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Look but don't touch: Tactile disadvantage in processing modality-specific words

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ABSTRACT

Recent neuroimaging research has shown that perceptual and conceptual processing share a common, modality-specific neural substrate, while work on modality switching costs suggests that they share some of the same attentional mechanisms. In three experiments, we employed a modality detection task that displayed modality-specific object properties (e.g., unimodal *shrill*, *warm*, *crimson,* or bimodal *jagged*, *fluffy*) for extremely short display times and asked participants to judge whether each property corresponded to a particular target modality (e.g., auditory, gustatory, tactile, olfactory, visual). Results show that perceptual and conceptual processing share a tactile disadvantage: people are less accurate in detecting expected information regarding the sense of touch than any other modality. These findings support embodied assertions that the conceptual system uses the perceptual system for the purposes of representation. We suggest that the tactile disadvantage emerges for linguistic stimuli due to the evolutionary adaptation of endogenous attention to incoming sensory stimuli.

1. Introduction

How do we think about objects that are not in front of us at the time? Do we see with the mind's eye and touch with the mind's fingers? Embodied theories of cognition hold that conceptual thought is grounded in the same neural systems that govern sensation, perception and action (Barsalou, 1999, 2008; Gibbs, 2003; Glenberg, 1997; Wilson, 2002). Barsalou's (1999) Perceptual Symbol Systems, for example, describes concepts as partial recordings of the neural activation that arises during perceptual and motor experiences, where these recordings can later be re-enacted as a perceptual simulation of a particular concept.

Recent neuroimaging work has provided evidence that perceptual experience and conceptual knowledge share a common, modality-specific neural substrate. For example, using fMRI, González and colleagues (2006) found that passively reading scent-related words (e.g., *cinnamon*) increased activation in the primary olfactory areas of the piriform cortex. Regarding visual processing, Simmons et al. (2007) showed that verifying colour properties in text (e.g., that a banana is *yellow*) led to activation in the same region of the left fusiform gyrus in the visual cortex as a perceptual task that involved judging colour sequences. Further comparisons by Goldberg, Perfetti, and Schneider (2006) found that verification of colour, sound, touch, and taste properties activated cortical regions, respectively, associated with encoding visual, auditory, tactile and gustatory experiences.

Our perceptual and attentional systems are intertwined, giving attention the power to direct perceptual processing towards modality-specific goals, both exogenously (where incoming stimuli automatically and obligatorily grab attention) and endogenously (where people consciously focus attention on a particular modality). In addition to sharing a neural substrate, it seems that exogenous attentional mechanisms, at least, are shared by the perceptual and conceptual systems. For example, when Spence, Nicholls and Driver (2001, see also Turatto, Galfano, Bridgeman,

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& Umiltà, 2004) asked people to respond to a series of perceptual stimuli, they found that switching modalities from one trial to the next (e.g., from a visual light flash to an auditory tone) incurred a processing cost. Similarly, when Pecher, Zeelenberg and Barsalou (2003; see also Lynott & Connell, 2009; Marques, 2006; van Dantzig, Pecher, Zeelenberg, & Barsalou, 2008) asked people to verify a series of unimodal object properties presented as text onscreen, they found that people were slower to verify a property in a given modality (e.g., auditory *leaves:rustling*) after verifying a property in a different modality (e.g., visual *apple:shiny*) compared to the same modality (e.g., auditory *blender:loud*). In both perceptual and conceptual tasks, such modality switching costs are thought to result from the re-allocation of exogenous attention from one modality-specific system to another.

If the conceptual system has co-opted the perceptual system for the purposes of representation, then it follows that one should expect modality-specific perceptual (and attentional) phenomena to emerge in conceptual processing. One such phenomenon is the tactile disadvantage in perceptual processing, relative to vision and audition. When people are asked to respond to the arrival of a perceptual stimulus, they are generally slower to detect tactile stimuli (e.g., finger vibration) than visual (e.g., light flash) or auditory (e.g., noise burst) stimuli, even when they are told which modality to expect (Spence et al., 2001; Turatto et al., 2004). In other words, asking people to focus their endogenous attention on a particular sensory modality creates anticipatory activation in the relevant area of the cortex (Foxe, Simpson, Ahlfors, & Saron, 2005) and allows information from that modality to be processed more quickly, but expected tactile stimuli still take longer to process than expected visual or auditory stimuli.

