Independent processing of form, colour, and texture in object perception

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Abstract. Most investigations of object recognition have focused on the form rather than the material properties of objects. Nevertheless, knowledge of the material properties of an object (via its surface cues) can provide important information about that object’s identity. In this study, we used Garner’s speeded-classification task to explore whether or not the processing of form and the processing of surface properties are independent. In experiment 1, participants made length and width classifications in an initial form task. Participants were unable to ignore length while making width classifications, and were unable to ignore width while making length classifications. This suggests that the perception of length and the perception of width share common processing resources. In a subsequent task, we examined possible interactions between the processing of form and the processing of surface properties. In contrast to the findings with the form task, participants were able to ignore form while making surface-property classifications, and to ignore surface properties while making form classifications. This suggests that the form of objects and their surface properties are processed independently. In experiment 2, we went on to show that the two prominent surface-property dimensions of colour and texture can also be processed independently. In other words, participants were able to ignore colour while making texture classifications, and vice versa. Finally, in experiment 3, we examined the possibility that the stimuli and required responses that we used in experiment 2 were too categorical and thus not optimal for assessing whether or not colour and texture share common processing resources. Using a different stimulus set, participants were again able to ignore colour while making texture classifications, and vice versa. Taken together, these results provided convincing evidence that the separate ventral-stream brain regions identified for form, texture, and colour in a recent neuroimaging study (Cant and Goodale, 2007 Cerebral Cortex 17 713–731) can indeed function independently.

1 Introduction

Our visual system allows us to individuate and recognise objects with remarkable ease and accuracy. A broad range of cues can be used to do this. We can, for example, recognise objects on the basis of shape, colour, texture, and specular patterns. Surprisingly, cognitive neuroscientists have focused almost all their attention on shape cues. Thus, they have explored in some detail how the geometric structure of objects facilitates their recognition, but have given little attention to the perception of the material properties of an object and their contribution to recognition. The material properties of an object are a function of the ‘stuff’ from which that object is made, such as wood, metal, or plastic. Adelson (2001) has eloquently argued that the recognition of material properties plays a critical role both in object recognition and in how we interact with objects in the world. He points out, for example, that the way in which we walk through our immediate environment depends upon our perception of whether we are walking on grass, rocks, or ice. We intuitively make the connection between the visual appearance of these different substrates and their friction coefficients and compliance. Similarly, our recognition of common objects in the world, from wine glasses

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to lumps of coal, is clearly modulated by our perception of the material properties of those objects. Despite the clear importance of the perception of material properties, little is understood about how the visual system makes use of surface properties to recognise the material or stuff from which objects are made.

Most of the work on surface properties, such as colour and visual texture, has been in the realm of scene recognition (Biederman et al 1982; Schyns and Oliva 1994, 1997; Moller and Hurlbert 1996; Oliva and Schyns 1997, 2000; Vailaya et al 1998; Gegenfurtner and Rieger 2000; Oliva and Torralba 2001), although there has been some work on face recognition as well (Tarr et al 2001, 2002; Russell et al 2006). In almost all of this work, the emphasis has been on colour rather than texture. Even in those studies that have looked at the contribution of surface properties to object recognition, most have focused on the contribution of colour. Tanaka and colleagues (Tanaka and Presnell 1999; Tanaka et al 2001), for example, have argued that colour can be a useful cue for identifying objects, particularly where colour is diagnostic for identity (eg orange carrots, red fire trucks). These studies, as well as several others (Naor-Raz et al 2003; Rossion and Pourtois 2004; Diplaros et al 2006; Reis et al 2006), suggest that we can and do use colour information in the recognition of common objects. In contrast, the role of texture in object recognition (independent of its role in revealing the form of objects) has not received a great deal of attention (but see Humphrey et al 1994; Adelson 2001; Liu et al 2005). Nevertheless, one can imagine any number of situations where texture information could be equally diagnostic for identity (eg grain in wood, the smoothness of metal, and the dimples on an orange).

