Auditory and Visual Crossmodal Correspondences with Haptically Perceived Liquid Viscosity

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Summary

Past research on cross-modal correspondences as they relate to tactile perception has largely been restricted to solid substances. We investigated the role of haptically explored liquid viscosity in crossmodal correspondences with visually presented luminance, saturation, roundedness, size, number and visual elevation, as well as pure-tone pitch and kiki-bouba-type letter strings. In Experiment 1, we presented two tactile and two visual or auditory stimuli simultaneously, and found significant inter-participant agreement (N = 32) when pairing viscosity with luminance, saturation, roundedness, size, pitch and letter string type. To assess whether these crossmodal correspondences were relative or absolute, another 32 participants were presented, in Experiment 2, with two tactile stimuli but only one visual/auditory stimulus per trial. In this second Experiment, we found that high viscosity was paired with low luminance, roundness, low saturation, and the bouba-type letter string, while low viscosity was paired with high pitch. However, the inverse associations (e.g. low viscosity with high luminance, high viscosity with low pitch) were not significant. These findings indicate that viscosity can be added to the list of dimensions that invoke crossmodal correspondences, and that the majority of crossmodal correspondences involving viscosity are absolute rather than relative, since they appear without explicit comparisons along the visual/auditory dimensions we measured.

Keywords: crossmodal correspondences; liquid; viscosity; haptics; vision; hearing

Introduction

The world is full of objects that can be apprehended through more than one sense. Imagine that you are walking down a street and you hear a high-pitched meow. Looking around, you see two cats – one large, and one small. Based on your prior experience of small animals making high-pitched noises and large animals making low-pitched noises, you are likely to assume that the smaller animal is the one that meowed, though this may not in fact be the case. This is an example of an experience-based, or statistical, crossmodal correspondence (CMC): a perceptual or cognitive bias to pair certain aspects of different sensory dimensions.

There are many different reasons for the existence of CMCs. In 2011, Spence suggested that there are at least three categories of CMC: structural, statistical and semantic. Structural CMCs are based purely on innate aspects of brain biology – for example, two sensory dimensions may be processed in adjoining areas, or may even have common neural correlates (see also Walsh, 2003). Statistical CMCs are based on learning – in the example we gave at the beginning, we have learned that soft things are normally also warm things because of our experiences with soft, warm animals. In Spence's model, semantic CMCs are meaning-based in the broadest sense– for example, the words 'high' and 'low' are used for both pitch and spatial elevation in English. Other researchers (e.g. Walker & Walker, 2012) draw a stricter distinction between semantic CMCs based on language (as in the pitch-height example above) and CMCs based on concepts (as in the framework of connotative meaning, discussed in further detail below). Spence further acknowledged that this list is not exhaustive and suggested that, for example, a similar emotional valence attached to points on different sensory dimensions might allow a CMC to form – for example, Palmer *et al*. (2013) suggest that the colours their participants matched with excerpts of classical music were chosen because of their shared emotional valence.

Further, it can be difficult to distinguish in what way(s) CMC occurs, since there are often multiple possible explanations for a single CMC and the distinctions between the ways are not clear. For example, the pitch-height CMC might be understood as structural as well as linguistic (Jonas, Spiller & Hibbard, submitted; Spence, 2011).

The earliest studies on CMCs focused mainly on sound symbolism – i.e. to what extent the sense of a word can be reflected in its sound (e.g. Fox, 1935; Hevner, 1937; see Spence, 2011, for a review). Later studies have extended the field of research to vision (e.g. Gilbert, Martin, & Kemp, 1996; Martino & Marks, 2000; Parise & Spence, 2012) taste (e.g. Deroy & Valentin, 2011; Hanson-Vaux *et al*., 2013; Rudmin & Cappelli, 1983), smell (e.g. Belkin *et al*., 1997; Morrot *et al*., 2001; Seo *et al*., 2010) and, of particular interest in the current study, touch.

The literature on CMCs in touch is quite large, in part because the sense of touch contains multiple dimensions, including vibrational frequency, size, smoothness, softness, and elasticity. However, the vast majority of research on CMCs involving tactile dimensions has been about solid objects, a summary of which we present in Table 1. There are also multiple studies on the effect of tactile dimensions on conceptual dimensions such as perceived expensiveness (e.g. Harrar & Spence, 2013; Ludden & Van Rompay, 2015), liking (Michel *et al*., 2015), femininity (Etzi *et al*., in press) and activeness (Walker & Smith, 1985), which we do not include in the table.