So why should tactile processing be disadvantaged? There are obvious physiological differences in processing stimuli from different perceptual modalities, with differential latencies for transduction in the skin, retina, and cochlea, and for transmission of their respective signals to the somatosensory, visual, and auditory cortices. However, since the retina is actually the slowest of the three in converting a stimulus to an electrical signal and delivering it to the brain, these physiological differences alone cannot explain the tactile disadvantage in stimulus perception. Rather, the tactile modality appears to be disadvantaged when it comes to the resolution of the raw sensory signal into a recognisable percept. Recent perceptual research has also suggested that tactile endogenous attention operates differently to attention on other modalities; when Karns and Knight (2009) examined how endogenous attention affected processing of visual, auditory and tactile stimuli, they found that attention modulated ERPs at early latencies for visual (62 ms) and auditory (29 ms) processing, but did not modulate tactile ERPs until much later (165 ms). This lag in attentional modulation suggests that selective focus on touch may not impact on the formation of tactile representations quite as effectively as similar focus affects other modality-specific representations. Researchers have speculated on a number of reasons why attention on the sense of touch might be a special case. The tactile modality may be special in requiring a "personal space" representation of the body, in contrast to the visual or auditory modalities requiring a peripersonal or extrapersonal representation of the world, and hence may require a different attentional perspective (Martin, 1995; Spence et al., 2001). For example, if something is being felt by touch, it is (by definition) located on the body's surface, and there may be costs involved in shifting attentional perspective to something that is seen or heard some distance away. Alternatively, there may be an adaptive advantage in coupling attention longer to visual and auditory modalities than to tactile (Turatto et al., 2004). In this account, approaching threats could be efficiently detected at a safe distance by keeping attention focused on sight or sound, but waiting to detect a potential danger by touch is unlikely to have evolved as a useful attentional mechanism.

The present study aimed to investigate whether the tactile disadvantage in perceptual processing also emerges during conceptual processing. In three experiments, we used a modality detection task to examine endogenous attention during the conceptual processing of modality-specific words. The modality detection task measures accuracy rates for extremely short display times above the subliminal threshold and is a variant of that previously used to examine the positive/negative detection of emotionally affective words (Dijksterhuis & Aarts, 2003). In Experiments 1 and 2, participants were presented with unimodal object properties (i.e., perceived through one sense alone) for a range of increasing display times and were asked to judge whether the property corresponded to a target modality (auditory, gustatory, tactile, olfactory, or visual). Experiment 3 used the same paradigm to compare unimodal and bimodal object properties (i.e., perceived equally through two senses) for visual and tactile target modalities.

2. Experiment 1: unimodal properties in yes/no task

In the modality detection task, participants first saw blocks for each modality (auditory, gustatory, tactile, olfactory, visual) for an extremely short display time at the threshold of subliminal perception (17 ms), then the blocks were repeated for increasing display times (33 ms, 50 ms, 67 ms, 100 ms). We expected accuracy rates to improve over successive repetitions, both because of practice effects and because longer display times increase the probability of successful detection. Importantly, following findings for perceptual stimuli (Spence et al., 2001; Turatto et al., 2004), we predicted more accurate detection of visual and auditory properties than tactile properties (i.e., the tactile disadvantage). Indeed, since previous work (Dijksterhuis & Aarts, 2003; Gaillard et al., 2006) has shown that conceptual processing of affective valence occurs before conscious access, we expected to see the tactile disadvantage even for subliminal presentation (i.e., the shortest 17–33 ms blocks).

Predictions for gustatory and olfactory properties varied according to the reasons researchers have offered for why tactile processing may be disadvantaged. Since the sense of taste presumably requires a representation in personal space as much as the sense of touch, Spence et al.'s (2001) notion of attentional perspective suggested that gustatory accuracy would be similar to tactile accuracy. Conversely, since the sense of smell can detect stimuli in peri or extrapersonal space, olfactory accuracy would be similar to visual and auditory accuracy. On the other hand, since neither taste nor smell is particularly useful in detecting an approaching predator, Turatto et al.'s (2004) idea of attentional adaptation for threat detection suggested that both gustatory and olfactory modalities would have similar accuracy to tactile.

2.1. Method

2.1.1. Participants

Forty-five native speakers of English from the University of Manchester, with no reported reading or sensory deficits, participated in the experiment for course credit or a fee of £5. Three participants' data were removed prior to analyses; two due to pressing incorrect buttons during the experiment and one due to a consistently high error rate (>80%).

2.1.2. Materials

Modality-specific words were taken from Lynott and Connell's (2009) modality exclusivity norms. These norms comprise 423 adjectives, each describing an object property, with mean ratings (0–5) of how strongly that property is experienced through each of five perceptual modalities: auditory, gustatory, tactile (haptic), olfactory, visual. For this experiment, test items were unimodal properties and consisted of 20 words from each modality, where each word had the highest strength rating in the target modality (minimum of three) and all other modalities were at least one full point lower on the ratings scale (see Table 1 for examples or Appendix A for all items). Only 17 and 15 words met this criterion for the tactile and olfactory modalities, respectively, and so morphological variants of existing words were included (e.g., *odorous*, *malodorous*) to ensure balanced blocks of 20 items per modality; data relating to these variants were removed prior to analysis[1]. There were no differences between modalities in British National Corpus (BNC) word frequency (auditory $M_a = 8.2$, gustatory $M_g = 2.6$, olfactory $M_o = 1.2$, tactile $M_t = 16.0$, visual $M_v = 22.8$), orthographic length ($M_a = 6.9$, $M_g = 6.1$, $M_o = 7.1$, $M_t = 5.9$, $M_v = 6.5$), or target modality strength ratings ($M_a = 4.7$, $M_g = 4.7$, $M_o = 4.7$, $M_t = 4.4$, $M_v = 4.7$) of test words (all Bonferroni comparison $ps > .18$). In addition, using the English Lexicon Project database (Balota et al., 2007), there were no differences between modalities in lexical decision time ($M_a = 696$, $M_g = 702$, $M_o = 743$, $M_t = 672$, $M_v = 679$) or accuracy ($M_a = .94$, $M_g = .90$, $M_o = .87$, $M_t = .92$, $M_v = .95$) of test words[2] (all Bonferroni comparison $ps > .3$). Twenty filler items were selected per block to represent a wide range of unimodal and multimodal properties that did not correspond to the target modality (e.g., tactile fillers included auditory *howling*, visual *dark*, olfactogustatory *cheesy*). Each filler word had a low strength rating (less than 2) on the target modality, meaning that all fillers had significantly lower strength on the target modality ($M_a = .09$, $M_g = .02$, $M_o = .01$, $M_t = .31$, $M_v = 1.08$) than the corresponding test words (all $ps < .001$).