With the advent of functional magnetic resonance imaging (fMRI), there has been a concerted effort to understand the neural substrates of object recognition in the human brain. After a decade or more of research, it is generally agreed that the lateral occipital area, or area LO, in the ventral stream of visual processing is a critical region for visual object recognition (eg Malach et al 1995; Large et al 2005; for review, see Grill-Spector and Malach 2004). Although the majority of fMRI studies have focused on the geometric structure of objects (eg Grill Spector et al 1998; Wilson and Wilkinson 1998; Kourtzi et al 2003), in a few studies the neural substrates of surface-property perception, particularly colour, have been examined. It has been suggested that the processing of colour is mediated in large part by an area or areas in the fusiform and surrounding cortex, variously referred to as V4 and/or V8 (McKeefry and Zeki 1997; Hadjikhani et al 1998; Tootell et al 2003). In contrast, the processing of texture has usually been studied for its role in revealing information about the shape of objects. For example, previous research has demonstrated that the ventral region of area V4 (ie V4v) shows increased activation to line textures with texture-defined boundaries compared to line textures with no boundaries (Kastner et al 2000).

In a recent fMRI study, Peuskens and colleagues (2004) found that regions within the lingual gyrus (LG) and collateral sulcus (CoS) appeared to be specialised for processing the surface properties of objects with distinctive colours and textures, whereas area LO appeared to be specialised for processing the form of those same objects. More recently, we demonstrated a similar dissociation between the areas in the ventral stream involved in the processing of surface properties and those involved in the processing of form (Cant and Goodale 2007). We showed that attention to surface properties (both colour and texture) activated the CoS and a region in the inferior occipital gyrus (IOG), whereas attention to object form activated area LO. We went on to show that specific attention to texture activated regions in the IOG and the CoS, as well as regions in the lingual sulcus (LS) and the inferior temporal sulcus (ITS). Surprisingly, no colour-specific cortical areas were identified in the brain, although parts of the primary visual cortex (V1) and the cuneus yielded higher activation for colour as opposed to texture—but this activation was never higher than the activation to form.
Taken together, these neuroimaging studies suggest that the processing of object form is independent of the processing of surface properties. Moreover, the Cant and Goodale (2007) study suggests that, within the surface-property domain, the extraction of information about an object’s colour occurs relatively early in visual analysis as compared to the extraction of surface texture, perhaps because the latter requires more complex computations.

The claim for separate pathways for the processing of form versus surface properties is quite consistent with neurological evidence from patients with visual form agnosia. The well-known patient DF, for example, is unable to use form information to recognise objects, but can use surface-property information such as colour and texture (Milner et al 1991; Humphrey et al 1994; Goodale and Milner 2004). Interestingly, an MRI scan revealed large bilateral lesions to area LO, while her fusiform gyrus and parahippocampal cortex remained largely intact (James et al 2003). Not surprisingly, an fMRI study showed that there was no differential activation in DF’s brain when she was shown stimuli that could be distinguished only on the basis of their form (line drawings). In contrast, when DF was presented with high-resolution colour photographs of objects which she could recognise on the basis of diagnostic surface cues, robust bilateral activation was observed in her fusiform gyrus, extending to some degree into parahippocampal cortex (James et al 2003). More recent fMRI experiments revealed that DF showed higher activations in the parahippocampal gyrus for appropriately coloured scenes (which she could often correctly categorise) than for black-and-white versions of those same scenes (Steeves et al 2004). Taken together, these results converge on the earlier fMRI studies of healthy volunteers, suggesting that area LO plays a critical role in object recognition by preferentially processing the geometric structure of objects. These results also suggest that the processing of the material properties of objects (via their surface cues) independently of their form may depend on neural networks that are located more medially in the fusiform and parahippocampal regions.