As Table 1 shows, some perceptual characteristics are linked to multiple dimensions of touch. For example, high luminance is linked with high vibrational frequency, low weight, high smoothness, low sharpness, high softness, high elasticity, low adhesion, and small size. This is a particularly good illustration of the framework of connotative meaning (Walker & Walker, 2012; Walker *et al*., 2012). In this framework, CMCs lead us to make certain assumptions about the visual properties of objects we have only felt or heard, the tactile properties of objects we have only seen, etc. For example, if you know an object is soft, you are also likely to predict that it is light in colour. There is clearly a role for experience in making such predictions – earlier in this paragraph, the link between softness and lightness was presented and so this information is now readily available to the reader. However, there are also more distal considerations of experience such as the soft toys often given to babies, which are rarely dark in colour (though they are sometimes highly saturated rather than pale). In sum, Walker's position is that the explicit sensory information we have about an object allows access to a network of implicit (or connoted) information about that object. Note that this network, too, is semantic, but in the broad sense of being based in meaning rather than in Spence's (2011) more restricted sense of being based in language.

[Table 1 about here]

The framework is not perfect – if we look at the CMCs assigned to saturation in Table 1, a high value on this dimension is linked to medium weight, medium elasticity, and medium adhesion. However, in different studies, high saturation has been linked to high *or* medium smoothness, and high *or* medium softness. This inconsistency may be explained by isolated cases of Garner interference (i.e. the integration of two separate dimensions such as saturation and luminance into one super-dimension) in an otherwise consistent framework (see Jonas *et al*., submitted).

There are also gaps in the framework. A particularly large one relates to non-solid substances. In contrast to the literature on CMCs of tactile dimensions of solid objects, there are three studies on CMCs as (approximately) applied to liquids and, as far as we know, none at all on gases. The first of the studies on CMCs of liquids was by Churchill *et al*. (2009), who found that scent could influence the perceived tactile attributes (e.g. stickiness and creaminess) of a shampoo, such that, for example, camphor-scented shampoos were perceived as more sticky and less creamy, while citrus-scented shampoos were perceived as less sticky and more creamy.

The second study on CMCs in liquids was rather different from the first; rather than rating liquids based on their scents, Eitan and Rothschild (2010) asked participants to rate various musical notes on a scale from 'wet' to 'dry' (among other metaphorical attributes; see table 1 for further examples). Here, participants were more likely to rate high-pitched, violin and non-vibrato notes as drier than low-pitched, flute and vibrato notes, respectively. Since the framework of connotative meaning suggests that relationships between different dimensions of a CMC should be reciprocal, it is plausible that should a participant be given a soaked sponge and a damp sponge, the soaked sponge would likewise be paired with low-pitched, flute and non-vibrato notes at a higher rate than the damp sponge.

The most recent study of CMCs in liquids was conducted by Risso *et al*. (2015), who asked participants to rate perceived and expected carbonation of water presented in blue, red or white cups, as well as rating which colour of cup they would rather have when drinking still, slightly carbonated or carbonated water. Participants generally perceived carbonation to be lower in blue or red cups compared to white, and likewise expected carbonation to be greater in white or red cups compared to blue. However, when asked to choose what cup they would like for each type of water, participants were most likely to choose white cups for still water, blue or red cups for slightly carbonated water, and blue cups for carbonated water.

As can be seen from the summaries above, very little is known about how the tactile qualities of liquids fit into the framework of connotative meaning. Consequently, we designed a study in which participants were presented with two Natrosol™ (hydroxyethyl cellulose) and water solutions of differing viscosity. Natrosol™ is a nontoxic substance derived from plant cells and used as a gelling/thickening agent in many household products such as shampoo and shaving gel. In Experiment 1, participants were presented with four stimuli at a time: two tactile and two auditory or visual. Participants were asked to decide which tactile stimulus went with which visual/auditory stimulus. In Experiment 2, participants were presented with three stimuli at a time: two tactile and *one* auditory or visual. This time, participants were asked to choose which of the two tactile stimuli went better with the auditory or visual stimulus. Together, the Experiments allow us to establish which of the tested CMCs are relative (i.e. require the presence of two stimuli on both sensory dimensions to be apparent) and which are absolute (i.e. require the presence of only one visual or auditory stimulus to be apparent). Relative CMCs may be interpreted as indicative of meaning-based relationships between the sensory dimensions, while absolute CMCs may be interpreted as indicative of perceptual relationships between the sensory dimensions (e.g. Marks, 1987; Walker & Walker, 2015).