Table 1
Sample object property words for each modality used in Experiments 1 and 2 (all unimodal) and Experiment 3 (unimodal tactile and visual, bimodal).

Modality	Properties
Unimodal	
Auditory	Bleeping, echoing, loud, shrill, squeaking
Gustatory	Bitter, bland, palatable, savoury, tangy
Tactile	Chilly, itchy, lukewarm, stinging, ticklish
Olfactory	Aromatic, fragrant, musty, perfumed, smelly
Visual	Crimson, flickering, murky, radiant, shiny
Bimodal	
Visuotactile	Angular, fluffy, jagged, prickly, round

2.1.3. Procedure

Participants were instructed that they would be asked to judge whether or not words appearing onscreen could be experienced through a particular sense (heard, tasted, felt through touch, smelled or seen). They were told that words would appear onscreen one at a time and be covered very quickly by a row of Xs, and that they should press "Yes" (the comma key) if the word could be perceived through that sense or "No" (the full stop key) if it could not. Stimuli were arranged into blocks of test and filler words for each modality; since all test items pertained to the given modality and all fillers did not, there was an equal ratio of yes:no responses within each block. At the start of each block, participants were told which sense they would be making judgements about. When participants had completed all five modality blocks with a display duration of 17 ms, the same five blocks were repeated at 33 ms, 50 ms, 67 ms, and 100 ms. Items were presented randomly within each block, with each trial beginning with a central fixation (250 ms), followed by a word (displayed for different durations depending on the block), followed by a mask (a row of Xs) until the participant responded. Response times (RTs) were measured from mask onset to keypress.

2.1.4. Design

The experiment employed a two-factor repeated measures design with factors of modality (auditory, gustatory, tactile, olfactory, visual) and display duration (17 ms, 33 ms, 50 ms, 67 ms, and 100 ms). As per Dijksterhuis and Aarts (2003), the proportion of correctly detected words per participant per condition are subjected to analyses of variance. Effect sizes are reported as generalized eta-squared (η_G^2), which allows direct comparison of within- and between-participants designs (Olejnik & Algina, 2003).

2.2. Results and discussion

Responses to test words less than 200 ms or more than three standard deviations away from a participant's mean

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[1] Analysis including these words yielded little difference to the reported results.

[2] Fifteen of our test words were not featured in the database (distributed across modalities); analysis was run on those words present.

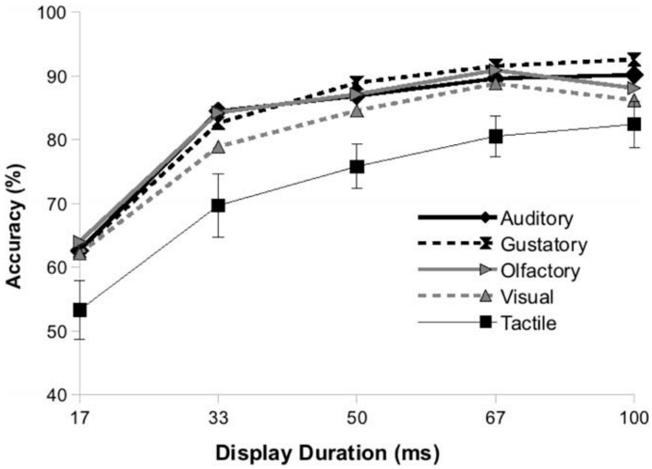

Fig. 1. Percentage of correctly-detected unimodal properties per modality and display duration in Experiment 1 (yes/no task). Error bars represent 95% confidence intervals for within-participant designs (Loftus & Masson, 1994), calculated per display duration.

per display duration were removed as outliers to reduce noise in the dataset (3.7% of data). The percentage of correctly detected test words per modality per display time is shown in Fig. 1, with correct response times for comparison in Table 2.

Overall, performance differed by modality [$F(4, 164) = 14.00$, $p < .0001$, $\eta^2_G = .06$]. Planned contrasts between tactile and other modalities showed a distinct tactile disadvantage: people were indeed worse at detecting tactile words than any other type (all $ps < .001$). As expected, there was also a main effect of display duration [$F(4, 164) = 89.25$, $p < .0001$, $\eta^2_G = .26$], with people becoming more accurate with each increasing duration up to 67 ms (all $ps < .001$), and performance levelling out between 67 ms and 100 ms ($p = .599$). The interaction between factors was non-significant [$F < 1$, $\eta^2_G = .01$].