A fascinating complement to the research on visual form agnosia comes from research on the disorder known as cerebral achromatopsia. People with this disorder have spared form processing but their colour perception is severely compromised. The lesions responsible for this visual deficit have been localised to more medial regions of occipito-temporal cortex, in the lingual and fusiform gyri (Heywood et al 1995; Duveleroy-Hommet et al 1997; for a review, see Heywood and Kentridge 2003). The double dissociation of spared and compromised visual abilities (and the lesions responsible for these behavioural observations) in visual form agnosia and cerebral achromatopsia again present striking evidence for the notion that there are separate form and surface-property pathways in the primate visual system.

But the demonstration of independent brain regions for the processing of form and surface properties does not necessarily mean that these brain regions function independently during object recognition. In the present study, we tested for possible interactions between the processing of object form and the processing of surface properties by using a well-established and sensitive behavioural paradigm. After all, behavioural measures are the final arbiter of whether or not the processing of one object property interferes with the processing of another. In addition, we used the same behavioural paradigm to investigate whether or not the processing of colour is independent of the processing of texture, where the neuroimaging data are more equivocal. Colour and texture both convey information about an object’s surface (and thus its material properties), and in nature these two visual properties are often inextricably linked. Nevertheless, there are many instances where texture and colour can be quite independent.
The behavioural paradigm that we used is known as Garner’s speeded-classification task. Garner’s task measures how efficiently people can process one dimension of an object while ignoring its other dimensions (Garner 1974). In a typical Garner experiment, participants are asked to attend to a single dimension of an object under two different conditions. In the ‘baseline’ condition, only the relevant (attended) dimension varies, while another, irrelevant dimension is kept constant. In the ‘filtering’ condition, however, both the relevant and irrelevant dimensions vary. If participants are able to process these two dimensions independently, then the speed and accuracy of their responses to the relevant dimension should be identical in both the baseline and filtering conditions. In Garner’s language, the dimensions would be classified as separable. An example of this would be the position of lines and their luminance contrast: participants can discriminate changes in the position of a line while successfully ignoring their luminance contrast, and vice versa (Shechter and Hochstein 1992). If the participants cannot process the two dimensions independently, however, then the speed and accuracy of their responses to the relevant dimension should be worse in the filtering condition than in the baseline condition, because participants would not be able to ‘filter out’ the changes in the irrelevant dimension. In Garner’s language, the two dimensions would be classified as integral. An example of this would be the length of lines and their orientation; participants cannot help attending to the orientation of the lines when asked to discriminate their length, and vice versa (Dick and Hochstein 1988). In this case, the two dimensions are said to show ‘Garner interference’.

We conducted three experiments. In experiment 1, we looked for potential interference between the processing of object form and the processing of surface properties. Given the neuropsychological and neuroimaging evidence for a separation in the neural substrates for the processing of form and surface properties (mainly colour), one might expect that these two object properties would show no interference and could be classified as separable dimensions in Garner’s terminology. But, as we indicated earlier, the fact that separate brain regions are activated for form and surface properties does not mean that these two brain regions are independent. In order to demonstrate true independence, it is necessary to look at the behavioural evidence. There is some evidence already from Garner experiments that shape and colour are separable dimensions (Gottwald and Garner 1972). In this early study, however, colour was very much an arbitrary and disconnected surface property. In other words, the colours were not linked to the material properties of the objects. In our experiment, we used colours and textures on highly rendered objects that could be linked with real-world materials (brick and wood). We reasoned that, by using realistic stimulus displays, we would optimise the chances of observing any interference between different stimulus dimensions, even though we still expected that such interference would not be present.

In experiments 2 and 3, we explored the processing of surface properties in greater detail, by looking at the effect of colour on judgments of texture differences, and vice versa. Here we were uncertain about what might happen. Given the results of our earlier neuroimaging study (Cant and Goodale 2007), it was possible that colour and texture information would be treated as separable dimensions. Alternatively, since colour and texture are often correlated in nature, it seemed equally possible that these two properties would be treated as integral dimensions. Again we used highly rendered objects in which the surface properties were linked to real-world materials, optimising the chances of observing Garner interference if it were present.

