force and the resulting velocity, an observer is able to infer the liquid’s viscosity. The questions that the present research attempts to answer are: how well are people able to distinguish between viscosities in this way? And how does this ability depend on the way the liquid is stirred?

These questions are relevant in relation to teleoperation and haptic feedback [1], [2]. Viscosity perception plays a role in recognising substances or in intuitive interaction with a virtual environment. Thus, in order to provide appropriate haptic feedback, it is necessary to know how viscosity is perceived. But also from a viewpoint of fundamental research, these questions are interesting. Since viscosity perception depends on velocity and force perception, an underlying question might be: do people form a direct percept of a liquid’s viscosity, or do they consciously construct this percept from separately perceived velocity and force, by making mental calculations? In the latter case, viscosity perception should follow the same patterns in terms of discrimination thresholds and dependence on physical values as force perception, if a constant velocity is used. By investigating how viscosity discrimination depends on viscosity magnitude, this question may be answered.

Physically, viscosity is the internal resistance of a liquid against shear force. It is expressed as the ratio between *shear stress* and *shear rate*. Shear stress is the amount of force applied in the direction of shear per unit area (in $\mathrm{N/m^2}$ or Pa). Shear rate is the gradient perpendicular to the force of the liquid’s moving speed (in m/s/m or $\mathrm{s^{-1}}$). Viscosity is thus expressed in units of Pa·s. Water has a viscosity of 1 mPa·s. If this ratio of shear stress and shear rate is approximately constant over the whole range of forces for a particular liquid, this is called a *Newtonian liquid*.

Perception can be characterised in a number of ways: for instance, by magnitude estimation (also called ‘scaling’) or by discrimination experiments. Magnitude estimation tells us something about the relationship between physical and perceived viscosity, and discrimination about the accuracy of perception. For magnitude estimation, we can—as always—turn to Stanley Stevens, who found a power function exponent of 0.43 for blindfolded magnitude estimation of the viscosity of stirred silicone liquids in the range of 10–95,000 mPa·s [3]. Somewhat lower exponents, ranging from 0.35–0.40, were found for direct contact of the fingers with various solutions of gum in water [4]. On average, the various types of gum produced a relationship that can be described by a power function, but there were many individual variations between the different types of gum. Still, in general we can conclude that the strength of the dependence of perceived viscosity on physical viscosity (slope of the relationship) decreases with increasing viscosity.

Research into haptic viscosity *discrimination* has been limited. There has been some interest from the food science community, but this is mainly focused on oral perception. For example, using mixtures of corn syrup and water that were presented on tea spoons, oral discrimination of viscosity was investigated [5]. In this

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experiment, discrimination ability was assessed by asking subjects to identify seven different viscosities. It was found that in general, people were able to correctly identify stimuli of which the viscosity was about three times that of the previous stimulus in the set in the range from 3 to 2240 mPa·s. However, not all stimuli were always correctly identified, suggesting that the Weber fraction for oral viscosity discrimination in this range is about 2. It was shown earlier that oral and manual viscosity perception are quite comparable, using solutions of gum in water [6]. That would suggest that this Weber fraction of 2 might also apply to manual viscosity discrimination. However, in a comparison of two types of thickened apple juice, differing a factor of 1.7 in viscosity, all of 16 subjects were correct in identifying the more viscous one, both orally and through stirring [7]. This would point to a Weber fraction of less than 0.7 at about 1000 mPa·s. The discrepancy with [5] might be due to the fact that the thickened apple juice was highly non-Newtonian, meaning that the measured viscosity depends very much on the speed of movement during the measurement. The reported viscosity was for a shear rate range of 6–15 s^{-1}, but it is unknown if this corresponds to what subjects used. Shear rates used for oral viscosity perception range from 10–1000 s^{-1} [8]. For non-Newtonian liquids, the shear stress does not necessarily co-vary with the shear rate, whereas for Newtonian liquids, there is a fixed ratio between the two for each liquid. When stirring non-Newtonian liquids, it is mainly the shear stress that is used as a cue while the shear rate is kept more or less constant [9]. When viscosity is perceived by tilting the container, there is much more variation in shear rate. Thus, for non-Newtonian liquids, results may very much depend on the way of interacting with the liquid. Therefore, in order to prevent confounding shear rate with apparent viscosity, Newtonian liquids should be used.

Much earlier, viscosity discrimination was studied using balls of bitumen that were handled underwater [10]. These have very high viscosities in the order of 10^8 mPa·s. They found about 80 % correct discrimination for viscosity differences of 30 %, corresponding to a Weber fraction of 0.3 in this high range. It is unknown whether this value also applies to viscosities encountered in daily life, but in general it seems that Weber fractions for discrimination decrease with increasing viscosity. This would be in line with what was found in a study on discrimination of the viscosity of a mechanical system (the ratio of force over movement speed) [11]. In this study, subjects were asked to match the mechanical viscosity of linear electric motors connected to their arms. In this situation, the Weber fractions also decreased with increasing mechanical viscosity, but the two situations cannot be compared directly. The Weber fraction went down from 0.83 to 0.34 between a mechanical viscosity of 2–32 N·s/m and levelled off after that. A lower Weber fraction of 0.14 at 120 N·s/m was found for mechanical viscosity, using a different method [12]. In that study, subjects were asked to perform a grasping task and choose whether the pattern of forces they encountered whilst squeezing represented a high or low 'viscosity'. In short, a considerable range of discrimination thresholds has been found, suggesting that discrimination performance depends both on the reference viscosity and on the interaction type. In order to confirm this, the present study investigates haptic viscosity discrimination of liquids over a wide range of reference viscosities. In experiments 1 and 2, different ways of manual viscosity discrimination are tested: using a spatula and using the index finger to stir. Then, the results are compared to physical force measurements. In experiment 3, the different ways are directly compared to each other. Finally, two control experiments are performed to validate the methods used. The three experiments use the same general methods, which are discussed first.

2 GENERAL METHODS

2.1 Materials

The three experiments used the same stimulus set. The set comprised two series of 29 silicone liquids with ascending viscosity (78–31,000 mPa·s). These were produced by mixing suitable standard liquids in predefined ratios. Seven different standard liquids were used (AK 10, AK 100, AK 350, AK 1000, AK 5000, AK 12500 and AK 30000, Wacker-Chemie GmbH). These numbers refer to the nominal kinematic viscosity in units of mm^2/s. In this paper, the measured dynamic viscosity is used, which is defined as the kinematic viscosity multiplied by the density, in units of mPa·s. The density of the standard liquids ranged from 0.96–0.97 g/cm^3. Based on pilot experiments, five ranges of viscosities were selected, each with six test stimuli and one reference stimulus (see table 1). The test stimuli were chosen in such a way that within each range, subsequent test stimuli differed by a constant factor. This factor was chosen to be larger for the lower ranges because in the pilot experiments, discrimination turned out to be relatively harder for the lower ranges than for the higher ranges. In this way, an adequate spacing of the stimuli within each range is attained for sampling the psychometric curve.