In each Experiment, visual stimuli varied on the dimensions pointed/rounded; light/dark; saturated/unsaturated; small/large; high/low visual elevation; many/one (i.e. many small shapes occupying approximately the same total surface area as one large shape); and KEETAY/NOHMOO. The last of these was unusual in that participants were shown the two letter strings and asked to read them aloud before making their decision so that the experimenter could check that they were being vocalised in the way we intended[1];

[1] We intended for participants to pronounce these words /kiːteɪ/ and /nəʊmuː/, though some pronounced the latter as /nɔ$^{(h)}$ːmuː/. KEETAY contains voiceless, plosive consonants and front vowels, while NOHMOO contains voiced, nasal consonants and central or back vowels respectively for the two pronunciations.

thus, this particular stimulus pair had both visual and auditory properties. Auditory stimuli varied on the dimension high/low pitch.

Because so little is known about CMCs as they relate to liquids, we are unable to make strong hypotheses about the findings. However, weight, elasticity and adhesion of solid objects may be thought of as similar to the viscosity of liquid objects, since they all directly relate to the resistance an object puts up to movement. Thus, based on the findings of Eitan and Rothschild (2010), Slobodenyuk *et al*. (2015), Walker *et al*. (2010) and Ward *et al*. (2008), we can predict that high viscosity should be matched with low luminance and low pitch. Based on Slobodenyuk *et al*., the relationship between saturation and viscosity is likely to be non-linear – however, since we are using a 2AFC paradigm this relationship may not be apparent; rather, this CMC is likely to be weakly significant or non-significant (a non-significant result here may, of course, also indicate the lack of a CMC).

Based on the above hypotheses about luminance and pitch, we can also use Walker's framework of connotative meaning to make secondary hypotheses. Walker *et al*. (2012) found that low luminance was associated with large size and roundedness rather than pointedness; thus, if high viscosity is associated with low luminance it should also be associated with large size and roundness. Further, work by Eitans and Timmers (2010) indicates that low visual elevation is matched with low pitch; therefore, low visual elevation should be associated with high viscosity. Lastly, D'Onofrio (2013) found that rounded shapes are associated with voiced consonants and (under some conditions) non-front vowels, as in our stimulus NOHMOO, while pointed shapes are associated with voiceless consonants and (under some conditions) front vowels, as in our stimulus KEETAY. Again, if high viscosity is associated with low luminance, which is associated with roundness, which in turn is associated with NOHMOO-type words, then our participants should pair the high-viscosity liquid with NOHMOO rather than KEETAY.

To our knowledge, there is no previous research on CMCs related to the many/one distinction we describe above; thus, for the many/one dimension we are unable to make a prediction.

Experiment 1: Material and methods

Participants

Thirty-two participants (22 female, 10 male; mean age = 30.97 years, SD = 12.09, range = 18-63; 27 right-handed, 5 left-handed [by simple self-report]) were recruited for this Experiment from among the students and staff of the University of East London, using a snowball sampling technique from the personal contacts of the researchers. All participants were native speakers of English: 18 were monolingual speakers of English and the remaining 14 were fluent in English and another language[2], with English being their mother tongue.

Materials and design

The tactile stimuli were two room-temperature solutions of Natrosol™ powder (from www.messysupplies.com) and water. The thick solution contained 100ml of water and 1tsp of Natrosol™ powder; the thin solution 100ml of water and 0.5tsp of Natrosol™ powder. Tactile stimuli were presented in non-lidded Tupperware containers measuring 22cm width x 22cm depth x 11cm height. During the Experiment, the two solutions were hidden from sight using cardboard boxes with hand holes for participants. The hand (left or right) to which each mixture was presented was counterbalanced across participants.