2 Experiment 1
In this experiment, participants completed two tasks. In the main task (form–surface task), participants were required to classify objects on the basis of their width (or length), while ignoring the surface properties (colour or texture) of those objects, and
vice versa. The objects were high-resolution images of bricks or pieces of wood. In the control task (form-only), participants were required to classify objects on the basis of their width while ignoring their length, and vice versa. In this task, surface properties never varied.

We included the form-only task because, on the basis of previous research, we could predict Garner interference between the dimensions of width and length (Felfoldy 1974; Dykes and Cooper 1978; Macmillan and Ornstein 1998; Ganel and Goodale 2003). It was important to include this task, because the prediction that form and surface properties would be separable dimensions rests on a null result. If this null result was found without using the form-only task, then we would not be sure if such a result was obtained because of our prediction of separable dimensions, or rather because of some consequence of the experimental design or stimuli we used.

In this experiment, we recorded participants’ response latencies and accuracy in each classification task. In the form–surface task, we expected that there would be no differences in the response latencies and the number of errors in the baseline trials (where only the relevant dimension varied) and the filtering trials (where both the relevant and irrelevant dimensions varied). In other words, we expected that participants could attend to form and completely ignore changes in surface properties (and vice versa). In contrast, in the form-only task, we expected that participants would show longer response latencies and commit more errors in the filtering trials than in the baseline trials. In other words, we expected that they could not ignore changes in length when making width judgments, and vice versa.

2.1 Methods
2.1.1 Participants. Twelve individuals (six male, six female; nine right-handed, three left-handed; mean age 27.5 years, range 20–35 years) participated in this experiment. The participants were selected from research assistants, undergraduate students, and graduate students studying psychology or neuroscience at the University of Western Ontario. Participants had normal or corrected-to-normal visual acuity and reported no history of neurological impairment. They received Can $10 for their participation. All participants gave their informed consent and the experiment was approved by the Review Board for Health Sciences Research involving Human Participants for the University of Western Ontario.

2.1.2 Stimuli and apparatus. Stimuli used in this experiment consisted of computer-rendered rectangular blocks which varied along two form (width and length) and two surface-property (colour and texture) dimensions (see figure 1). With respect to the form dimensions, the stimuli were rendered in two different widths (wide, 30 mm; narrow, 24 mm) and two different lengths (long, 58 mm; short, 43 mm). With respect to surface properties, the stimuli were rendered in two different colours (yellow and beige) and two different textures (brick and wood).

Participants sat at a desk in a darkened room with their head mounted in a headrest and stimuli were presented on a CRT monitor (1280 × 1024 pixels) located directly in front of them. Stimulus presentation was controlled by Superlab Pro version 2.0.4 (Cedrus Corporation, San Pedro, CA). Stimuli were always presented at the centre of the computer screen and the distance from the participants’ eyes to the screen was approximately 40 cm. When classifying the stimuli on the basis of the two form and two surface-property dimensions listed above, participants responded by pressing either the ‘1’ or ‘3’ key on the number pad of the keyboard with their right index or ring finger respectively. Response latency and accuracy measures were recorded by the Superlab Pro software.
2.1.3 Procedure. All participants completed both the form-only task and the form–surface task. The order of these tasks was counterbalanced across participants. In the form-only task, there were two conditions. In the width condition, participants classified the stimuli on the basis of their width (ie ‘wide’ versus ‘narrow’); in the length condition, participants classified the stimuli on the basis of their length (ie ‘long’ versus ‘short’; see figure 2). The order of these conditions was counterbalanced across participants. The surface properties (both colour and texture) of the stimuli in the form-only task were kept constant for each participant (but all combinations were counterbalanced across the twelve participants). In the form–surface task, there were also two conditions. In the form condition, half the participants classified the stimuli on the basis of their width and the other half classified the stimuli on the basis of their length. In the surface-property condition, half the participants classified the stimuli on the basis of colour (‘yellow’ versus ‘beige’) and the other half classified the stimuli on the basis of texture (‘brick’ versus ‘wood’). The different combinations of form and surface-property cues were counterbalanced across participants in the form–surface task. In other words, the four possible combinations, width–colour, width–texture, length–colour, and length–texture, were equally represented, with one combination being randomly assigned to each participant. Thus, in the form–surface task, each participant made both form judgments and surface-property judgments. Again, the order of presentation of the two conditions was counterbalanced across subjects.