Five ranges of seven stimuli would mean 35 stimuli. Due to some overlap of the ranges, only 29 different liquids were necessary. 27 different liquids needed to be mixed and two were used in pure form. The mixing ratios were calculated based on the manufacturer's data. The viscosity of the resulting liquids was measured using a Physica Modular Compact Rheometer 300 (Anton Paar GmbH). The measurement was performed over a range of shear rates spanning 0.1–100 s^{-1}. The measured viscosity differed less than 1 % over the range of shear rates, showing that the liquid is highly Newtonian. The values averaged over shear rates are shown in table 1.

250 ml of each liquid was poured into containers of 8 cm diameter and 8 cm height. For each viscosity, there were two containers. In one set, wooden spatulas with

TABLE 1

Measured viscosities of the stimuli in mPa·s. T_i are the test stimuli, while R is the reference of each range. The last line shows the ratio between subsequent test stimuli in a range.

Range	A	B	C	D	E
T_1	76	180	449	1093	10100
T_2	98	243	606	1237	11580
T_3	155	334	817	1646	13830
R	199	449	938	1853	16060
T_4	243	555	1093	2553	18950
T_5	363	740	1458	3185	23200
T_6	555	1093	1853	3883	29335
Ratio	1.49	1.44	1.33	1.30	1.24

rounded ends (Romed TS-100, 150 × 18 × 1.5 mm) were placed. Subjects were free to grasp the spatula in any way they liked. Most used a pen-like grasp or pinch grasp between thumb and index finger. The other set of containers were covered with a rubber glove (duoSHIELD LPS latex 240, size L), of which the middle finger was hanging in the liquid. The "wrist" of the glove was put around the rim of the container and was held in place by an elastic band. By inserting their index finger into the middle finger of the glove, subjects could stir the liquid with their finger without the liquid sticking to it, which could have lead to unwanted mixing of the liquids. Subjects could stir the liquid by rotating their finger around a point at the entrance of the glove's finger without having to stretch the glove. The glove was powdered with talcum powder (Unicura Balance) to make it easy to slide into.

2.2 Procedure

A two-alternative forced-choice procedure was used for the three experiments. For the discrimination experiments (experiments 1 and 2), the method of constant stimuli was used, whereas for the matching experiment (experiment 3), a staircase procedure was followed. Each trial, a test and a reference stimulus were presented side by side to the blindfolded subject. In experiment 1, the subject stirred both liquids with a spatula using his/her dominant hand. In experiment 2, s/he inserted the index finger of the dominant hand into the rubber glove and stirred the liquids. In experiment 3, a combination of these methods was used, and also a method with a spatula inside the rubber glove. The subject was told each trial what methods to use for the stimulus on the right and on the left. The type of movement to be made was not specified. Most subjects stirred in a circular manner. The left/right placement of the stimuli was randomised and counterbalanced. After stirring, the subject said which of the two liquids was the 'thicker' one. Then, a new trial started.

In experiments 1 and 2, each test/reference pair was presented 10 times. The ordering of the trials was also randomised; trials from all ranges were mixed. With five ranges of six test stimuli and two discrimination experiments, this corresponds to 600 trials per subject. These were performed in five sessions of about 50 minutes, either on different days or with sufficient time in between. Half the subjects first completed the trials from experiment 1 and then those from experiment 2; the other half the other way around.

Experiment 3 consisted of two conditions: in the first, a stimulus felt with a spatula in the liquid was paired with a stimulus felt with the index finger in a rubber glove. In the second condition, the stimulus felt with a spatula directly in the liquid was paired with a stimulus felt with a spatula in a rubber glove. In each condition, two reference stimuli were used: 1646 and 10100 mPa·s, representing the lower and higher viscosity ranges, repectively. The reference stimuli were always felt with the rubber glove surrounding either the finger or the spatula. Each reference was paired with a series of test stimuli that were felt using the spatula directly in the liquid. The value of the test stimulus was determined by means of a computer-driven one-up-one-down staircase procedure: If in a particular trial the test stimulus was perceived to be of a higher viscosity than the reference stimulus, the next test stimulus in the series would be one step less viscous, and vice versa. In this way, the viscosity of the test stimulus converged to the point of subjective equality (PSE). For each reference stimulus, there were two staircases: one starting at the low end of the range and one at the high end. The starting points for the low reference were 180 and 1646 mPa·s, and for the high reference 1093 and 3883 mPa·s. These ranges were chosen to be centered around the expected matching viscosity, based on pilot experiments. The four staircases for the two reference stimuli were interleaved. 50 trials were performed in each condition. The two conditions together took about 45 minutes per subject.

2.3 Analysis

For each subject and each reference stimulus, the percentage of times that a test stimulus was perceived to be of higher viscosity than the reference stimulus was plotted as a function of its viscosity. For test viscosities much lower than the reference viscosity, this percentage will tend towards zero as subjects can easily discriminate between the two. Conversely, for test viscosities much higher than the reference viscosity, this percentage will tend to 100 %. For the test viscosities in-between, there is a smooth transition from 0 to 100 %. The steepness of this transition is a measure for the discrimination threshold: the steeper the transition, the lower the discrimination threshold. To determine this threshold, a psychometric function of the form

$$f(x) = 50\,\% + 50\,\% \cdot \operatorname{erf}\left(\frac{\log(x/p)}{\sqrt{2}\log(w+1)}\right) \tag{1}$$

was fitted to the data. Here, erf is the error function, p is the viscosity of the reference stimulus and w is the Weber fraction for discrimination, which is a free parameter in the fit. From the Weber fraction, the absolute (as opposed to relative) threshold value can be calculated by multiplying it by the reference value. This threshold indicates the minimum difference between two stimuli necessary for reliable discrimination. It is equal to the difference between the reference viscosity p and a viscosity one Weber fraction higher (i.e. $(w+1)p$), which is a difference equal to wp. When substituting $(w+1)p$ for x, we see that the value of this function at the discrimination threshold corresponds to approximately 84 %. This is a consequence of using the widely used error function as the psychometric function. The logarithm is used in the function's argument because it makes the function antisymmetric on a logarithmic scale [13].

In experiment 3, the measurements were intended not to yield a discrimination threshold, but instead a bias, i.e. a shift in perceived viscosity for the same physical viscosity due to different conditions. To determine the size of this bias, p in equation (1) was also left a free parameter in the analysis of experiment 3, and corresponds to the PSE. In this way, psychometric curves and Weber fractions (exps. 1&2) or PSEs (exp. 3) were determined for all subjects and all ranges.

