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Tactual perception of liquid material properties

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ABSTRACT

In this paper, studies into the tactual perception of two liquid material properties, viscosity and wetness, are reviewed. These properties are very relevant in the context of interaction with liquids, both real, such as cosmetics or food products, and simulated, as in virtual reality or teleoperation. Both properties have been the subject of psychophysical characterisation in terms of magnitude estimation experiments and discrimination experiments, which are discussed. For viscosity, both oral and manual perception is discussed, as well as the perception of the viscosity of a mechanical system. For wetness, the relevant cues are identified and factors affecting perception are discussed. Finally, some conclusions are drawn pertaining to both properties.

1. Introduction

Material properties form a very important part of our perceptual world. For both vision and haptics, the material an object is made of is one of the most salient aspects of the object (Baumgartner, Wiebel & Gegenfurtner, 2013). For haptic perception of material properties, I have reviewed the literature in a previous issue of this journal (Bergmann Tiest, 2010), but only as far as *solid* material properties are concerned. Objects (in a broad sense of the word) can also be *liquid* or even *gaseous*. For tactual perception, these other states of matter share some aspects with solids, such as coldness or compliance, but there are some tactual aspects that are unique to liquids: viscosity and wetness. Viscosity refers to the resistance to deformation of the liquid, and is most noticeable when moving a probe (like a spoon) through a liquid, or moving the container about, for example when stirring paint or swirling wine. The wetness of an object is actually not a property of the object itself, but refers to the presence (and amount) of liquid on, or absorbed by, the object, for example a wet sponge. Therefore, similar to viscosity, I classify this as a liquid material property.

Perception of liquid material properties has not received a lot of attention, yet they are of great importance in fields such as food science or cosmetics. In a study involving ten diverse fluids and creams that were applied on the skin, Guest et al. (2012) asked subjects to rate the stimuli on a number of sensory and emotional attributes. Of the sensory attributes, "wet" was found to be the one the stimuli differed most in. The authors identified this as part of a "lubricating" dimension. Other dimensions identified were "textured", "silken", and "viscous" (Guest et al., 2012). Of these, the wetness and viscosity dimensions are the two material properties that most clearly define a liquid from a tactual point of view. Furthermore, in the context of virtual reality or teleoperation, the simulation of interaction with liquids is a challenge (Vines, Lee & Mavriplis, 2012). Also for this purpose, these two properties are of defining importance.

The purpose of the present paper is to review the current state of understanding of the tactual perception of these properties. Since no specific receptor types for either have been identified, nor neural correlates, this review mainly focuses on psychophysical investigations into the tactual perception of viscosity and wetness. First, viscosity is discussed, followed by wetness. Finally, some conclusions are drawn that pertain to tactual perception of liquid material properties in general.

2. Viscosity

Viscosity can be described as the "thickness" of a liquid: wall paint is highly viscous, whereas water is very low in viscosity. From daily life experience, it is clear that viscosity is a liquid material property that is easily perceived tactually. In this section, both physical and perceived viscosity are discussed, and their relationship. This relationship is characterised by several types of psychophysical experiments, such as magnitude estimation and discrimination threshold measurements. In addition, perception of the viscosity of a mechanical system is discussed.

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2.1. Physical viscosity

In the physical sense, viscosity is defined as a liquid's amount of resistance against *shear stress* (Symon, 1960, section 8–14). That is, the force necessary for layers of the liquid to move at different speeds. The shear stress is expressed as the force exerted on the liquid by the probe, divided by the surface area of the probe, in units of N/m^2 or Pa. For example, when a solid probe is moved through a liquid, the liquid close to the probe will move at approximately the same speed as the probe itself. In contrast, the liquid close to the wall of the container will be almost stationary. This causes a *gradient* of moving speeds to exist within the liquid, called the *shear rate*. The shear rate indicates how quickly the liquid's velocity changes as the position changes perpendicular to the direction of movement. For instance, if the liquid's velocity close to the wall of the container is 1 cm/s, and the liquid's velocity 2 cm further away is 6 cm/s, then the shear rate is (6 cm/s) / (2 cm) = 3 s^{-1}. The factor of proportionality between this shear rate and the shear stress is defined as the *dynamic viscosity*. It is expressed in units of Pa s, or Pascal second. Water has a dynamic viscosity of 1 mPa s, while for instance liquid honey has a dynamic viscosity of 10,000 mPa s. Motor oil has a viscosity in the range of 100 mPa s, and numbers can go up to 10^{11} mPa s for pitch. For so-called *Newtonian liquids*, the viscosity is independent of the shear rate; that is, the viscosity does not change with different movement speeds of the probe. There also exist *non-Newtonian liquids*, such as corn starch dissolved in water, for which the resistance encountered when moving through the liquid depends strongly on the movement speed. Viscosity is usually measured with a *rheometer*, which registers the force necessary for moving a plate relative to another with a given speed, with the liquid between them.

