UC Merced
Proceedings of the Annual Meeting of the Cognitive Science Society

Title
Hard to put your finger on it: Haptic modality disadvantage in conceptual processing

Permalink
https://escholarship.org/uc/item/3390k2jx

Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 31(31)

ISSN
1069-7977

Authors
Connell, Louise
Lynott, Dermot

Publication Date
2009

Peer reviewed

eScholarship.org Powered by the California Digital Library
University of California

Hard to Put Your Finger on it: Haptic Modality Disadvantage in Conceptual Processing

Louise Connell (louise.connell@manchester.ac.uk)
Dermot Lynott (dermot.lynott@manchester.ac.uk)
School of Psychological Sciences, University of Manchester
Oxford Road, Manchester M13 9PL, UK

Abstract

Recent neuroimaging research has shown that perceptual and conceptual processing share a common, modality-specific neural substrate, while work on modality switching costs shows that they appear to share some of the same attentional mechanisms. In two experiments, we employed a modality detection task that displayed modality-specific object properties (e.g., *shrill, warm, crimson*) for extremely short display times and asked participants to judge whether each property corresponded to a particular target modality (auditory, gustatory, haptic, olfactory, or visual). Results show that perceptual and conceptual processing share a haptic disadvantage: people need more time to detect expected information regarding the sense of touch than any other modality. These findings support the assertions of embodied views that the conceptual system uses the perceptual system for the purposes of representation and are discussed with reference to differences in endogenous attentional control.

Introduction

It has become increasingly clear of late that cognition cannot be successfully studied by marginalising the roles of body, world and action. Embodied cognition research represents a recent trend to cease viewing conceptualisation and mental representation in terms of abstract information processing, but rather as perceptual and motor simulation.

While early, influential work in cognitive psychology advocated symbolic knowledge structures (Collins & Quillian, 1969; Newell & Simon, 1972; Tulving, 1972), recent years have witnessed a multidisciplinary convergence of opinion from cognitive psychology (Barsalou, 1999; Glenberg, 1997), linguistics (Gibbs, 2003; MacWhinney, 1999) and artificial intelligence (Anderson, 2003; Chrisley, 2003) that cognition is situated in, rather than independent from, its environment. Embodied theories of cognition hold that conceptual thought is grounded in the same neural systems that govern sensation, perception and action (Glenberg & Kaschak, 2002; Johnson-Laird, 1983; Pecher & Zwaan, 2005) and one of the most influential views is Barsalou's (1999, 2008) Perceptual Symbol Systems account. According to this theory, concepts are essentially partial recordings of the neural activation that arises during perceptual and motor experiences. These recordings (known as perceptual symbols) can later be re-enacted as a perceptual simulation of that concept.

One of the most important elements of the embodied view, separating it from other theories of mental representation, is the dependence of conception on perception. In other words, the same factors that facilitate and inhibit how we perceive an entity in the real world should also influence how we conceive of that entity during language comprehension. Several studies demonstrate instances where this is indeed the case (Goldstone & Barsalou, 1998; Pecher, Zeelenberg & Barsalou, 2003). For example, Spence, Nicholls and Driver (2001; see also Turatto, Galfano, Bridgeman & Umiltà, 2004) asked people to indicate the left/right location of a series of perceptual stimuli, and 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. Pecher et al. (2003) investigated whether this switching cost effect extended to conceptual processing by asking people to verify a series of object properties from different modalities, 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*) than after verifying a property in the same modality (e.g., auditory *blender:loud*), and that this effect was not due to associative priming. Pecher et al. (see also van Dantzig, Pecher, Zeelenberg & Barsalou, 2008) concluded that these switching costs during language comprehension, like those found by Spence et al. during perceptual tasks, resulted from the re-allocation of attention from one modality-specific brain system to another.