Measured Weber fractions and biases were further analysed for their dependence on reference viscosity and method of stirring using linear regression, t-tests, and analysis of variance (ANOVA). The Weber fractions from the first two experiments were analysed together in a repeated-measures ANOVA, with the within-subject factors of viscosity range (A through E, as given in table 1) and experiment (1 or 2, differing in the method of stirring the liquids). Because Weber fractions are not normally distributed, the data were log-transformed before the analysis, which makes them approximately normally distributed.

From the perceptual shifts found in experiment 3, relative biases were calculated by dividing the difference between the matching physical viscosities by the reference viscosity. These relative biases were subjected to a repeated-measures ANOVA, with the within-subject factors of reference viscosity (1646 or 10100 mPa·s) and methods of stirring (spatula/finger vs. spatula/spatula).

3 EXPERIMENT 1

In this experiment, viscosity discrimination thresholds for stirring a liquid with a rigid probe were established for a wide range of viscosities. Parts of this experiment have been published before in a conference paper [14].

3.1 Subjects

Five men and three women in the age range of 20–30 years took part in the study. All were strongly right-handed according to Coren's test [15]. After receiving instructions, they gave informed consent. They were paid for their efforts.

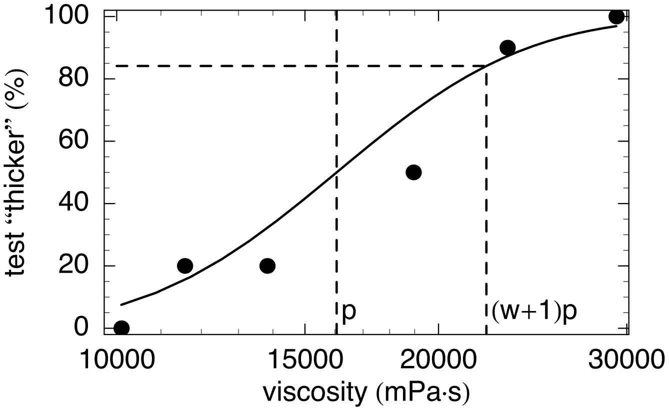

Fig. 1. Representative example of a psychometric curve of one subject in the highest viscosity range. The solid curve is a fit to the data. The dashed lines indicate the reference value p and the value corresponding to the 84 % level, which is at a viscosity of $(w+1)p$, where w is the Weber fraction, in this case equal to 0.38.

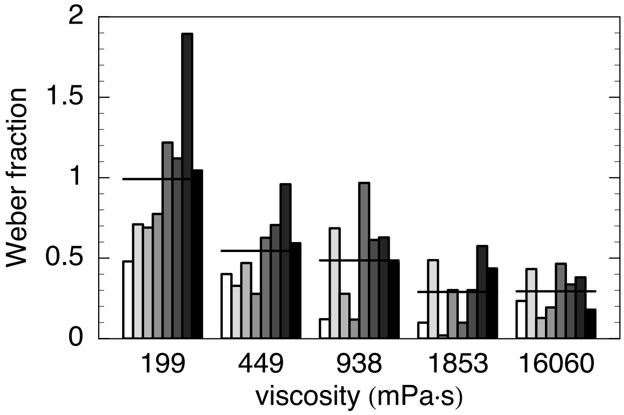

Fig. 2. Weber fractions for viscosity discrimination with a spatula for eight subjects (different shades) and five ranges of viscosity. The horizontal lines indicate the averages over subjects.

3.2 Results

An example of a measured psychometric curve is shown in figure 1. From these psychometric curves, Weber fractions were determined. These are shown for all subjects in figure 2. Looking at the figure, there seems to be a dependence of discrimination performance on viscosity. Therefore, a linear regression was performed on the slopes. For all subjects, a negative slope between Weber fraction and reference viscosity was found. On average, the slope of the linear regression is -2.2×10^{-5} (mPa·s)$^{-1}$. Since the slopes for all individual subjects are negative, this is significantly different from zero (sign test[1], $p = 0.0078$). However, this significant slope does not necessarily mean that a negatively sloped straight line is

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[1] The non-parametric sign test is used here because due to the low number of subjects, it cannot be reliably ascertained whether the slopes are normally distributed.

the best description of the relationship between viscosity and Weber fraction.

3.3 Discussion

As expected, people are able to distinguish different liquids by simply stirring them. However, the accuracy with which they do this, does not show a simple relationship with the viscosity itself. In fact, only for the two viscosities above 1800 mPa·s is a constant Weber fraction of 0.29 ± 0.07 (SE) observed. Below this value, Weber fractions increase with decreasing viscosity, up to about 1 for the lowest viscosity in the range (199 mPa·s). This is a very high value compared to other perceptual continua that involve force perception. For example, for weight perception, Weber fractions are within the range of 0.03–0.12 [16]. For compliance perception, it is about 0.15 [17]. The reason for this difference is not clear. It could be that the forces involved in viscosity perception of thin liquids are in another range than those involved in weight or compliance perception. In fact, when we look at the absolute thresholds rather than the Weber fractions (see figure 5, dotted line), we see that they more or less level off below 1800 mPa·s. There seems to be a floor effect here, similar to the one observed for perception of mechanical viscosity [11], where the threshold value did not seem to go below a certain level.

In this experiment, there is no direct interaction between the hand and the liquid. The forces are mediated by a rigid link, the spatula. This might affect viscosity perception. In order to investigate this, experiment 2 was performed.

4 EXPERIMENT 2

In this experiment, it was attempted to achieve a more direct interaction between the subject's hand and the liquid. It was hypothesised that with such a direct interaction, more information about the liquid's consistency would be available, leading to lower discrimination thresholds. Ideally, we would have liked the subject to manipulate the liquid with the bare fingers. However, to avoid inadvertent mixing of the different liquids, the hand would have to be cleaned after each stimulus, which is very time-consuming and would lead to large loss of liquid. For this reason, it was decided to approach the ideal situation as closely as practicable and have the subject's fingers separated from the liquid by only a thin rubber membrane. By having the subject insert his/her index finger into a finger of a rubber glove that covered the container, discrimination thresholds were measured for stirring a liquid with the finger for a wide range of viscosities.

4.1 Subjects

The same eight subjects from experiment 1 participated.