In order to examine when the tactile disadvantage first appears, and whether relative performance changes when more time is given to process the word, we examined each display duration separately. At 17 ms, modalities differed in performance [$F(4, 164) = 3.21$, $p = .014$, $\eta^2_G = .02$]: in planned contrasts, accuracy for tactile words was significantly worse than for all other modalities (all $ps < .03$). The same pattern emerged for 33 ms [$F(4, 164) = 5.88$, $p < .001$, $\eta^2_G = .07$; all contrast $ps < .01$], 50 ms [$F(4, 164) = 8.51$, $p < .001$, $\eta^2_G = .09$; all contrast $ps < .002$], and 67 ms [$F(4, 164) = 8.16$, $p = .001$, $\eta^2_G = .09$; all contrast $ps < .002$]. By 100 ms, where accuracy had begun to plateau, performance still varied by modality [$F(4, 164) = 4.25$, $p = .004$, $\eta^2_G = .05$]; people continued to be significantly less accurate in detecting tactile words than auditory, gustatory or olfactory words ($ps < .05$), and marginally less accurate than visual ($p = .052$) words.

Table 2
Means response times (ms) to correctly-detected unimodal properties per modality and display duration in Experiment 1 (yes/no task). 95% confidence intervals are for within-participant designs (Loftus & Masson, 1994), calculated per display duration.

Modality	Display duration				
	17 ms	33 ms	50 ms	67 ms	100 ms
Auditory	1328	884	727	675	650
Gustatory	1072	796	691	635	573
Olfactory	1010	749	669	644	599
Tactile	1192	903	824	779	692
Visual	1134	850	757	709	627
95% CI = M±	81	35	31	33	27

In summary, results show a distinct tactile disadvantage in conceptual processing. Even when a word is displayed for only 17 ms, and people are not necessarily conscious of having read it, they can successfully detect auditory, gustatory, olfactory and visual modalities better than the tactile modality. This tactile disadvantage is not due to differences in modality strength (i.e., tactile properties were as strongly touch-related as other properties were related to their relevant modalities), nor to other psycholinguistic variables such as word frequency, length, or lexical decision time/accuracy. Furthermore, the tactile disadvantage is not due to differences in response bias between modalities (Stanislaw & Todorov, 1999); signal detection analysis yielded the same results as accuracy analysis[3]. Since accuracy for both gustatory and olfactory modalities closely followed that for auditory and visual, and remained significantly better than tactile accuracy throughout, neither the attentional perspective nor threat detection explanations for the tactile disadvantage can adequately explain the results. We return to this issue in Section 5.

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[3] Experiment 1's design makes it appropriate for d′ analysis, which showed a main effect of modality [$F(4, 164)=20.76$, $p < 0.001$] and display duration [$F(4, 164)=117.73$, $p < 0.001$], but no interaction [$F < 1.04$]. Tactile words were detected less effectively than all other modalities at 17 ms [$F(4, 164) = 3.12$, $p = 0.017$; all contrast $ps < .05$ except visual $p = .088$], with the same pattern at 33 ms [$F(4, 164) = 5.89$, $p < 0.001$; all ps<.01 except visual $p = .463$], 50 ms, [$F(4, 164) = 11.28$, $p < 0.001$; all $ps < .01$], 67 ms [$F(4, 164) = 10.29$, $p < 0.001$; all $ps < .05$], and 100 ms [$F(4, 164) = 9.77$, $p < 0.001$; all $ps < .05$].

3. Experiment 2: unimodal properties in go/no-go task

Since the task in Experiment 1 required pressing "Yes" and "No" buttons in response to stimuli, participants would have experienced tactile feedback from their fingers on every trial. It could be argued that this feedback, and its expectation, swamped the tactile processing system and interfered with the simultaneous processing of tactile words (similar to e.g., Kaschak et al., 2005, for visual motion processing), thus contributing to the tactile disadvantage. In this experiment, we employed a verbal go/no-go task where participants responded with a voice trigger rather than a button press. Since we considered the tactile disadvantage effect to be more than a mere artifact of the button-pressing task, we expected it to be replicated in the current experiment.

3.1. Method

Identical to Experiment 1, with the following exceptions:

3.1.1. Participants

Forty-six new participants took part. Data from two participants were excluded prior to analysis due to equipment malfunction during testing.

3.1.2. Procedure

Following calibration of the unidirectional microphone (worn as a headset), participants were instructed to say "yes" as clearly as possible if the word could be perceived through the target sense or remain silent if it could not (constituting a "no" response). RTs were measured from mask onset to registration of a voice response. If no response was made within 1500 ms, it was considered a "no" response and the next trial was presented.

3.2. Results and discussion

Responses due to disfluencies (e.g., lip pops and coughs) were excluded from analysis. Responses to test words less than 200 ms or more than three standard deviations away from a participant's mean per display duration were removed as outliers (1.7% of data). Fig. 2 shows the percentage of correctly detected test words per modality per display time, with correct response times for comparison in Table 3.

Table 3
Means response times (ms) to correctly-detected unimodal properties per modality and display duration in Experiment 2 (go/no-go task). 95% confidence intervals are for within-participant designs (Loftus & Masson, 1994), calculated per display duration.