Before starting each condition of each task, participants were given 40 practice trials to become familiar with the task. The participant’s task upon presentation of the stimulus on any given trial was to classify that stimulus as quickly and accurately as possible. Verbal feedback was provided where necessary. The stimulus remained on the computer screen until a response was made, at which point a 2000 ms interval separated the presentation of the next stimulus. For the experiment proper, each task consisted of eight blocks of trials. In each condition of each task, participants classified stimuli in four separate blocks of 32 trials each. Two of the four blocks of trials served as baseline blocks (where only the relevant dimension varied), while the other two blocks of trials served as filtering blocks (where both the relevant and irrelevant dimensions varied). The order of presentation of the four blocks was counterbalanced across conditions and participants. For each block of 32 trials, the two possible responses for the relevant dimension (eg ‘wide’ or ‘narrow’ in the case of width) were presented an equal number of times in pseudorandom order. Half of the participants pressed ‘1’ for wide and ‘3’ for narrow, for example, and the other half of the participants had these button assignments reversed. Again, the assignment of the response buttons was counterbalanced across participants and conditions. An instruction screen separated each block, informing participants that they could take a short break if they desired, and reminded them to respond as quickly and accurately as possible in the next block of trials. Each participant completed 512 trials during the entire experimental session (32 trials × 4 blocks × 2 conditions × 2 tasks).

2.2 Results
Because of the inherent differences in design between the two tasks, separate analyses of variance were conducted for the form-only and the form–surface tasks. Response latencies (for correct trials only) and the number of errors committed were analysed in both cases with a $2 \times 2$ repeated-measures analysis of variance ($\alpha = 0.05$). Main effects of interest included condition (width and length for the form-only task; form and surface properties for the form–surface task) and block type (baseline and filtering). Pairwise a posteriori comparisons were performed with the Bonferroni procedure ($\alpha = 0.05$). An outlier analysis was performed, and response latencies that were
Figure 1. Examples of the stimuli used in experiments 1 and 2. The stimuli could vary along two form dimensions (width and length), and two surface-property dimensions (colour and texture).

Figure 2. Schematic of the experimental methodology used in this study, with the form-only task from experiment 1 (which is identical to the form tasks used in experiments 2 and 3) serving as an illustrative example. Participants completed four blocks of trials (two baseline blocks and two filtering blocks) in both the width and the length conditions. In the width condition, we recorded how quickly and accurately participants could classify the stimuli as being either ‘wide’ or ‘narrow’. In the length condition, participants classified the stimuli as being either ‘long’ or ‘short’. In the baseline blocks of trials, only the relevant dimension varied (eg in the width condition, width would vary but length, which was the irrelevant dimension, would remain constant). In the filtering blocks of trials, however, both the relevant and the irrelevant dimensions varied. For each task, the order of the conditions (eg width and length) and the block types (baseline and filtering) was counterbalanced across participants. $W_B = $ baseline block of trials in the width condition; $W_f = $ filtering block of trials in the width condition; $L_B = $ baseline block of trials in the length condition; $L_f = $ filtering block of trials in the length condition; $T_1 = $ trial 1; $T_2 = $ trial 2; $T_3 = $ trial 3; $T_N = $ last trial.
2.5 standard deviations above or below the mean reaction time for each condition in each task were excluded from analysis. An outlier analysis was not performed on the number of errors committed.