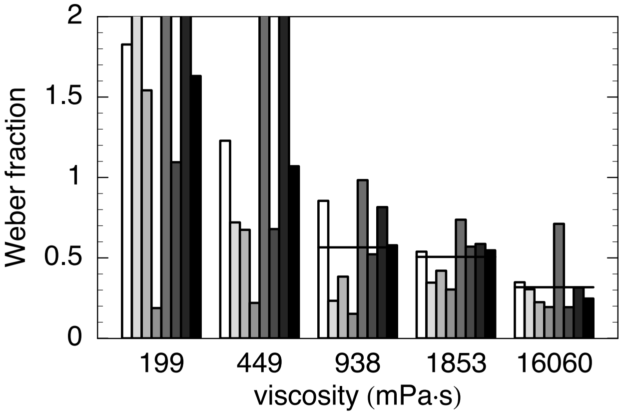

Fig. 3. Weber fractions for viscosity discrimination with the index finger for eight subjects (different shades) and five ranges of viscosity. The horizontal lines indicate the averages over subjects. Some values are very high and fall outside of the plotting range.

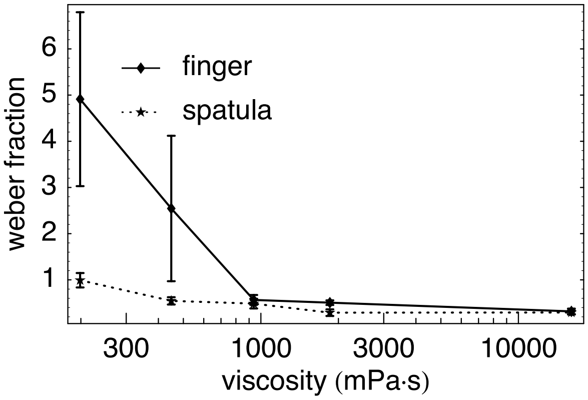

Fig. 4. Average Weber fractions for viscosity discrimination using two methods of perception as a function of reference viscosity. Note that the horizontal axis is logarithmic. The error bars represent the standard error of the sample mean.

4.2 Results

The Weber fractions for all subjects are shown in figure 3. The Weber fractions seem to decrease with increasing viscosity. The average slope is -1.4×10^{-4} (mPa·s)$^{-1}$. Since the slopes for all individual subjects are negative, this is significantly different from zero (sign test, $p = 0.0078$). The average Weber fractions from both experiments 1 and 2 are plotted as a function of reference viscosity in figure 4. A 2 (experiment) × 5 (viscosity range) repeated-measures ANOVA on the log-transformed data of the two experiments together indicated a significant effect of reference viscosity ($F_{4,28} = 22,\ p = 2.4 \times 10^{-8}$) and of method of stirring ($F_{1,7} = 6.8,\ p = 0.035$). No significant interaction effect of method × range was observed.

Another way of regarding the data is in terms of the absolute thresholds, rather than the Weber fractions. The

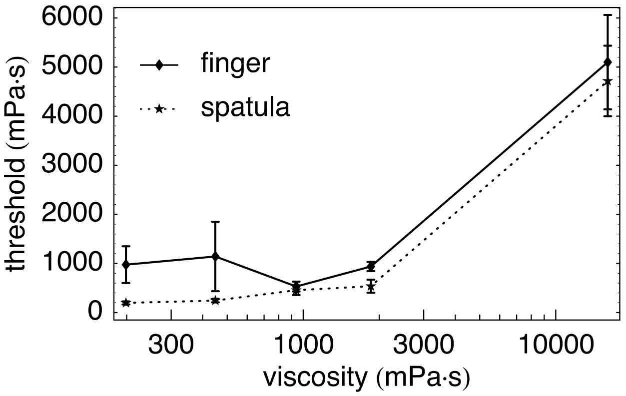

Fig. 5. Average thresholds for viscosity discrimination using two methods of perception as a function of reference viscosity. Note that the horizontal axis is logarithmic. The error bars represent the standard error of the sample mean.

absolute thresholds are shown in figure 5.

4.3 Discussion

Judging by the high average thresholds and large variation, most subjects find it very difficult to distinguish viscosities using their finger at the low end of the range (< 500 mPa·s). At the higher viscosities (thicker liquids), performance is on par with stirring with a spatula. On average, perception with the finger yields higher Weber fractions than with the spatula, especially for thin liquids. It is not clear why this should be. It might be that with the spatula, discrimination is made easier because there is a modulation in the force when the spatula is alternately moved in the direction of its wide or narrow side. However, this does not explain why the difference is not observed in the higher viscosity range. Alternatively, the rubber glove might have interfered with perception. The disrupting effect might be especially noticeable at the low end because of the low forces involved in viscosity perception in that range. For the thicker liquids, the forces are larger and the relative role of the glove might diminish. As another alternative, it might be that for the same liquid and movement speed, the forces involved are lower in the case of the finger in the glove than with the spatula. Since Weber fractions for weight discrimination (directly related to force discrimination) are higher at lower forces [18], this would result in higher discrimination thresholds in the case of stirring with the finger. It would be interesting to try and measure objectively the forces involved in stirring the liquid, in order to find an explanation for the observed differences between experiments 1 and 2. In this way, the effect of the rubber glove might be disentangled from that of a possible difference in forces. For this reason, some force measurements were conducted.

5 INTERMEZZO: FORCE MEASUREMENTS

Viscosity can be interpreted as the ratio between force and velocity of an object moving through a liquid. Therefore, changes in perceived force may lead to changes in perceived viscosity. If perception of the same physical viscosity is done using different levels of force, then differences in the level of force may also lead to differences in the *accuracy* of viscosity perception. For this reason, an explanation of the differences in discrimination thresholds for the same physical viscosity between experiments 1 and 2 might be found in differences in the forces involved. In this section, we will describe objective measurements of these forces.

5.1 Method

The idea is to measure the force that is involved in stirring a liquid with a spatula with and without a rubber glove around it, in order to find an explanation for the large difference in discrimination thresholds for viscosity. For this purpose, a simple setup was build for pushing a spatula through a liquid with a certain speed and measuring the force involved. A spatula was used in both situations (with and without glove) in order to focus on the role of the glove without confounding influence of the differences in geometry between a spatula and a finger. A sketch of the setup is shown in figure 6. An electric motor moves a block forward and backward, to which a force sensor is attached (FSR-149NS, International Electronics Engineering S.A.). On top of the force sensor is a rounded bumper that pushes against the spatula. The spatula can pivot in a slot in a surface which covers the liquid container. This cover was used to guide the spatula and was not present in the other experiments. The spatula sticks either directly into the liquid or is surrounded by the finger of a rubber glove. The silicone liquid with a dynamic viscosity of 10100 mPa·s was used. This high viscosity was chosen because it involves higher forces for a given movement speed, which can be measured more accurately. Since the liquids are highly Newtonian, any differences found for this high-viscosity liquid should also hold for the low-viscosity liquids used in the experiments. The spatula is held in place against the bumper using an elastic band, which provides a baseline force on the sensor. Differences in force are measured by reading out the change in electrical resistance of the sensor using an ADC board (PCI-1200, National Instruments). The force sensor was calibrated using a mechanical force gauge. Starting from the centre position with the spatula vertical, the bumper moved either backwards or forwards with a speed of about 4 mm/s. The signal from the sensor was sampled at 100 Hz for 10 s. Before the movement started, about 2 s of baseline samples were collected. In both directions, 10 measurements were collected. This was done for the situations with and without the rubber glove, resulting in 40 measurements in total. An example of such a measurement is shown figure 7. The difference between the