Visual stimuli were presented on a flatscreen monitor using Microsoft PowerPoint (Fig. 1). Each pair of visual stimuli varied on one of the following dimensions: pointed/rounded; light/dark; saturated/unsaturated; small/large; high/low visual elevation; many/one; and KEETAY/NOHMOO. All stimuli were presented on a white background. With the exception of KEETAY/NOHMOO, which was presented in black (HSL value: 170,0,0) 28pt Calibri, the stimuli were all presented in green (HSL hue value 85). For the pointed/rounded, small/large, high/low and many/one, both stimuli were presented in the same colour (HSL value: 85,129,128). For the light/dark pair, the light stimulus HSL value was 85,128,191 and the dark stimulus HSL value was 85,128,64. For the saturated/unsaturated pair, the

[2] Of the bilingual participants, there were two speakers of each of Arabic, Bengali, Creole, Farsi and French, and one speaker of each of Finnish, Greek, Italian and Lithuanian.

saturated stimulus HSL value was 85,191,128 and the unsaturated stimulus HSL value was 85,64,128.

Auditory stimuli were embedded in the PowerPoint and presented over headphones. The sole pair of auditory stimuli were two pure sine wave tones of 1000ms duration at 261.63Hz (C_4/middle C) and 523.25Hz (C_5/one octave above middle C). Participants were able to adjust the volume of these sounds to a comfortable level but did not change the volume level once they had finished hearing the first sound.

The order of visual and auditory stimulus presentation was counterbalanced across participants using a Latin square design.

[Figure 1 about here]

Procedure

The Experiment took place in a quiet room in the School of Psychology at the University of East London. Participants were individually tested. Following briefing, consent and the collection of demographic data, the participant was asked to sit at a table in front of a computer monitor and to wear over-ear headphones (which did not prevent them from being able to hear the experimenter). On the table were two identical containers, each containing 100ml of Natrosol™ solution of differing viscosities. These containers were obscured from the participant's sight by cardboard boxes labelled 'A' and 'B' with holes for the participant's hands. The participant was asked to place one hand in each of the containers and run their fingers through the Natrosol™ solutions. Once the participant was familiar with the solutions the experimenter presented pairs of visual/auditory stimuli, one pair at a time, on the monitor or over the headphones and asked the participant to decide which of the solutions 'went with' which of the visual/auditory pairs. Participants were told that there was no time limit for their decision and in the case of the auditory stimuli were told that they could request the sounds to be repeated as many times as they wished. Once the participant responded, the experimenter recorded the answer on a coding sheet.

All participants gave informed consent and were debriefed by the experimenter. This study was approved by the University of East London's Research Ethics Committee.

Experiment 1: Results and Discussion

The data for this study were analysed using a chi-square goodness of fit test. Since we carried out multiple comparisons, we corrected the α-level using Benjamini and Hochberg's (1995) false detection rate. The 8 p-values which appear in this results section were ranked in order of their size from smallest to largest and the inequality $p_i \leq (\alpha/m)*i$ was tested[3]. Any p-value for which the inequality was true was considered significant; in this particular experiment, the largest value for which the inequality was true was .013.

Findings for all participants are presented in Table 2 and Fig. 2. As we predicted, there were significant associations between viscosity and roundedness, luminance, saturation, size, letter string type and pitch. Counter to our hypotheses, the viscosity-elevation CMC was not significant, though it did trend in the predicted direction. The viscosity-many/one CMC was also not significant, though we were not sure whether this would appear since the many-one dimension has not been tested in CMC research before.

[Table 2 about here]

[Figure 2 about here]

The reliability of the individual significant CMCs varies somewhat, with viscosity-lightness and -pitch the most reliable, followed by -roundedness and -size, and finally -saturation and -letter string type.

Importantly, though our results vary in their reliability, all of our findings point in the same direction: the viscosity dimension aligns with other dimensions in Walker's framework of connotative meaning, such that low viscosity is, for example, associated with high pitch

[3] Where i = the rank of the p-value, α = the threshold p-value (i.e. 0.05) and m = the total number of p-values.

and high luminance, which are in turn associated with each other. We further explore these associations in our General Discussion.

Our results should be interpreted with caution as we presented two tactile stimuli and two visual or auditory stimuli together, meaning that it is impossible to tell whether the thick liquid, the thin liquid, or both together are driving our findings. Following a suggestion from a reviewer, we ran a second Experiment to disambiguate. In Experiment 2, two tactile stimuli were still presented together, but now with only one visual or auditory stimulus at a time. We did not present the inverse (one tactile stimulus and two visual or auditory stimuli) for practical reasons: switching the tactile stimulus trial-to-trial would require the participant to clean their hand thoroughly to prevent any risk of cross-contamination.