2.2.1 Form-only task. The main effect of condition [width: mean (M) = 520 ms, standard error of the mean (SEM) = 21 ms; length: M = 469 ms, SEM = 14 ms] for response latency was significant \( F_{1,11} = 10.04, p < 0.009, \) mean square error (MSE) = 3117.02]. This presumably reflects the fact that the difference in length was much larger than the difference in width. The main effect of block type (baseline: M = 480 ms, SEM = 15 ms; filtering: M = 509 ms, SEM = 17 ms) was also significant \( F_{1,11} = 33.51, p < 0.001, \) MSE = 301.61). The interaction between condition and block type did not reach significance \( F_{1,11} = 0.07, p > 0.75, \) MSE = 274.60). In line with our predictions, we conducted Bonferroni-corrected pairwise comparisons to investigate the differences between baseline and filtering blocks in each condition. As we predicted, response latencies in the baseline blocks of the width condition (M = 505 ms, SEM = 22 ms) were significantly faster than the response latencies in the filtering blocks (M = 536 ms, SEM = 21 ms) \( t_{11} = 4.51, p < 0.001 \)—see figure 3a. Similarly, response latencies in the baseline blocks (M = 456 ms, SEM = 12 ms) of the length condition were significantly faster than those in the filtering blocks (M = 483 ms, SEM = 16 ms) \( t_{11} = 3.89, p < 0.003 \).

*Figure 3.* Results from experiment 1. Results are based on data from twelve participants, in a repeated-measures design. Bonferroni corrections were applied to control for Type I error rates. Error bars indicate 95% confidence intervals derived by using the mean square error term from the repeated-measured analyses of variance. (a) Results for participants’ response latencies in the form-only task (width and length) and the form–surface task (form and surface properties). \* \( p < 0.001 \); ** \( p < 0.003 \). (b) Results showing the number of errors committed in both tasks of experiment 1. \* \( p < 0.05 \).

In the analysis on the number of errors committed, the main effect of condition (width: M = 2.92, SEM = 0.47; length: M = 1.88, SEM = 0.38) did not reach significance \( F_{1,11} = 2.40, p > 0.1, \) MSE = 5.43). The main effect of block type (baseline: M = 1.54, SEM = 0.32; filtering: M = 3.25, SEM = 0.44), however, did reach significance \( F_{1,11} = 9.23, p < 0.02, \) MSE = 3.79). The interaction between condition and block type was not significant \( F_{1,11} = 1.02, p > 0.60, \) MSE = 3.52). We again conducted a posteriori pairwise comparisons to investigate differences between the baseline and filtering blocks in each condition (see figure 3b). As in the case of response latency, participants committed significantly fewer errors in the baseline blocks (M = 1.92, SEM = 0.48) of the width condition than in the filtering blocks (M = 3.92, SEM = 0.78) \( t_{11} = 2.21, p < 0.05 \). In the length condition, participants also committed significantly fewer errors in the baseline blocks (M = 1.17, SEM = 0.41) than in the filtering blocks (M = 2.58, SEM = 0.57) \( t_{11} = 2.24, p < 0.05 \).
2.2.2 Form–surface task. For response latencies, the main effect of condition (form: \(M = 447\) ms, \(SEM = 10\) ms; surface properties: \(M = 482\) ms, \(SEM = 15\) ms) was significant (\(F_{1,11} = 8.84, p < 0.02, MSE = 1672.07\)). This was the only effect, however, to reach significance, as the main effect of block type (baseline: \(M = 465\) ms, \(SEM = 12\) ms; filtering: \(M = 465\) ms, \(SEM = 11\) ms; \(F_{1,11} = 0.01, p > 0.98, MSE = 99.10\)) and the interaction between condition and block type (\(F_{1,11} = 0.03, p > 0.87, MSE = 120.25\)) were both found to be non-significant. In this task, we predicted that we would not find a significant difference in response latencies between the baseline and filtering blocks in each condition. Thus, to confirm this prediction, we conducted Bonferroni-corrected pairwise comparisons between the baseline and filtering blocks in both the form and the surface-properties condition (see figure 3a). We found that response latencies in the baseline and filtering blocks did not differ significantly in both the form condition (baseline: \(M = 447\) ms, \(SEM = 10\) ms; filtering: \(M = 447\) ms, \(SEM = 11\) ms; \(t_{11} = 0.09, p > 0.92\)) and the surface-properties condition (baseline: \(M = 482\) ms, \(SEM = 16\) ms; filtering: \(M = 483\) ms, \(SEM = 14\) ms; \(t_{11} = 0.16, p > 0.87\)). Indeed, none of these differences between baseline and filtering blocks even approached significance.