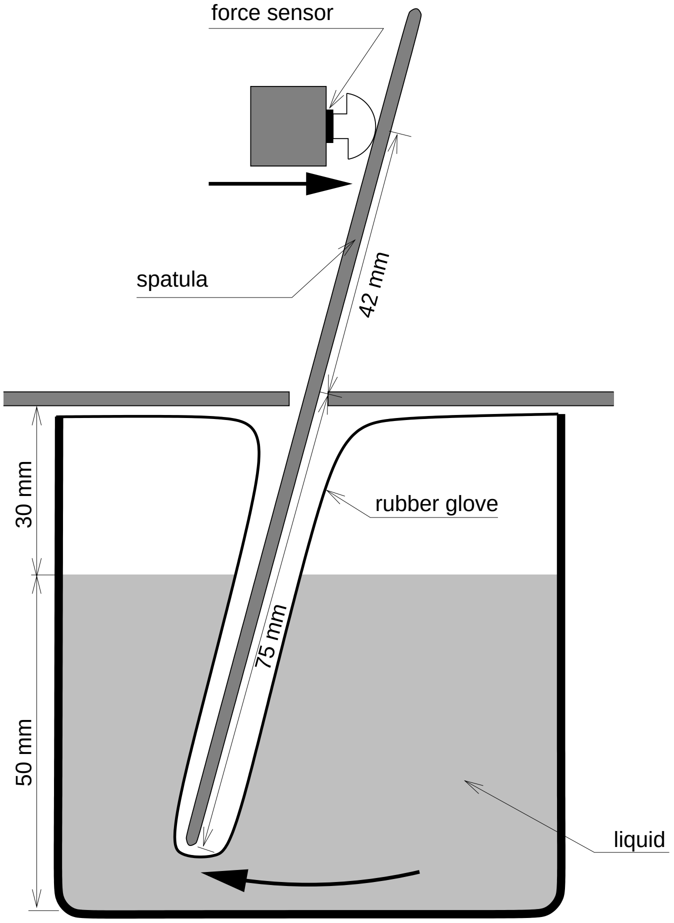

Fig. 6. Schematic depiction of the setup used to measure the force involved in moving a spatula through a liquid.

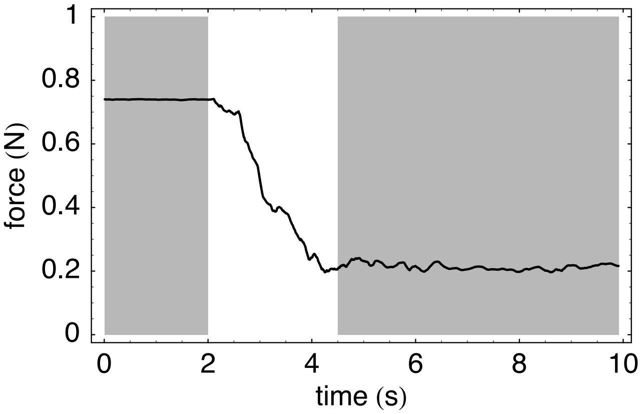

Fig. 7. Example of a force measurement with the spatula in a rubber glove being pulled through the liquid. The shaded areas indicate the ranges between which the change in force is calculated.

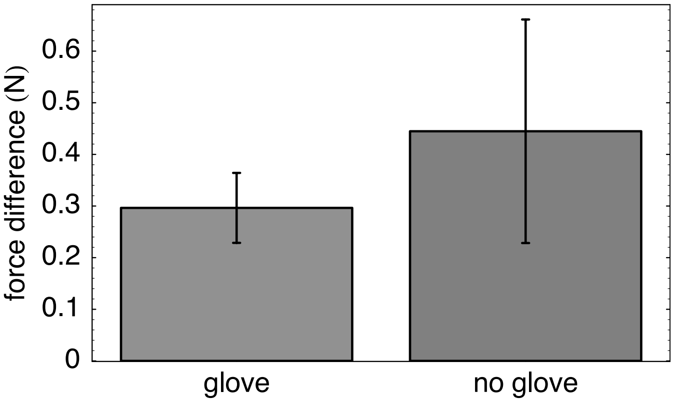

Fig. 8. The average force necessary for moving a spatula through a liquid with and without the presence of a rubber glove around the spatula. The error bars represent the standard deviation.

force before and after the transition was calculated for each measurement by averaging the measured force over the shaded areas in figure 7 and taking the difference. The calculated force differences from the measurements in both movement directions were averaged to eliminate any direction bias. Note that moving the spatula did not stretch the glove, as it pivoted around a centre point, so the measured forces are not the result of elastic forces.

5.2 Results

The average force differences for the situations with and without the rubber glove are shown in figure 8. As can be seen in the figure, the force in the condition without the glove is on average higher. Welch's t-test shows that this difference is significant ($t_{27} = 2.7,\ p = 0.013$). The ratio of the forces is 1.5.

5.3 Discussion

The fact that with the glove, less force is involved is a little surprising since we would expect that the glove would introduce additional friction. The opposite seems to be the case, perhaps due to a 'streamlining' effect of the glove, reducing turbulence in the liquid. As a result, less force is experienced when moving with the same velocity through a liquid with the glove than without, resulting in a different percept of the liquid's viscosity. This may have had an impact on the accuracy with which this viscosity is perceived, i.e. the discrimination threshold. Note that the observed ratio of forces between without and with glove of 1.5 is valid for the 10100 mPa·s viscosity, which is towards the high end of the range. It might be that for lower viscosities, other ratios apply, resulting in big differences in discrimination thresholds.

If such an explanation were to hold, it would predict that the same physical viscosity would lead to different perceived viscosities, depending on the method of stirring (finger or spatula, with or without glove). This

TABLE 2
PSEs and relative biases for the two conditions and two viscosity ranges in experiment 3.

reference		feels equal to (PSE)	bias
glove on finger	glove on spatula	bare spatula	
1646 mPa·s		282 mPa·s	83 %
10100 mPa·s		2784 mPa·s	72 %
	1646 mPa·s	386 mPa·s	77 %
	10100 mPa·s	2800 mPa·s	72 %

was tested in experiment 3, in which not discrimination thresholds were measured, but perceptual biases instead. A perceptual bias occurs when the intensity of the same stimulus is perceived differently depending on the conditions of perception. The strength of such a bias can be measured by determining the difference in intensity of two stimuli that feel equal under different conditions.