Experiment 2: Materials and methods

Participants

Thirty-two participants (18 female, 14 male; mean age = 24.56 years, SD = 6.56, range = 18-46; 27 right-handed, 5 left-handed [by simple self-report]) were recruited for this Experiment from among the students and staff of the University of East London. All participants were native speakers of English: 8 were monolingual speakers of English and the remaining 24 were fluent in English and at least one other language[4], with English being their mother tongue.

Materials and design

Tactile materials were identical to those in Experiment 1. Visual and auditory materials were similar, but not identical. Firstly, we presented only one visual or auditory stimulus at a time. Secondly, following a suggestion by a reviewer, we exaggerated the difference between the stimuli used to test elevation (see Fig. 3). To do this, we moved the stimuli further apart in the vertical dimension, and added a black box around each stimulus (around which was a dark grey background) to further emphasise the physical locations of

[4] One of our participants was multilingual and spoke Farsi, Urdu and Pashtu in addition to English. The other 23 were bilingual and in addition to English, four spoke each of Urdu and Bengali, two spoke each of Somali and Swahili, and one spoke each of Afrikaans, Creole, Fatwari, German, Hawsa, Hungarian, Italian, Lingala, Polish, Portuguese, and Tagalog.

the objects with respect to each other. To maintain consistency, this background was applied to all stimuli.

[Figure 3 about here]

Because we were presenting visual and auditory stimuli one by one in this experiment, we had more trials (16 in total) and consequently did not use a Latin square counterbalancing method. Instead, we generated four different randomised orders for stimuli (see Appendix) and presented each of these to eight participants.

Procedure

The procedure was very similar to Experiment 1, with the exception that participants were presented with only one visual or auditory stimulus at a time. The experimenter also provided only a verbal prompt to choose a pairing, rather than a verbal and a visual prompt.

Experiment 2: Results and Discussion

The data for this study were analysed using a chi-square goodness of fit test, and we again corrected the α-level using false detection rate. In this Experiment, the largest p-value for which the inequality was true was .034.

Findings for all participants are presented in Table 3 and Fig. 4. There were significant associations between the thick liquid and the rounded, dark, unsaturated and NOHMOO stimuli. Conversely, there was a significant association between the thin liquid and the high-pitched stimulus. No significant associations were found between thin/thick tactile stimuli and small/large, high/low elevation, and many/one visual stimuli.

[Table 3 about here]

[Figure 4 about here]

Again, there is some variation in the reliability of individual significant CMCs, with thick-dark and thin-high pitch being the most reliable (as in Experiment 1), followed by thick-rounded and -unsaturated, and finally -NOHMOO. However, even among the non-significant associations, every association is numerically in the predicted direction. We further explore these findings, comparing them with those of Experiment 1, in the General Discussion.

General discussion

In the two Experiments presented in this paper, we explored whether there are tactile CMCs for liquid viscosity and various visual and auditory dimensions. Comparison of the results of the two Experiments allows us to establish whether each CMC tested is relative or absolute – that is, whether they require the presence of two immediately comparable stimuli to appear (Experiment 1) or will appear without this immediate comparison (Experiment 2). Note that this distinction is made with some caution, since participants may be implicitly comparing even the single tactile stimulus in Experiment 2 to an imagined other stimulus. See also Walker and Walker (2015), where, for example, medium-luminance stimuli are responded to more quickly with a larger response key than a smaller response key when presented at the same time as high-luminance stimuli, but vice versa when presented at the same time as low-luminance stimuli.

In Experiment 1, we found a significant relationship between viscosity and roundedness, luminance, saturation, size, letter string type and pitch. In Experiment 2, the CMCs based on roundedness, luminance, saturation and letter string type were found to be driven by the thicker liquid, while pitch was driven by the thinner liquid. No relationship was found between viscosity and size in Experiment 2. In neither Experiment did we find a significant relationship between viscosity and elevation or the many/one dimension. We now deal with how each of these CMCs may be explained, beginning with the proposed absolute CMCs, then the proposed relative CMC, then the hypothesised CMCs that did not have a significant result.