Modality-specific perceptual simulation has also been implicated in the processing of single words. In both behavioural and cognitive neuroscience research, while fine-grained sensory distinctions have been long been noted, more recent work has highlighted the continuity between conceptual and perceptual knowledge with respect to the different sensory modalities. For example, Gonzáles and colleagues (2006) found that passively reading scent-related words (e.g., *cinnamon*) increased activation in the primary olfactory areas of the piriform cortex (similar to Pulvermüller's 2005 finding of motor cortex activation for action words). 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. Similarly, Newman, Klatzky, Lederman and Just (2005) examined visual and haptic modalities by asking participants to compare various objects and found differential activation in the inferior extrastriate and intraparietal sulcus depending on whether visual features (e.g., which is *bigger*? pear OR egg) or haptic features (e.g., which is *harder*? potato OR mushroom) formed the basis for comparison. 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, haptic and gustatory experiences. In sum, such studies illustrate that perceptual experience and conceptual knowledge share a common neural substrate.

The Current Study

If the conceptual system uses perceptual simulations for the purposes of representation, then it follows that one should expect perceptual phenomena to emerge in conceptual processing. One such phenomenon is the haptic 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 haptic 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 attention on the sense of sight, hearing or touch allows information from the relevant modality to be processed faster than that from other modalities, but expected haptic stimuli take longer to process than expected visual or auditory stimuli.

So why should haptic 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 haptic disadvantage in stimulus perception. Rather, the haptic modality appears to be disadvantaged when it comes to the resolution of the raw sensory signal into a recognisable percept. Researchers have speculated on a number of reasons why this might be the case. The haptic modality may be special in requiring an internal, body-focused representation, in contrast to the visual or auditory modalities requiring a representation of the external 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 haptic (Turatto et al., 2004). In this account, approaching threats could be efficiently detected by keeping attention focused on sight or sound, but waiting to detect a potential threat by touch is unlikely to have evolved as a useful attentional mechanism.

The current study aims to investigate if the haptic disadvantage in perceptual processing also emerges during conceptual processing. In two experiments, we use a modality detection task to examine conceptual processing of modality-specific words. The modality detection task is a variant of that used to examine the positive/negative detection of emotionally affective words at near-subliminal thresholds (Dijksterhuis & Aarts, 2003). Participants will be presented with unimodal object properties (i.e., perceived through one sense alone, such as shiny, echoing) for extremely short display times and asked to judge whether the property corresponds to a target modality (e.g., visual). By measuring accuracy rates for a range of increasing display times above the subliminal threshold, we can examine whether the perceptual haptic disadvantage also emerges during conceptual processing.

Experiment 1

In this modality detection task, participants will first see blocks for each modality (auditory, gustatory, haptic, olfactory, visual) for an extremely short display time at the threshold of subliminal perception (17ms), then the blocks will be repeated for increasing display times (33ms, 50ms, 67ms, 100ms). We expect accuracy rates to improve from near-chance performance over successive repetitions, both because of practice effects and because longer display times increase the probability of successful detection, but we expect performance differences between modalities. In particular, we predict faster detection of visual and auditory properties (more accurate detection at earlier display times) than haptic properties (i.e., the haptic disadvantage). Since the sense of taste presumably requires as much of an internal body representation as the sense of touch, Spence et al.'s (2001) notion of attentional perspective suggests that gustatory accuracy should be similar to haptic accuracy. Likewise, since taste is not particularly useful in detecting an approaching danger, Turatto et al.'s (2004) idea of attentional adaptation for threat detection would suggest that the gustatory modality should have similar accuracy to haptic.

Method

Participants Forty-five native speakers of English, with no reported reading or sensory deficits, participated in the experiment for course credit or a fee of £5. Participants were recruited via university email lists and notice boards and through the university's research volunteering website. 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%).