6 EXPERIMENT 3

In this experiment, liquids perceived with a spatula were directly compared to liquids perceived with the index finger in a rubber glove. In addition, another condition was tested in which stirring with a spatula was compared to using a spatula in the rubber glove. In this way, the role of the rubber glove could be assessed separately.

6.1 Subjects

Eight new subjects (three women) participated. They ranged in age from 19–23 and were all strongly right-handed. They gave informed consent and were paid for their time.

6.2 Results

For this experiment, the interesting results are not the discrimination thresholds but the shift in the PSEs, i.e. the viscosity of the liquid that, when perceived with the spatula directly in the liquid, feels equal in thickness to a liquid perceived with a gloved finger or a gloved spatula, respectively. The average PSEs for the low (1646 mPa·s reference) and high (10100 mPa·s reference) ranges are given in table 2. From the PSEs, relative biases can be calulated by taking the difference between the reference viscosity and the PSE and dividing by the reference viscosity. This particular definition of the bias was chosen because in the current experiment, the values come out positive. In figure 9, the relative biases are plotted for all subjects and both conditions. There are two bars for each condition, corresponding to the two reference values. The low value (1646 mPa·s) is on the left and the high value (10100 mPa·s) on the right of every pair. All four averages are significantly greater than zero (two-tailed t-tests, $t_7 > 11$, $p < 8.1 \times 10^{-6}$). A positive value corresponds to a *higher* viscosity liquid felt with the rubber glove feeling equal in ‘thickness’ as a *lower* viscosity liquid felt with the spatula directly in the liquid. In other words, the same liquid felt with the spatula directly in the liquid feels ‘thicker’ than with the rubber glove. A 2 (reference viscosity) × 2 (comparative stirring method) repeated-measures ANOVA showed a significant effect of reference viscosity ($F_{1,7} = 8.3$, $p = 0.023$), but not of comparative stirring method. The lower reference viscosity (1646 mPa·s) corresponds to a greater relative bias than the higher reference viscosity (10100 mPa·s). At the same time, there is no significant difference in the relative biases between the “glove on finger” vs. “bare spatula” comparison and the “glove on spatula” vs. “bare spatula” comparison.

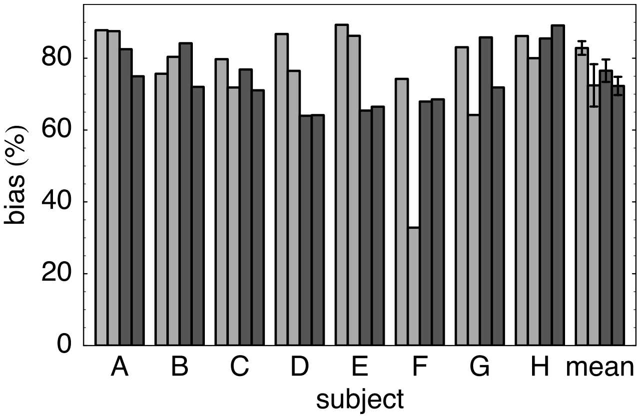

Fig. 9. Relative biases in matching viscosity perceived with a spatula to viscosity perceived with the index finger in a rubber glove (lighter bars), and matching viscosity perceived with a spatula directly in the liquid to viscosity perceived with a spatula in a rubber glove (darker bars). The four bars in each set correspond to the reference viscosities of 1646, 10100, 1646, and 10100 mPa·s, repectively. The error bars represent the standard error of the sample mean.

Although the staircase procedure is not designed to accurately measure discrimination thresholds, and the meaning of such thresholds is difficult to interpret when test and reference stimuli are perceived in different ways, they can still be used to assess whether the biases found are meaningful. The average Weber fractions ranged from 0.097 to 0.26 for the different conditions, which is small compared to the average biases found, which ranged from 72 % to 83 %.

6.3 Discussion

Since the average thresholds are small compared to the average biases, we can conclude that the biases found are meaningful. Although the difference between the relative bias for the two reference viscosities is statistically significant, this difference is very small compared to the magnitude of the biases. For both conditions and both high and low reference viscosity, very large biases are found: on average between 72 and 83 %. These biases are in the direction of the liquid stirred with the glove (either with a finger or a spatula) feeling much ‘thinner’

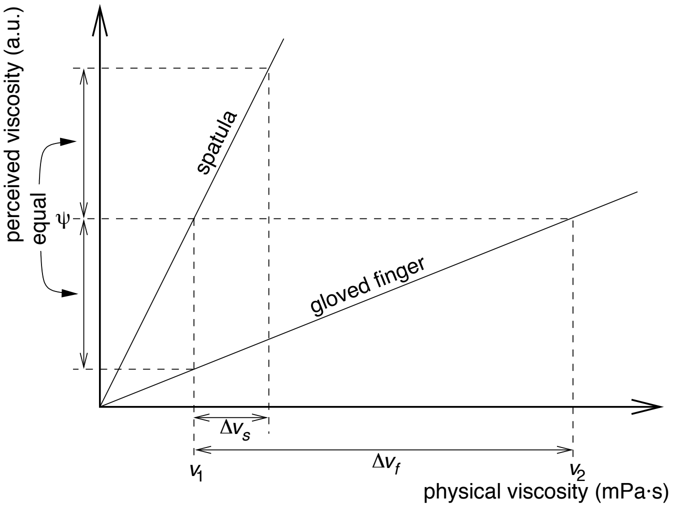

Fig. 10. Schematic illustration of a possible relationship between perceived viscosity and physical viscosity for two methods of stirring: ‘spatula’ and ‘gloved finger’. The accompanying thresholds Δv_s and Δv_f correspond to an equal difference in perceived viscosity on the vertical scale. The physical viscosities v_1 and v_2, corresponding to the same perceived viscosity ψ, differ greatly.

than the liquid stirred with the spatula directly in the liquid. To compare these results to the discrimination thresholds from experiments 1 and 2, we need to convert these biases to ratios of viscosities that are perceived to be equal. To do so, the relative biases are subtracted from 100 % to yield the ratio of the matched viscosity and the reference viscosity. A relative bias of roughly 80 % in this direction means that a liquid stirred with a spatula needs to have a viscosity of about 20 % (i.e. $100\,\% - 80\,\%$) of that of a liquid stirred with the gloved finger in order to feel equal. This is illustrated in figure 10. The physical viscosity v_2, when stirred with the finger, corresponds to the same perceived viscosity ψ as the physical viscosity v_1 when stirred with the spatula, while v_1 is about 20 % of v_2. So, the relationships between physical and perceived viscosity as depicted in figure 10 describe the observed bias in experiment 3.