In the case of thick-round, thick-dark, thick-unsaturated, thick-NOHMOO and thin-high pitch, the results suggest an absolute CMC between the two stimuli.

In the hypotheses, we suggested that luminance and pitch were likely to form CMCS with tactile viscosity because previous experiments (Eitan & Rothschild, 2010; Slobodenyuk *et al*., 2015; Walker *et al*., 2010; Ward *et al*., 2008) had indicated that there are links between the resistance a solid object puts up to movement and the dimensions of luminance and pitch. Viscosity can also be parsed as resistance to movement; hence, any CMC involving resistance to movement may have the same underlying mechanism – though this is unlikely given that only the thin liquid is linked with the high pitch and only the thick liquid is linked with low luminance in Experiment 2. One possibility here is that visual-tactile CMCs are generally driven by the thicker liquid, while auditory-tactile CMCs are generally driven by the thinner liquid. Since the KEETAY/NOHMOO stimuli were both visual (letter string) and auditory (participant reading aloud) ,but the CMC between these and viscosity relied on the relationship between NOHMOO and the thicker liquid, it may be that visual-tactile CMCs would also override auditory-tactile CMCs when both are present. We stress that this is only a possible interpretation of the results and that further research with more auditory stimuli that vary on different dimensions (e.g. volume, timbre) and on stimuli that have both visual and auditory dimensions will be required for full understanding of our findings.

The viscosity-saturation CMC is one of the least reliable findings in both Experiment 1 and Experiment 2, in line with a non-linear relationship between saturation and other sensory dimensions. Why this relationship is non-linear is not clear, though our previous research (Jonas *et al*., submitted) has found that when luminance and saturation both vary across a pair of visual stimuli, participants will prioritise luminance information in order to make a CMC with pitch. When luminance information is held steady and only saturation varies, participants may therefore make more random decisions about pairings.

The viscosity-roundness CMC can be interpreted as a linguistic or neurological phenomenon. In the linguistic interpretation, we can consider the verbal labels 'rounded', 'thick' and 'thin'- all words used to describe the human figure - unlike 'pointed', which is never used in this way. 'Rounded' and 'thick' both describe larger figures, so they would necessarily be paired together, because they are linguistically associated as terms for the human figure. Our findings in Experiment 2 do not support the existence of a thin-pointed CMC, which may indicate that without 'thick' and 'rounded', the forced association between 'thin' and 'pointed' breaks down because 'pointed' is not used in the same figure-related way as the other words. However, this interpretation requires that participants implicitly or explicitly verbally labelled the stimuli we presented, and furthermore that they used the same labels we did – which may or may not have been the case, especially considering that a large proportion of our participants were fluent in languages other than English, where different relations between labels may be in effect.

In the neurological interpretation, then, both the thick and rounded stimuli implicitly code for ‘more’ (more resistance, more spatial extent), which by Walsh’s (2003) model would mean that there is some neurological overlap between their representations (i.e. there is a structural explanation for their existence). Using Walsh’s theory as an explanation for this is problematical when we consider the other pairings made with ‘thick’, though – if pairings were reliant on a general magnitude system, we would also expect the high-luminance and high-saturation stimuli (both of which are also ‘more’ than the low-luminance and low-saturation stimuli) to be paired with the thick liquid, but participants behave in the opposite way.

In the case of the viscosity-size CMC, the results suggest a relative relationship. That is, both sizes of the visual stimulus must be present in order for the CMC to appear, indicating an explicit comparison is being made between large and small. It is not clear why this CMC, of all those we tested, would be the sole relative CMC. One possibility is that for two of the stimulus orders (see Appendix), either the large or the small stimulus was the first circular one that was seen by participants and there was therefore nothing to compare it to in terms of size. However, if we discount these stimulus orders then 7 of the remaining 16 participants pair thin with small, and the reverse is true for pairing thick with large. This finding is still non-significant (p = .617), so a more likely explanation is that without a direct comparison with both on the screen, it is not very obvious that the stimuli differ in size from the other circular stimuli.

Lastly, there were two proposed CMCs that were not significant in either Experiment: viscosity-visual elevation and viscosity-many/one.