Modality	Display duration				
	17 ms	33 ms	50 ms	67 ms	100 ms
Auditory	775	717	676	659	618
Gustatory	737	705	663	638	609
Olfactory	761	718	676	647	609
Tactile	802	791	753	718	682
Visual	776	759	699	656	633
95% CI = M±	38	25	18	19	20

As in Experiment 1, the main effect of modality $[F(4, 172) = 16.54, p < .0001, \eta_G^2 = .03]$ resulted from a tactile disadvantage: people were less accurate in detecting tactile words than words from the other modalities (all planned contrast $ps < .001$). Accuracy improved as display duration increased $[F(4, 172) = 12.74, p < .0001, \eta_G^2 = .35]$, with significant improvements up to 50 ms (planned contrast $ps < .001$) and no significant change between 50 and 67 ms ($p = .519$) or 67 and 100 ms ($p = .266$). The interaction of modality and display duration was marginal $[F(16, 688) = 1.62, p = .058, \eta_G^2 = .01]$.

Further investigation of the timeline of the tactile disadvantage also replicated Experiment 1. At 17 ms, accuracy differed across modalities $[F(4, 172) = 2.99, p = .020, \eta_G^2 = .02]$, with planned contrasts showing lower accuracy for tactile words than any other modality (all $ps < .02$). Tactile performance remained consistently worse than other modality words at 33 ms $[F(4, 172) = 12.94, p < .001, \eta_G^2 = .08;$ all contrast $ps < .003]$, and 50 ms $[F(4, 172) = 6.59, p < .001, \eta_G^2 = .03;$ all contrast $ps < .001]$.

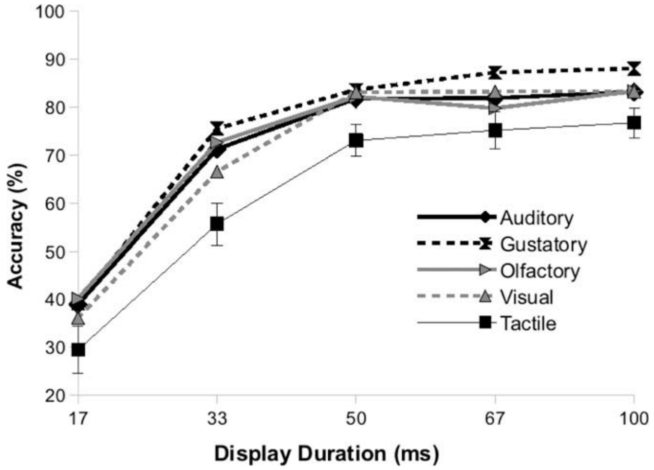

Fig. 2. Percentage of correctly-detected unimodal properties per modality and display duration in Experiment 2 (go/no-go task). Error bars represent 95% confidence intervals for within-participant designs (Loftus & Masson, 1994), calculated per display duration.

At 67 ms [$F(4, 172) = 4.92$, $p = .001$, $\eta^2_G = .03$], where overall performance had begun to plateau, tactile accuracy was similar to that of olfactory words ($p = .12$), but still worse than the remaining modalities (all $ps < .02$). By 100 ms, tactile responses were again less accurate than all other modalities [$F(4, 172) = 6.35$, $p < .001$, $\eta^2_G = .03$; all contrast $ps < .01$].

In short, the replication of the tactile disadvantage effect using a voice-trigger task confirms that the results of Experiment 1 were not due to the fact that participants registered responses by pressing buttons, but rather were due to differences in the conceptual processing of modality-specific words.

4. Experiment 3: bimodal properties in yes/no task

The above experiments used unimodal properties, where each word referred to a single perceptual modality, which leaves open the question that some unknown characteristics of the specific words used were driving the tactile disadvantage effect. However, most object property words in English are multimodal, with bimodal combinations of visual and tactile information being the most common (Lynott & Connell, 2009). This experiment therefore aimed to test whether the tactile disadvantage also emerged for bimodal visuotactile words, where the same lexical items can be used to test processing of visual and tactile information. Perceptual studies show that directing endogenous attention towards a particular modality during presentation of bimodal stimuli can suppress activation in the cortex corresponding to the unattended modality (Johnson & Zatorre, 2005). We therefore expected bimodal properties to follow the same pattern as unimodal properties, with better detection of visual information (whether a unimodal visual property or the visual component of a visuotactile property) than tactile information.

4.1. Method

Identical to Experiment 1, with the following exceptions:

4.1.1. Participants

Sixty new participants took part.