The analysis on the number of errors committed yielded no significant results for the main effects of condition (form: \(M = 1.33, SEM = 0.36\); surface properties: \(M = 1.79, SEM = 0.36; F_{1,11} = 2.47, p > 0.14, MSE = 1.02\)), block type (baseline: \(M = 1.71, SEM = 0.42; F_{1,11} = 1.42, SEM = 0.33; F_{1,11} = 0.57, p > 0.46, MSE = 1.79\)), and the condition-by-block type interaction (\(F_{1,11} = 0.22, p > 0.65, MSE = 0.87\)). Using the same logic as outlined in the analysis on response latencies above, we conducted a simple main-effects analysis to investigate the interaction in greater detail (see figure 3b). Again, no significant differences were observed in the number of errors committed in the baseline and filtering blocks for both the form condition (baseline: \(M = 1.42, SEM = 0.47; F_{1,11} = 1.25, SEM = 0.35; t_{11} = 0.39, p > 0.70\)) and the surface-properties condition (baseline: \(M = 2.00, SEM = 0.46; F_{1,11} = 1.58, SEM = 0.42; t_{11} = 0.81, p > 0.43\)).

2.3 Discussion

As expected, in the form-only task we found that the two components of form (width and length) acted as integral dimensions. Varying the length of an object (between long and short) interfered with participants’ width judgments (classifying objects as wide or narrow), and varying the width of an object interfered with their length judgments. For example, participants were significantly faster (and more accurate) at making width or length judgments when only the relevant dimension varied (baseline blocks); their performance deteriorated (slower response latencies and more errors) when both the relevant and irrelevant dimensions varied (filtering blocks). This result is entirely consistent with earlier work showing interference between width and length in the Garner task (eg Ganel and Goodale 2003). The evidence that object shape is perceived holistically is overwhelming; it is impossible to attend to one dimension, such as width, while ignoring another, such as length (indeed, other dimensions of object shape, such as orientation and the length of lines, have also shown Garner interference; see Dick and Hochstein 1988). This replication of the standard finding is critical to the present experiment, since it demonstrates that we can replicate well-established findings in the Garner interference literature with the stimuli and apparatus employed in this experiment.

The results of the form–surface task were quite different. Varying either of two form dimensions (width or length) did not interfere with the participants’ surface-property judgments (classifying the colour or texture of objects). Similarly, varying surface properties did not interfere with form judgments. The speed and accuracy of

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\(F\): F-ratio, \(SEM\): Standard Error of the Mean, \(M\): Mean, \(t\): t-value, \(p\): significance level.
responses to the relevant dimension (whether it was a form cue or a surface-property cue) were virtually identical in both the baseline and filtering blocks. In other words, participants were able to process these two stimulus properties independently; in Garner’s terms, form and surface properties are separable.

These results converge nicely on previous experiments which suggest that form and surface properties may be encoded independently in the brain (Boucart and Humphreys 1994, 1997). Using a sequential-matching paradigm, Boucart and Humphreys (1994, 1997) assessed the impact of semantic information on the processing of form (orientation, shape, and size) and surface properties (colour, luminance, and texture). Results indicated that semantic information interfered with the processing of form, but did not interfere with the processing of surface properties. Boucart and Humphreys suggested that the difference in selective attention between form and surface properties may be a consequence of the existence of physiologically separate processing channels for form and surface-based cues (eg Livingstone and Hubel 1987).