The non-significance of the visual elevation-viscosity CMC, even when we exaggerated the difference between the stimuli, may be due to participants’ understanding of the property of visual elevation as a temporary or unimportant condition of the stimuli, as compared to, say, roundedness. Supporting this interpretation, some participants expressed confusion at being asked to make decision between two otherwise identical stimuli of different elevation.

The non-significance of the viscosity-many/one CMC is likely to have a different explanation. Unlike the other visual stimuli, these have two conflicting dimensions, size and number, tied up in each of the two choices. From our other findings, we know that participants pair small visual stimuli with the thinner liquid (which appears to be the dominant factor in their decision about many vs. one). However, 'large' and 'small' are also used metaphorically to refer to numbers in English – thus, there is a large number of small stimuli and a small number of large stimuli. Participants are therefore likely to be confused as to which dimension to prioritise.

Future directions

We would first like to note that our results should be interpreted with caution as nearly half of our participants in Experiment 1 and the majority of our participants in Experiment 2 were multilingual. This may have had effects on responses including, for example, the non-words KEETAY and NOHMOO being homophones or near-homophones for words in other languages; for example KEETAY (/kiːteɪ/) is a near-homophone of the French word *quitter* (/kite/, 'to leave'). Since our participants spoke many languages from a wide range of language families including Semitic, Finnic and Baltic, and our experiment was not specifically designed to test the effect of bilingualism on CMCs, we do not analyse this effect here but are currently conducting follow-up studies that will test the effect of bilingualism.

Since we were attempting to establish the existence of new CMCs related to the tactile viscosity of liquids, we used a very simple methodology that was open to demand characteristics. An essential first step in establishing whether the CMCs we have found truly exist is to see the impact they might have on our information processing, using a modified version of a speeded classification task well used with audio-visual CMCs (e.g. Evans & Treisman, 2010; Gallace & Spence, 2006). Some of the tactile CMCs found with the current study may be more difficult to assess, but one could certainly ask participants to rate the viscosity of liquids varying in visual dimensions (e.g. saturation) and see if this unrelated factor influences speed of categorisation.

Finally, it is unclear exactly what the relationships are between viscosity and the other sensory dimensions we tested. Are they linear, like the relationship between elasticity and luminance, or non-linear, like the relationship between elasticity and saturation (Slobodenyuk *et al*., 2015)? Again, we are assessing this in follow-up studies.

Conclusion

The results of our study provide evidence for several new CMCs (thick-round, thick-dark, thick-unsaturated, thick-NOHMOO, thin-high pitched, and viscosity-size). The way(s) in which the CMCs operate – i.e. structural, statistical, semantic, or some other (Spence, 2011) – have yet to be established, though some hints are available from our findings: for example, a semantic explanation seems more likely than a structural explanation for the roundedness-thickness CMC.

These CMCs do not fit completely Walker's framework of connotative meaning (Walker & Walker, 2012; Walker *et al*., 2012) since the framework also predicts that there should be an association between visual elevation and thickness based on the transitive relation between pitch and thickness established in our experiment and the known relationship between pitch and visual elevation (e.g. Eitan & Timmers, 2010). Walker's framework is still useful for explaining the majority of relationships between CMCs but more research is needed on these isolated cases where transitivity between different CMCs does not occur. Our results also argue against CMCs being based on a general system of magnitude in the brain (e.g. Walsh, 2003), since our participants sometimes appeared to associate the thicker liquid with more (e.g. roundedness) and sometimes with less (e.g. low luminance). This knowledge of how different CMCs relate to each other has more general implications for research questions around the design of sensory substitution devices (SSDs), which transform information from one sensory modality to another (e.g. Bach-y-Rita *et al*., 1998). In our study, we have shown that CMCs are not always transitive, nor always based on magnitude, indicating that researchers investigating multiple simultaneous CMCs (as SSDs usually require) will need to examine their assumptions about the 'default' settings of SSDs. Using a more nuanced account of CMCs than currently exists will allow these researchers to develop SSDs such that new adopters can intuitively understand and use them.

Our findings also have the potential to aid in product design for containers of liquids that can vary in thickness, for example milkshakes or shampoos (see Spence, 2012; Spence

& Gallace, 2011), and in the presentation of food and drink in restaurants (Spence *et al*., 2013), for example by presenting thin soups in light-coloured, bright bowls and thicker soups in darker, less saturated bowls.

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