4.1.2. Materials

Modality-specific words were extracted from Lynott and Connell's (2009) modality exclusivity norms. Unimodal visual and tactile test items (16 of each) were selected with the same criteria as Experiment 1. Thirty-two bimodal visuotactile test items had joint highest strength ratings in visual and tactile modalities (both ratings over three and within one ratings point of each other) and all other modalities were at least one full point lower (see Table 1 for examples or Appendix B for all items). There were no differences between unimodal visual, unimodal tactile, and bimodal visuotactile words (all Bonferroni comparison $ps > .3$) in British National Corpus (BNC) word frequency ($M_t = 16.8$, $M_v = 14.9$, $M_{vt} = 47.5$), orthographic length ($M_t = 5.9$, $M_v = 5.9$, $M_{vt} = 5.3$), or strength ratings on the relevant target modality ($M_t = 4.5$, $M_v = 4.4$, $M_{vt} = 4.2$ tactile, $M_{vt} = 4.4$ visual). In addition, lexical decision times ($M_t = 668$, $M_v = 689$, $M_{vt} = 668$) and accuracy ($M_t = .92$, $M_v = .93$, $M_{vt} = .94$) were equivalent (English Lexicon Project database; Balota et al., 2007: all Bonferroni $ps > .8$). Bimodal properties were split into two lists: one to appear in visual blocks and one in tactile blocks (counterbalanced). Thus, participants saw an equal number of unimodal and bimodal items in each block. Thirty-two filler items were selected per block as per Experiment 1 so that each filler word had a low strength rating (less than 2) on the target modality, meaning that fillers had significantly lower strength on the target modalities ($M_t = 1.2$, $M_v = 1.3$) than the corresponding test words ($ps < .001$).

4.1.3. Design

A three-factor repeated measures design employed the factors of modal specificity (unimodal, bimodal), target modality (tactile, visual) and display duration (17 ms, 33 ms, 50 ms, 67 ms, and 100 ms).

4.2. Results and discussion

Responses to test words less than 200 ms or more than three standard deviations away from a participant's mean per display duration were removed as outliers (2.1% of data). The percentage of correctly detected test words per modal specificity per display time is shown in Fig. 3, with correct response times for comparison in Table 4.

As in our previous experiments, a main effect of target modality emerged from a tactile disadvantage [$F(1, 59) = 14.61$, $p < .0001$, $\eta^2_G = .01$], that interacted with display duration [$F(4, 236) = 3.17$, $p = .015$, $\eta^2_G = .01$]. Modal specificity had no overall effect [$F < 1$, $\eta^2_G < .001$] but did interact significantly with duration [$F(4, 236) = 4.76$, $p = .001$, $\eta^2_G = .004$]. Performance improved as display duration increased [$F(4, 236) = 79.51$, $p < .0001$, $\eta^2_G = .26$], with planned contrasts showing that people became more accurate with each increasing duration up to 67 ms (all $ps < .003$) and performance levelling out between 67 ms and 100 ms ($p > .2$). No other interactions appeared ($Fs < 1$, $\eta^2_G < .001$).

At 17 ms display duration, there was no reliable difference in accuracy between the tactile and visual modalities ($F < 1$, $\eta^2_G < .001$), neither for unimodal (planned contrast $p > .3$) nor bimodal words ($p > .1$), suggesting that dividing attention in bimodal stimuli, while attempting to suppress the unattended modality, caused problems for processing all words in a block. The tactile disadvantage emerged at longer display durations, with people detecting tactile information less accurately than visual information at 33 ms [$F(1, 59) = 7.51$, $p = .008$, $\eta^2_G = .02$], 50 ms [$F(1, 59) = 5.73$, $p = .020$, $\eta^2_G = .01$], 67 ms [$F(1, 59) = 25.38$, $p < .001$, $\eta^2_G = .06$] and 100 ms [$F(1, 59) = 7.34$, $p = .009$, $\eta^2_G = .02$]. Contrasts showed that the tactile disadvantage held for unimodal properties, replicating our earlier experiments (33 ms $p = .017$, 50 ms $p = .039$, 67 ms $p < .001$, 100 ms $p = .071$). Importantly, bimodal properties also showed a robust tactile disadvantage: visuotactile properties were more difficult to process tactilely than visually

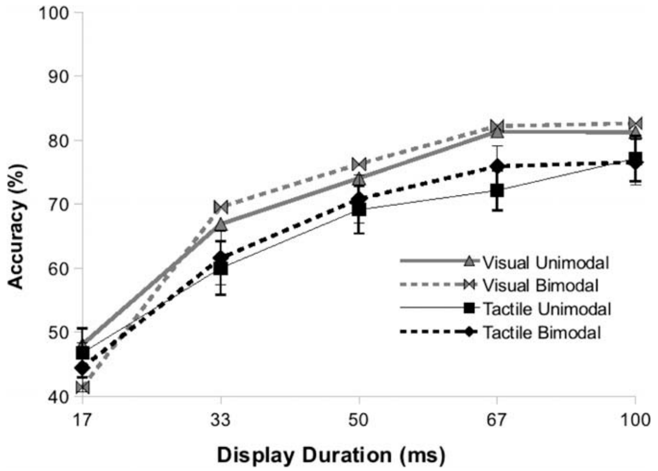

Fig. 3. Percentage of correctly-detected unimodal and bimodal properties per target modality and display duration in Experiment 3 (yes/no task). Error bars represent 95% confidence intervals for within-participant designs (Loftus & Masson, 1994), calculated per display duration.

Table 4
Means response times (ms) to correctly-detected unimodal and bimodal properties per target modality and display duration in Experiment 3 (yes/no task). 95% confidence intervals are for within-participant designs (Loftus & Masson, 1994), calculated per display duration.