Materials A set of 200 words were taken from Lynott & Connell's (2009) modality exclusivity norms: 100 test items and 100 fillers. 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, haptic, olfactory, visual) plus a number of other useful statistics. For this experiment, test items were selected to be unimodal, and consisted of 20 words from each modality, where each word had the highest score in the target modality (minimum strength rating of 3) and all other modalities were at least one full point lower on the the ratings scale (see Table 1 for examples). Only 17 and 15 words met this criterion for the haptic 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. There were no differences between modalities in British National Corpus (BNC) word frequency, orthographic length, or target modality strength ratings of test words (all Bonferroni comparison *p*s>.18). In addition, we used the English Lexicon Project database (Balota et al., 2007) to examine further lexical characteristics of the test words. Seventeen of our test words were not featured in the eLexicon database (distributed across modalities), but tests on those words present showed that there were no differences between modalities in the lexical decision time or accuracy of each word, nor in the number of orthographic, phonological or phonographic neighbours of each word (all Bonferroni comparison *p*s>.2).

Twenty filler items were selected per modality so that each filler word had a low strength rating (less than 2) on the target modality. This meant that all fillers had significantly lower strength on the target modality than the corresponding test words (all Bonferroni comparison *p*s<.001). However, there were no differences between test and filler words in BNC frequency or orthographic length (all Bonferroni *p*s>.25).

Table 1: Sample words for each modality used in Experiments 1 and 2.

Auditory	Gustatory	Haptic	Olfactory	Visual
bleeping	bitter	chilly	aromatic	crimson
echoing	bland	itchy	fragrant	dazzling
loud	palatable	silky	musky	flickering
shrill	salty	ticklish	perfumed	pale
squeaking	tangy	warm	stinky	shiny

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 17s, the same five blocks were repeated at 33ms, 50ms, 67ms, and 100ms. Items were presented randomly within each block, with each trial beginning with a central fixation (250ms), 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.

Design A two-factor repeated measures design employed the factors of modality (auditory, gustatory, haptic, olfactory, visual) and display duration (17ms, 33ms, 50ms, 67ms, 100ms). 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^2_G), which allows direct comparison of within- and between-participants designs (Olejnik & Algina, 2003).

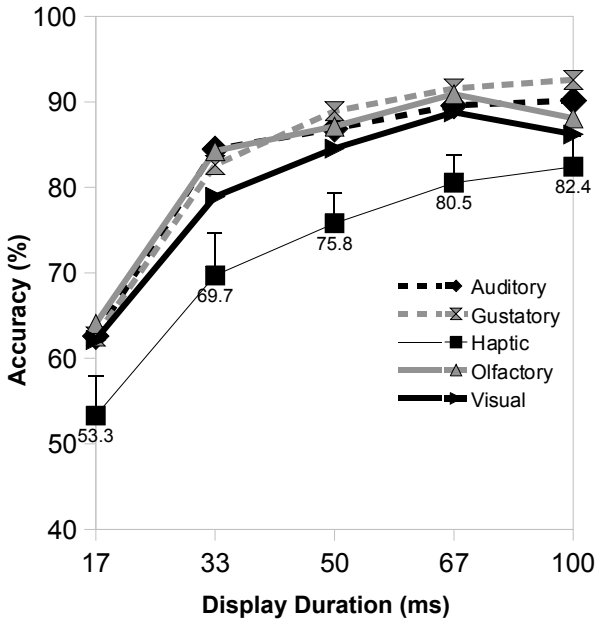

Figure 1: Percentage of correctly-detected words per modality and duration in Experiment 1 (yes/no task). Error bars represent 95% confidence intervals for within-participant designs (Loftus & Masson, 1994), calculated per display duration, and for clarity are only shown for the haptic modality.

Results & 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 (3.7% of data). The percentage of correctly detected test words per modality per display time is shown in Figure 1, where 50% represents performance at chance level.