In addition to a liquid's viscosity, there is also the viscosity of a mechanical system. This is one of the terms in the system's *mechanical impedance*, which describes the system's resistive force as a function of position, velocity, and acceleration. In this context, viscosity is defined as the factor of proportionality between moving speed and resistive force, expressed in units of Ns/m. Although not actually a liquid material property, it is discussed here as well because of its similarity to the viscosity of a liquid.

2.2. Magnitude estimation of viscosity

Magnitude estimation is used to characterise the relationship between the physical intensity of a stimulus and the perceived intensity. For stirred silicone liquids in the range of 10–95,000 mPa s, a power function with an exponent of 0.43 was found (Stevens & Guirao, 1964). That is, for a doubling of the physical viscosity, the perceived viscosity increases by a factor of 1.34. In a similar experiment, in which subjects directly touched the liquids (various solutions of gum in water), a somewhat lower average exponent of 0.37 was found (Moskowitz, 1972). The exponents of the power functions for the different types of gum varied substantially, from ~ 0.02 for pectin up to ~ 0.7 for cellulose gum. The reason for this might be differences in the way the physical viscosity depended on the shear rate (most of the gum solutions were non-Newtonian). Subjects might have used other shear rates than the one used in the analysis of the data. Typical shear rates used for stirring are around 100 s^{-1} (Shama, Parkinson & Sherman, 1973), but may range from 1 to 10,000 s^{-1}, depending on the viscosity of the liquid (Houska et al., 1998). A very comparable exponent of 0.35 was found using a nearly-Newtonian series of gum solutions in water that were stirred using a glass rod (Christensen & Casper, 1987). These authors also compared viscosity perception using the fingers directly and using the mouth, resulting in almost identical exponents of 0.33 and 0.34, respectively. We can say that independent of the way of exploration and the type of liquid, a power function with an exponent of ~ 0.3—0.4 is a good description of the relationship between physical and perceived viscosity. Remarkably, despite this equality of the exponent, Christensen and Casper (1987) found a shift in the scaling factor for the different exploration methods: perception using oral methods generally yields a higher perceived viscosity than non-oral methods (rod, fingers) for the same physical viscosity. This difference is not likely due to mixing with saliva in the mouth, as saliva has a very low viscosity (Roberts, 1977), which would only bring the total viscosity down, not up. It is unclear whether the effect is due to differences in receptors or higher-level processes.

Oral viscosity perception has been the subject of some more studies, mainly from the food science community. Shama and Sherman (1973) found shear rates ranging from 1000 s^{-1} for oral exploration of highly fluid liquids down to an asymptotical value of 10 s^{-1} for highly viscous liquids. With regard to the relationship between physical and perceived viscosity, a power function with an exponent of 0.29 was found for oral perception of viscosity of aqueous solutions thickened with a food-grade gum (Christensen, 1979). Perception of higher-viscosity solutions was affected by taste: perceived viscosity decreased with increasing sourness and saltiness, but increased slightly with increasing sweetness of solutions with the same physical viscosity (Christensen, 1980). Furthermore, swallowing and compression between tongue and palate gave nearly identical results, while slurping resulted in a somewhat stronger dependence of perceived on physical viscosity (Houska et al., 1998). Incidentally, these authors found a better fit using a logarithmical relationship between physical and perceived viscosity, rather than a power function. Also, they did not confirm the asymptotical behaviour with respect to shear rate found by Shama and Sherman (1973), but rather found that the used shear rates kept decreasing with increasing viscosity. Finally, viscosity perception seems to be affected by age: in a magnitude estimation study with three age groups, Smith, Logemann, Burghardt, Zecker, and Rademaker (2006) found a power function exponent that decreased from 0.39 for the youngest to 0.27 for the oldest group. All in all, it seems that oral viscosity perception is quite comparable to non-oral viscosity perception, but is somewhat affected by the exploration method, age, and taste.

2.3. Discrimination of viscosity

As magnitude estimation is concerned with the relationship between physical and perceived stimulus magnitude, so are discrimination experiments concerned with the smallest difference in stimulus intensity that is still perceivable (i.e. Just Noticeable Difference, JND). For manual viscosity perception, this was pioneered by Scott Blair and Coppen (1939) using balls of bitumen (viscosity in the order of 10^8 mPa s) that were handled underwater. They found correct discrimination rates of about 80% for viscosity differences of 30%. This corresponds to a Weber fraction (ratio of JND and stimulus magnitude) of 0.3 for manual discrimination. This Weber fraction for highly viscous liquids was confirmed by Bergmann Tiest, Vrijling and Kappers (2013), who measured viscosity discrimination thresholds over the range of 200–16,000 mPa s. They tested viscosity perception using silicone liquids both by stirring with a spatula and by moving the index finger through the liquid, covered by a rubber glove to prevent mixing of the different liquids. As shown in Fig. 1, Weber fractions for both conditions go down to 0.3 for higher viscosities. However, for the lower viscosities (<1000 mPa s), Weber fractions are considerably higher, up to 1 for the spatula condition, and much higher still for the finger in the rubber glove, mainly due to a few very high individual thresholds (note also the large error bars). This deviation between the two conditions suggests that the presence of a