From the results of experiments 1 and 2, we can say that the discrimination thresholds for the gloved finger are about five times as high as those for the spatula, in the lower range of viscosities (see figure 4). That is, the difference in physical viscosity Δv needs to be five times as high for the gloved finger as for the spatula in order for the difference in perceived viscosity to be the same. This is also illustrated in figure 10: The same difference in perceived viscosity on the vertical scale, being one discrimination threshold, corresponds to a physical viscosity difference of Δv_s when perceived with the spatula, and Δv_f with the gloved finger, which should be five times as large as Δv_s. This is the case when the local slope of the function describing the relationship between physical viscosity and viscosity perceived with the gloved finger were one-fifth of the local slope of the function describing the relationship between physical viscosity and viscosity perceived with the spatula.

So, we have two conditions for these functions: From experiments 1 and 2, we know that the local slopes for a given physical viscosity should be in a proportion of 5:1. From experiment 3, we know that the physical viscosities corresponding to a given perceived viscosity should be in a proportion of 1:5. These conditions can be satisfied if we were to assume linear functions through the origin with a slope ratio of 5:1. That means that the results of the three experiments are in agreement under the assumption of a linear dependence of perceived viscosity on physical viscosity. Is such an assumption justified? This assumption predicts that discrimination thresholds would be independent of reference viscosity. Looking at figure 5, this seems to be true for viscosities below 2000 mPa·s. We can conclude that within this range, perceiving viscosity with a spatula directly in the liquid has a five times steeper dependence on physical viscosity than perceiving it with a rubber glove, either with a finger or a spatula in it.

Although the biases are very large in magnitude, there is no significant difference in bias between those two conditions, so it seems that the bias is mostly due to the presence of the glove and has little to do with whether a finger or a spatula is used. The question now presents itself: is the large bias we find between perceiving viscosity with a spatula directly in the liquid and with the index finger in a rubber glove due to the different way of touching or the presence of the glove? To answer this question, we would like to compare the results to an experiment without the rubber glove. Unfortunately, performing the entire experiment with the subjects inserting their fingers directly into the liquid is not feasible because of the contamination of the different liquids or the large loss of liquid that sticks to the fingers and has to be wiped off. Instead, we have performed two small control experiments to check how the liquid is perceived without the rubber glove.

7 CONTROL EXPERIMENTS

Two control experiments were performed to check whether the arrangement with the rubber glove is representative for stirring with the finger directly in the liquid in terms of perceived viscosity. In the first control experiment, stirring with the bare finger was compared to stirring with a spatula. If stirring with the finger with and without rubber glove are indeed equivalent, we would expect a bias that is similar to that found in the first condition of experiment 3, i.e. in the order of 70–80 %. In the second control experiment, stirring with the bare finger was compared directly to stirring with the finger in the glove. This is a direct test of the validity of using the rubber glove as a substitute for direct contact. If this is valid, we would expect no biases, i.e. around 0 %.

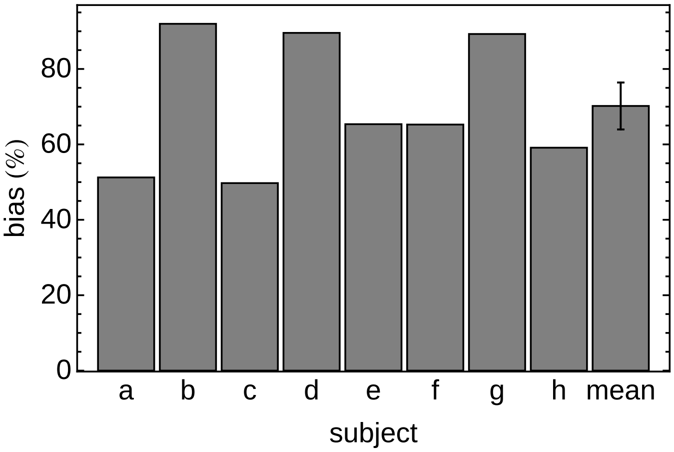

Fig. 11. Relative biases in matching viscosity perceived with a spatula to viscosity perceived with the bare index finger. The error bar represents the standard error of the sample mean.

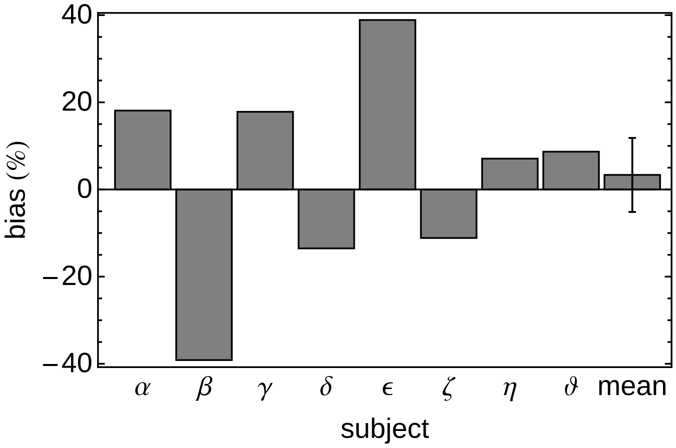

Fig. 12. Relative biases in matching viscosity perceived with a gloved index finger to viscosity perceived with the bare index finger. The error bar represents the standard error of the sample mean.

7.1 Method

In the experiments, two different sets of eight colleagues (four male in the first and three male in the second experiment, all right-handed and naïve to the exact purpose and circumstances of the experiment) were asked to stir a container with 250 ml of silicone oil with a dynamic viscosity of 973 mPa·s using the index finger of one hand. To avoid having to wipe off the subject's finger after each trial, one hand is used to stir the same liquid throughout the whole experiment. Half of the subjects used their right hand for this; the other half the left. With their other hand, they stirred another container with silicone oil using a wooden spatula (first experiment) or their index finger in a rubber glove (second experiment). Their task was to indicate which liquid was the more viscous (thicker). Using a double interleaved staircase procedure similar to experiment 3, 25 trials were performed. This took about 10 min. The following test viscosities were used: 76, 98, 155, 199, 243, 334, 449, 606, 740, and 906 mPa·s for the first experiment and 334, 449, 606, 740, 938, 1093, 1236, 1646, 2552, and 3185 mPa·s for the second. The reference value of 973 mPa·s was chosen because it corresponded to one of the standard liquids of which we had some left, such that the container could be replenished after each subject to account for the loss of the liquid that stuck to the subjects' fingers. The fraction of times the test stimulus was chosen to feel the "thickest" was plotted against the test viscosity. To these data, psychometric curves were fitted to determine the points of subjective equality.