There was an overall main effect of modality [$F(4, 164) = 14.00$, $p < .0001$, $\eta^2_G = .06$]. Planned contrasts between haptic and other modalities showed a distinct haptic disadvantage: people were indeed worse at detecting haptic words than any other modality (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 67ms (all ps<.001), and performance levelling out between 67ms and 100ms ($p = .599$). The interaction between factors was not significant [$F<1$, $\eta^2_G = .01$].

In order to examine when the haptic disadvantage first appears, and whether relative performance changes when more time is given to process the word, we examined each

display duration separately. At 17ms, modalities differed in performance [$F(4, 164) = 3.21$, $p = .014$, $\eta^2_G = .03$]: in planned contrasts, accuracy for haptic words was significantly worse than for all other modalities (all ps < .03). The same pattern emerged for 33ms [$F(4, 164) = 5.88$, $p < .001$, $\eta^2_G = .07$; all contrast ps < .02], 50ms [$F(4, 164) = 8.51$, $p < .001$, $\eta^2_G = .09$; all contrast ps < .004], and 67ms [$F(4, 164) = 8.16$, $p = .001$, $\eta^2_G = .09$; all contrast ps < .004]. By 100ms, where accuracy had begun to plateau out, 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 haptic words than auditory or gustatory words (*p*s < .002), and marginally less accurate than olfactory ($p = .072$) and visual ($p = .104$) words.

When accuracy at the 17ms display duration was compared to chance (50%) in one-sample t-tests, performance was significantly better for auditory [$t(41) = 3.70$, $p = .001$], gustatory [$t(41) = 3.86$, $p < .001$], olfactory [$t(41) = 4.12$, $p < .001$], and visual [$t(41) = 4.22$, $p < .001$] modalities, but not for haptic [$t(41) = 1.00$, $p = .321$]. At 33ms, accuracy for haptic words reached a level above chance [$t(41) = 5.51$ $p < .001$]. Since performance consistently improved with longer display durations, we do not report further above-chance statistics.

In summary, results show a distinct haptic disadvantage in conceptual processing. More time is needed for the successful processing of haptic information than any other modality. Even when a word is displayed for only 17ms, and people are not necessarily conscious of having read it, they can successfully detect auditory, gustatory, olfactory and visual modalities at a rate above chance. Haptic words, on the other hand, need to be displayed for longer (33ms) before they can be reliably detected. This haptic disadvantage, ranging between 4 and 15 percentage points, remains consistent across increasingly longer display times up to 100ms, where performance begins to plateau out and the differences between modalities become less pronounced. Since accuracy for both gustatory and olfactory modalities closely followed that for auditory and visual, and remained significantly better than haptic accuracy throughout, neither the attentional perspective nor threat detection explanations for the haptic disadvantage can adequately explain the results. We return to this issue in the General Discussion.

Experiment 2

Since the task in Experiment 1 required pressing "yes" and "no" buttons in response to stimuli, participants would have experienced haptic feedback from their fingers on every trial. It could be argued that this feedback, and the expectation of such feedback, could have swamped the haptic simulators and interfered with the simultaneous processing of haptic words (similar to e.g., Kaschak et al., 2005, for visual motion processing), potentially contributing to the haptic disadvantage. In this experiment, we employ a verbal go/no-go task where participants respond with a voice trigger rather than a button press. If the haptic disadvantage effect is more than a mere artifact of the button-pressing task, then we should see it replicated in the current experiment.

Method

Identical to Experiment 1, with the following exceptions:

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

Procedure Following calibration of the unidirectional microphone (worn as part of 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 the mask onset to the registration of a voice response. If no response was made within 1500ms, it was considered a "no" response and the next trial was presented.