Modality	Display duration				
	17 ms	33 ms	50 ms	67 ms	100 ms
Tactile					
Unimodal	1184	1066	986	898	800
Bimodal	1151	1052	964	908	795
Visual					
Unimodal	1161	1038	932	867	758
Bimodal	1141	1019	922	861	775
95% CI = M±	60	51	39	32	30

(33 ms $p = .004$, 50 ms $p = .016$, 67 ms $p = .001$, 100 ms $p = .003$).

Performance for unimodal words was more accurate than for bimodal words at 17 ms [$F(1, 59) = 10.59$, $p = .002$, $\eta^2_G = .02$], but unimodal and bimodal words were processed with equal accuracy thereafter: 33 ms [$F(1, 59) = 1.45$, $p > .2$, $\eta^2_G < .01$], 50 ms [$F(1, 59) = 1.08$, $p > .3$, $\eta^2_G < .01$], 67 ms [$F(1, 59) = 1.72$, $p > .2$, $\eta^2_G < .01$] and 100 ms [$F < 1$, $\eta^2_G < .001$]. At no point did target modality interact with the modal specificity of the words [17 ms: $F(1, 59) = 1.89$, $p = .17$, $\eta^2_G < .01$; all other Fs < 1, $\eta^2_G < .001$). The disappearing difference between unimodal and bimodal performance suggests that 33 ms exposure offers enough opportunity to suppress the unattended component modality of bimodal stimuli (Johnson & Zatorre, 2005) and allow the bimodal property to be processed only on the attended target modality.

The above results replicate and extend the tactile disadvantage effect found in earlier experiments. When people are presented with bimodal properties such as *round*, that are equally strongly tactile and visual, they find it more difficult to process the constituent information that relates to the sense of touch than the sense of sight. In other words, even when the same lexical items are presented, there are modality-specific differences in conceptual processing that reflect the differences observed for perceptual processing.

5. General discussion

In this paper, we have demonstrated that a phenomenon observed during perception – the tactile disadvantage – also emerges during conceptual processing. Results showed that the processing of modality-specific information is rapid, automatic, and does not require conscious awareness of the word, but that, even with extra time to process the word, people are less accurate at detecting properties that pertain to the sense of touch than to hearing, taste, smell or vision. These novel findings further support the assertions of embodied theories that the conceptual system utilises the perceptual system for the purposes of representation. Furthermore, these findings indicate that the conceptual system also utilises the same endogenous attentional mechanisms that operate during perception. People need more time to detect expected information regarding the sense of touch – whether perceptual or conceptual – because of modality-specific differences in attentional control.

Specifically, we propose that the tactile disadvantage arises from weak tactile endogenous control: people find it more difficult to sustain attentional focus on the tactile modality than on any other. When conscious attention is not well-anchored in the sense of touch, stimuli from other modalities (when they exogenously wrest away attentional control during their processing) could disrupt endogenous focus sufficiently so that attention may not be on the target modality when the next stimulus appears. In other words, weak tactile endogenous attention is more prone to exogenous disruption than other modalities and so tactile stimuli are harder to detect successfully.

So how did this tactile disadvantage come into being? Spence et al.'s (2001) speculation that tactile processing is special because it requires a personal attentional perspective is not borne out by the results. Taste is detected inside the mouth, and hence also requires attention in personal space, but gustatory information was processed as easily as visual and auditory information. Turatto et al.'s (2004) suggestion of the attentional system having evolved to stay coupled longer to visual and auditory modalities than tactile due to an adaptive advantage in threat detection was also not supported: taste (or indeed smell) is of little use in detecting approaching danger but did not share the tactile disadvantage. While it is certainly important for survival to detect damaging things that burn or sting, for example, we do not wait for a burning or stinging sensation to register with the attentional system before responding. Rather, withdrawal from a painful or unpleasant tactile stimulus is a spinal reflex, triggered by neuronal circuitry in the spinal cord without any input from the somatosensory cortex. In other words, endogenous attention on the sense of touch can offer little to threat detection because we have more efficient physiological mechanisms to protect the body from damage initiated by skin contact. However, threat detection is not the only reason that adaptive advantages may have emerged for certain modalities, and we would speculate that Turatto et al.'s account may be partially correct. Being able to sustain attentional focus on a particular sensory modality (i.e., endogenous control) is also useful in hunting, where efficacious looking, listening and even smelling for traces of prey could afford an adaptive advantage. Similarly, contaminant detection in gathering and feeding (visual, olfactory and gustatory information) and mate selection (visual and olfactory information) will be most successful if attention can be deliberately and consciously turned towards these cues. In other words, the attentional system may have evolved to stay coupled at length to visual, auditory, olfactory and gustatory modalities because of their usefulness in detecting stimuli that affect the ability to survive and reproduce, whereas sustained attentional focus on the tactile modality brought no such adaptive advantage. Whether and how individual experience with the sense of touch can overcome the adaptive tactile disadvantage is a matter for future research.