7.2 Results

The relative biases (difference between reference viscosity as felt with the bare index finger and perceptually equal viscosity as felt using the spatula, divided by the reference viscosity) are plotted in figures 11 and 12. On average, there is a relative bias of 70 % (SE 6 %) in the first control experiment. This is significantly different from zero (two-tailed t-test, $t_7 = 11,\ p = 9.5 \times 10^{-6}$). This bias means that a liquid with a dynamic viscosity of 973 mPa·s felt with the bare finger feels equally thick as a liquid with a dynamic viscosity of 290 mPa·s stirred with a spatula. The relative bias in this experiment is not significantly different from the relative bias found for 1646 mPa·s in the first condition of experiment 3 (Welch's t-test, $t_{8.5} = 1.9,\ p = 0.087$).

In the second control experiment, the average bias is only 3 % (SE 8 %). This is not significantly different from zero (two-tailed t-test, $t_7 = 3.9,\ p = 0.71$). This means that on average, there is no difference in perceived viscosity between using a rubber glove or not. It is significantly different from the results for 1646 mPa·s of the first condition of experiment 3 (Welch's t-test, $t_{7.8} = 9.1,\ p = 2.0 \times 10^{-5}$). For the individual subjects, there does seem to be an effect of which hand was used for direct perception, with all subjects except subject ϑ having a slight bias in the direction of the dominant hand perceiving the liquid as thinner than the non-dominant hand.

7.3 Discussion

The fact that also with a bare finger, biases of a large magnitude are found indicates that the bias found in the first condition of experiment 3 is not due to the presence of the rubber glove. The difference in bias between experiment 3 and the control experiment did not reach significance, suggesting that the method of using the index finger in the rubber glove is representative of the situation without rubber glove. This is confirmed by the second control experiment, where no statistically significant bias was found for the direct comparison, suggesting that the effect of the rubber glove is very small in this case. The finding of an effect of which hand (dominant or non-dominant) is used for perception has no consequences for the main experiments 1–3, in which only the dominant hand was used. These results mean that we can interpret the results of the first condition of experiment 3 as valid, irrespective of whether a rubber glove is used or not.

However, this does not account for the bias of almost equal magnitude that was found in the second condition of experiment 3: the comparison of stirring with a spatula directly in the liquid to stirring with the spatula in a rubber glove. That bias might be explained in part by the differences in forces involved, as found in the physical force measurements. Lower forces were observed in the case of stirring with the spatula with a rubber glove around it, which might have been interpreted as a lower viscosity. Combined with a hypothetical expectation of the subjects that the glove would actually lead to higher forces, this might account for the bias observed in the second condition of experiment 3.

8 GENERAL DISCUSSION AND CONCLUSIONS

From the results it is clear that viscosity discrimination is not described by Weber's law. Although Weber fractions appear to be constant at higher viscosities, they increase with decreasing viscosity in the lower range. A similar behaviour was observed earlier for the 'viscosity' of a mechanical system [11]. Although the measurements cannot be directly compared because they are on a different continuum, the Weber fractions at the higher viscosities are very similar at ~ 0.3. This value was also found in the measurement made at a very high viscosity [10]. This suggests that in the high range ($\gtrsim 2000$ mPa·s), Weber's law does apply. However, in the lower range, another model seems more likely: a more or less constant value of the absolute discrimination thresholds, meaning that the Weber fractions in this range are inversely proportional to the reference viscosity. This is a similar pattern to what is observed for discrimination of weight [18], which is of course directly related to force discrimination and therfore to viscosity discrimination.

An obvious difference between viscosity perception on the one hand and force or weight perception on the other is that the latter usually involves constant forces, whereas for the former, the force changes as a function of the velocity. This changing force may have an impact on the discrimination performance. In addition, within a confined space such as a cup, there are the forces related to acceleration and deceleration of the hand and probe that confound perception further, especially for the lower range. This might be an additional explanation of the increased Weber fractions for viscosity discrimination for the lower viscosities.

The model of constant absolute discrimination thresholds is in line with a linear dependence of perceived viscosity on physical viscosity. After all, in that case the perceptual difference between a test and a reference stimulus only depends on their physical difference, and not on their magnitude. This linear dependence follows from the fact that a liquid felt with a rubber glove feels five times as thin as a liquid felt without rubber glove (experiment 3), combined with the fact that discrimination thresholds are five times as high with the rubber glove as without (experiments 1 and 2). The only way to reconcile these facts mathematically is to assume a linear relationship between perceived and physical viscosity in the low viscosity range. In the higher viscosity range, the model of the power law as found in the magnitude estimation experiments [3], [4] could still be valid.

This linear relationship for the lower range seems at odds with the power function exponent of ~ 0.4 found in the magnitude estimation experiments (a linear function is identical to a power function with an exponent of 1). However, it might be that the results of a magnitude estimation procedure do not exactly correspond to perceived viscosity, i.e. an internal representation of the sensation. A similar phenomenon was observed in the perception of roughness and compressibility [19]. The reason might be a non-linear transformation between the internal representation of the sensation and the reported number during the magnitude estimation.

The steepness of the linear relationship between physical and perceived viscosity depends on the way of exploring the liquid: when using a spatula, the slope is five times as high as when using a finger. From the control experiment, we can conclude that this also occurs when there is no rubber glove present around the finger. However, when a rubber glove is present around that spatula, a liquid is found to feel much thinner compared to a spatula directly in the liquid. From the physical measurements, we know that the force necessary for moving a spatula through the liquid is indeed lower when a rubber glove is present. However, this difference is only a factor of 1.5, not 5. It might be that the factor of 5 is explained by a combination of two effects: the effect of the physically lower force necessary and an effect of expectations. A subject might expect to need more force in the case of the rubber glove (even though the reverse is true), and tries to correct his/her perception for this, thus perceiving a thicker liquid with the rubber glove as thinner. Therefore, s/he is not able to correctly account for the differences between stirring with a spatula directly in the liquid and stirring with a spatula in a rubber glove.

To conclude, we can say that the perception of viscosity depends on the way it is perceived: directly or indirectly. This is very important to keep in mind when designing haptic displays capable of rendering liquid viscosity, because these are often interacted with using a rigid probe instead of direct skin contact.

ACKNOWLEDGEMENTS

This research was supported by a grant from the Netherlands Organisation for Scientific Research (NWO). The authors thank ing. Emile Bakelaar (dept. of Chemistry) for his assistance with the rheometer measurements.

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