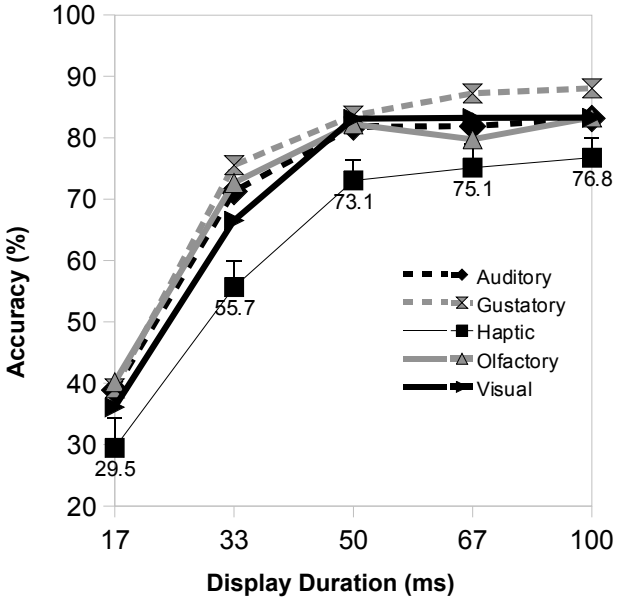

Figure 2: Percentage of correctly-detected words per modality and duration in Experiment 2 (go/no-go task). Error bars are as Figure 1.

Results & Discussion

Responses due to disfluencies (e.g., lip pops, 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). Figure 2 shows the percentage of correctly detected test words per modality per display time.

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

Further investigation of the timeline of the haptic disadvantage also replicated Experiment 1. At 17ms, accuracy differed across modalities [$F(4, 172) = 2.99$, $p = .020$, $\eta^2_G = .02$], with planned contrasts showing lower accuracy for haptic words than any other modality (all ps $< .03$). Haptic performance remained consistently worse than other modality words at 33ms [$F(4, 172) = 12.94$, $p < .001$, $\eta^2_G = .08$; all contrast ps $< .01$], and 50ms [$F(4, 172) = 6.59$, $p < .001$, $\eta^2_G = .03$; all contrast ps $< .001$]. At 67ms [$F(4, 172) = 4.92$, $p = .001$, $\eta^2_G = .03$], where overall performance had begun to plateau, haptic accuracy was similar to that of olfactory words ($p = .23$), but still worse than the remaining modalities (all ps $< .03$). By 100ms, haptic responses were again less accurate than all other modalities [$F(4, 172) = 6.35$, $p < .001$, $\eta^2_G = .03$; all contrast ps $< .02$].

Comparison to chance performance showed that people were generally more conservative in the current go/no-go task than in the previous experiment's yes/no task, which was not unexpected given that uncertain participants tend to withhold their responses in go/no-go tasks (thus registering an incorrect "no" to target items), whereas, in a yes/no task, they must press one of the two available buttons (thus carrying a 50% chance of being correct). At 17ms, people detected words at below-chance accuracy for all modalities: auditory [t(43) = -2.79, p = .008], gustatory [$t(43) = -2.85$, $p = .007$], haptic [$t(43) = -5.12$, $p < .001$], olfactory [$t(43) = -2.59$, $p = .013$], and visual [$t(43) = -3.16$, $p = .003$]. By 33ms, performance had risen above chance for auditory [$t(43) = 6.49$, $p < .001$], gustatory [$t(43) = 8.37$, $p < .001$], olfactory [$t(43) = 5.87$, $p < .001$] and visual [$t(43) = 4.07$, $p < .001$] words, but not haptic [$t(43) = 1.37$, $p = .178$], which took until 50ms to achieve above-chance accuracy [$t(43) = 6.76$, $p < .001$].

In short, the replication of the haptic 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 are due to differences in the conceptual processing of modality-specific words.

General Discussion

In this paper, we have demonstrated that a phenomenon observed during perception – the haptic disadvantage – also emerges during conceptual processing. Results showed that the processing of modality-specific information is rapid and automatic, with above-chance performance after just 17ms exposure in Experiment 1 and 33ms in Experiment 2. Haptic information, however, is the hardest to process. 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, and this effect emerged even though the strength on the given modality and the lexical decision times for each word were equal across modalities. These findings support the assertions of embodied theories that the conceptual system utilises the perceptual system for the purposes of representation.