Although we have shown that a conceptual processing task replicates an effect from perceptual processing, it could be argued that amodal representations rather than perceptual simulations underlie the tactile disadvantage. We believe the results of Experiment 3 argue against this possibility. If bimodal words such as "round" or "jagged" were being processed with amodal representations, then the same amodal representations would be in play regardless of whether the task required participants to detect them as tactile or visual. For example, a participant's attention would be focused on the modality of touch or sight when the word "jagged" was presented, and then the participant would have to use the amodal representation of "jagged" to judge whether it corresponded to the perceptual modality in question. However, an amodal representation of "jagged" would not have closer connections to one part of the perceptual system over another without abandoning its amodal status in favour of modality-specific representation. An alternative amodal explanation could be that people are sensitive to the relation between the words used to cue attention to a particular modality and the modality-specific property words, similar to the encoding of spatial relations in language reported by Louwerse (2008). If such an explanation could account for the tactile disadvantage effect, then people would respond more easily to "see…jagged" than "touch…jagged" because "see" more often precedes "jagged" in language. However, further investigation did not support this explanation[4], suggesting that the kinds of embodied relation that are encoded amodally in language do not appear to include the distinction between the visual and tactile modalities (see also Louwerse & Connell, 2009). Rather, asking people to attend to a particular modality engages the perceptual system, and people are faster to detect "jagged" as visual rather than tactile because of modality-specific representations.

However, the present findings regarding the tactile disadvantage do not imply that every kind of touch-related conceptual processing will show similar decrements in performance. In perceptual tasks that show the tactile disadvantage, considerable care is taken to isolate unimodal processing – participants are usually seated in a quiet, comfortable, darkened room with minimal sensory variation apart from the experimental stimuli (e.g., light flash, finger vibration, and beeping sound). We chose to develop the modality detection paradigm in order to get close as possible to the kind of stripped-down unimodal processing used in perceptual tasks. Other conceptual tasks that examine modality-specific representations, such as property verification or comparison, will not necessarily be sensitive enough to register modality-specific differences because the presence of a concrete noun object will always invite a relatively multimodal simulation. For example, asking whether *toast can be warm* will certainly require that touch be the dominant part of the toast's representation, but its golden-brown colour, appetising smell, crunching noise, savoury/sweet taste (depending on preferences), and shape and weight in the hand are in there somewhere too. The fact that one perceptual modality is dominant over others allows effects like modality switching costs to emerge (e.g., Pecher et al., 2003) but tasks and stimuli that limit the intrusion of extraneous modalities are more suited to investigating modality-specific differences like the tactile disadvantage.

It is clear that conceptual and perceptual processing share common, modality-specific resources for the purposes of representation. What we have shown here is that endogenous attention – the ability to focus consciously and deliberately on a particular modality – is also a shared resource. If such attentional mechanisms evolved as part of our perceptual systems, and these same attentional and perceptual systems are utilised during conceptual process-

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[4] Taking frequencies from the Web 1T 5-gram corpus (Brants & Franz, 2006), that consists of over a trillion words culled from Google indexes, we calculated the conditional probability of encountering each bimodal property word in Experiment 3 given the target modality for that block (i.e., "see" and "seen" for visual blocks, "touch" and "touched" for tactile blocks). For example, the frequency of "see…jagged" was obtained when zero to three words occurred between the target words, and then divided by the frequency of the word "see". Analysis showed no difference between the conditional probabilities of the visual ($M = 0.017\%$) and tactile ($M = 0.018\%$) blocks, $t(31) = 0.086$, $p > .9$.

ing and language comprehension, then it should come as no surprise that modality-specific differences, such as the tactile disadvantage, emerge with linguistic as well as sensory stimuli.

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Appendix A

Unimodal test items used in Experiments 1 and 2:

Auditory – Audible, beeping, blaring, bleeping, crackling, deafening, echoing, groaning, hoarse, hushed, loud, mumbling, mute, noisy, quiet, shrill, silent, soundless, squeaking, squealing.

Gustatory – Acidic, bitter, bland, buttery, chewy, citrusy, coconutty, lemony, malty, meaty, nutty, palatable, peppery, salty, savoury, sour, tangy, tart, tasteless, tasty.

Olfactory – Antiseptic, aromatic, fragrant, musky, musty, odorous, perfumed, pungent, reeking, scented, scentless, smelly, stenchy, stinky, whiffy.

Tactile – Aching, chilly, clammy, cold, cool, humid, itchy, lukewarm, silky, sore, sticky, stinging, tepid, ticklish, tingly, warm, weightless.

Visual – Beige, chequered, cloudy, crimson, dazzling, flickering, glistening, glowing, grey, hazy, khaki, pale, pink, purple, shadowy, shiny, striped, transparent, white, yellow.

Appendix B

Unimodal and bimodal test items used in Experiment 3:

Tactile – Aching, chilly, clammy, cold, cool, humid, itchy, lukewarm, sore, sticky, stinging, tepid, ticklish, tingly, warm, weightless.

Visual – Bronze, colourful, dim, drab, dull, elegant, falling, gleaming, glossy, huge, immense, misty, murky, radiant, rippling, rusty.

Visuotactile – Angular, bent, big, curly, deep, dusty, jagged, round, shaggy, sharp, soggy, solid, spiky, square, thorny, wispy, bouncy, bristly, broad, enormous, fat, flaky, flat, fluffy, large, prickly, scaly, skinny, slimy, smooth, tight, wet.

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