Neuroimaging research has shown that perceptual and conceptual processing share a common, modality-specific neural substrate, while work on modality switching costs shows that they appear to share the same attentional mechanisms. Our results further demonstrate that perceptual and conceptual processing share a haptic disadvantage: people need more time to detect expected information regarding the sense of touch because of modality-specific differences in attentional control.

Two attentional mechanisms are at play in our modality detection task: endogenous control (where participants consciously focus attention on the target modality) and exogenous control (where the modality involved in processing a word automatically and obligatorily grabs attention). In any given block, therefore, endogenous and exogenous control are in competition: endogenous control attempts to focus continuously on the target modality while exogenous control flickers between the target modality (test items) and other modalities (filler items). We propose that the haptic disadvantage described in this paper arises from difficulties in haptic endogenous control: people find it more difficult to sustain attentional focus on the haptic modality than on any other which leaves haptic blocks more prone to exogenous disruption and hence leads to lower accuracy in detection of haptic stimuli.

Endogenous control of attention towards a particular perceptual modality creates anticipatory activation in the relevant area of the cortex (Foxe, Simpson, Ahlfors & Saron, 2005). However, attentional control may vary in strength. Strong endogenous control means that conscious attention is anchored effectively in a specific modality and that stimuli from other modalities, while grabbing exogenous control during their processing, cannot hold onto attention and endogenous focus quickly returns to the target modality in preparation for the next stimulus. Weak endogenous control, on the other hand, means that conscious attention is not well-anchored and that stimuli from other modalities, when they wrest exogenous control away during their processing, are able to disrupt endogenous focus enough that attention may not be on the target modality when the next stimulus appears. We propose that the haptic modality suffers from weaker endogenous control of attention than the other perceptual modalities, which means more time is needed to detect words successfully, and thus the haptic modality lags behind in accuracy rates across display times.

So how did this haptic disadvantage in endogenous attentional come into being? Spence et al.'s (2001) speculation that haptic processing is special because it requires an internal attentional perspective is not borne out by the results. Taste is detected inside the mouth, and hence also requires body-focused attention, but gustatory information was processed as quickly 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 haptic due to an adaptive advantage in threat detection was also not supported: taste is of little use in detecting approaching danger but did not share the haptic disadvantage. 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 (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 haptic modality brought no such adaptive advantage. If such attentional mechanisms evolved as part of our perceptual systems, and these same attentional and perceptual systems are utilised during conceptual processing and language comprehension, then it should come as no surprise that modality-specific differences, such as the haptic disadvantage, emerge with linguistic as well as sensory stimuli.

Acknowledgments

This work was funded by grant RES-000-22-2407 from the UK Economic and Social Research Council to the first author.

References

Anderson, M. L. (2003). Embodied Cognition: A field guide. *Artificial Intelligence, 149*, 91-130.

Balota, D. A., Yap, M. J., Cortese, M.J., Hutchison, K. A., Kessler, B., Loftis, B., Neely, J. H., Nelson, D. L., Simpson, G. B., & Treiman, R. (2007). The English Lexicon Project. *Behavior Research Methods, 39*, 445-459.

Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences 22*, 577–660.

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology, 59,* 617–645.

Chrisley, R. (2003). Embodied artificial intelligence. *Artificial Intelligence, 149*, 131-150.

Collins, A. M., & Quillian, M. R. (1969). Retrieval time from semantic memory. *Journal of Verbal Learning and Verbal Behaviour, 8*, 240-248.

Dijksterhuis, A., & Aarts, H. (2003). On wildebeests and humans: The preferential detection of negative stimuli. *Psychological Science, 14*, 14–18.

Foxe, J. J., Simpson, G. V., Ahlfors, S. P., & Saron, C. D. (2005). Biasing the brain's attentional set: I. Cue driven deployments of intersensory selective attention. *Experimental Brain Research, 166*, 370–392.

Gibbs, R. W. (2003). Embodied experience and linguistic meaning. *Brain and Language, 84*, 1-15.

Glenberg, A. M. (1997). What memory is for. *Behavioral and Brain Sciences, 20,* 1–55.

Glenberg, A. M., & Kaschak, M. P. (2002). Grounding language in action. *Psychonomic Bulletin & Review, 9,* 558–565.

Goldberg, R. F., Perfetti, C. A., & Schneider, W. (2006). Perceptual knowledge retrieval activates sensory brain regions. *Journal of Neuroscience, 26*, 4917-4921.

Goldstone, R., & Barsalou, L.W. (1998). Reuniting perception and conception. *Cognition, 65*, 231-262.

González, J., Barros-Loscertales, A., Pulvermüller, F., Meseguer, V., Sanjuán, A., Belloch, V., & Ávila, C. (2006). Reading cinnamon activates olfactory brain regions. *Neuroimage, 32*, 906-912.

Johnson-Laird, P. N. (1983). *Mental models*. Cambridge, MA: Harvard University Press.

Loftus, G. R., & Masson, M. E. J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin & Review, 1*, 476-490.

Lynott, D. & Connell, L. (2009). Modality exclusivity norms for 423 object properties. *Behavior Research Methods, 41*, 558-564.

MacWhinney, B. (1999). The emergence of language from embodiment. In B. MacWhinney (Ed.), *The emergence of language*. Mahwah, NJ: Lawrence Erlbaum.

Martin, M. G. F. (1995). Bodily awareness: A sense of ownership. In J. L. Bermudez, A. Marcel, & N. Eilan (Eds.), *The body and the self.* Cambridge, MA:MIT Press.

Newell, A. & Simon, H. A. (1972). *Human Problem Solving*. Englewood Cliffs, NJ: Prentice-Hall.

Newman, S. D., Klatzky, R. L., Lederman, S. J., Just, M. A. (2005). Imagining material versus geometric properties of objects: An fMRI study. *Cognitive Brain Research, 23*, 235-246.

Olejnik, S., & Algina, J. (2003). Generalized eta and omega squared statistics: Measures of effect size for some common research designs. *Psychological Methods, 8*, 434-447.

Pecher, D., Zeelenberg, R., & Barsalou, L.W. (2003). Verifying properties from different modalities for concepts produces switching costs. *Psychological Science, 14,* 119-124.

Pecher, D., & Zwaan, R. A. (2005). Introduction to grounding cognition. In D. Pecher & R. A. Zwaan (Eds.), *Grounding cognition: the role of perception and action in memory, language, and thinking*. Cambridge: CUP.

Pulvermuller, F. (2005) Brain mechanisms linking language and action. *Nature Reviews Neuroscience, 6*, 576-582.

Simmons, W.K., Ramjee, V., Beauchamp, M.S., McRae, K., Martin, A., & Barsalou, L.W. (2007). A common neural substrate for perceiving and knowing about color. *Neuropsychologia, 45*, 2802-2810.

Spence, C., Nicholls, M. E. R., & Driver, J. (2000). The cost of expecting events in the wrong sensory modality. *Perception & Psychophysics, 63*, 330-336.

Tulving, E. (1972). Episodic and semantic memory. In E. Tulving & W. Donaldson (Eds.), *Organization and memory*. New York: Academic Press.

Turatto, M., Galfano, G., Bridgeman, B., & Umiltà, C. (2004). Space-independent modality-driven attentional capture in auditory, tactile and visual systems. *Experimental Brain Research, 155*, 301-310.

van Dantzig, S., Pecher, D., Zeelenberg, R., & Barsalou, L.W. (2008). Perceptual processing affects conceptual processing. *Cognitive Science, 32,* 579-5.