It is encouraging that the results from the present study converge with the results from the studies mentioned above, which utilised a different behavioural paradigm than the Garner task. To establish a stronger connection between these results, however, it would be necessary to adapt the stimuli used in this study to the sequential-matching paradigm developed by Boucart and Humphreys (1992, 1994, 1997). When using this paradigm, one might expect that surface-based visual cues such as colour and texture should not affect performance on a matching task on length or width, and vice versa (but, given the results of the form-only task, one might expect that width should affect matching on length, and vice versa).

These results also converge nicely on a recent neuroimaging study, which showed that the form and the surface properties of objects are processed in separate pathways in human occipito-temporal cortex (Cant and Goodale 2007). Moreover, these findings are also consistent with the neuropsychological research discussed earlier suggesting that visual form agnosia and cerebral achromatopsia can be doubly dissociated (Milner and Goodale 1995; Heywood and Kentridge 2003). In short, the present results add to a growing body of evidence that the processing of form and the processing of surface properties are mediated by relatively independent neural mechanisms.

As we noted earlier, width and length are two components of an object’s form, and the perception of these two components interfered with each other in Garner’s speeded-classification task. By extension, one might think that colour and texture, which are two components of an object’s surface, would also interfere with each other. But the results of Cant and Goodale (2007) showed some evidence that colour and texture are processed in separate regions of visual cortex (early versus late visual areas, respectively). Demonstrating that colour and texture are processed in separate regions of visual cortex regions, however, does not necessarily mean that these two stimulus dimensions are processed independently. It is entirely possible for the two regions to be highly interdependent in their processing of visual input. Thus, it becomes important to establish whether or not the processing of colour and the processing of texture are truly independent by using a behavioural assay, such as the Garner task. In experiment 2, we investigated the potential interaction between the processing of colour and texture in greater detail.

3 Experiment 2
In this experiment, participants completed two tasks. In the form task, participants classified stimuli based on their width and length in separate blocks of trials. We again predicted that width and length would interfere with each other in Garner’s task. [This task was included to make sure that it was possible to demonstrate integrality between two dimensions in our stimulus set.] In the surface-properties task, participants classified
stimuli on the basis of their colour and texture in separate blocks of trials. On the basis of the observations above, we were not sure whether colour and texture would be classified as integral or separable dimensions.

3.1 Methods
3.1.1 Participants. Twelve individuals (six male, six female; nine right-handed, three left-handed; mean age 25.5 years, range 23–31 years) participated in this experiment. The participants were selected with the use of the same inclusion/exclusion criteria as in experiment 1.

3.1.2 Stimuli and apparatus. The stimuli and apparatus in this experiment were identical to those used in experiment 1.

3.1.3 Procedure. All participants completed both the form task and the surface-properties task. The form task of this experiment was identical to the form-only task of experiment 1, and will therefore not be described in any more detail. The surface-properties task contained two different conditions. In the colour condition, participants classified the stimuli on the basis of one of two different colours (‘yellow’ versus ‘beige’); in the texture condition, participants classified the stimuli on the basis of one of two different textures (‘brick’ versus ‘wood’). The form (both width and length) of the stimuli in the surface-properties task was kept constant for each participant. In all other ways, the design of this experiment was identical to that used in experiment 1. Each participant completed 512 trials during the entire experimental session (32 trials × 2 conditions × 2 tasks).

3.2 Results
Separate analyses of variance were conducted for the form and the surface-properties tasks. Response latencies (from correct trials only) were analysed with a 2 × 2 repeated-measures analysis of variance ($\alpha = 0.05$). Main effects of interest included condition (width and length for the form task; colour and texture for the surface-properties task) and block type (baseline and filtering). Pairwise a posteriori comparisons were performed with the Bonferroni procedure ($\alpha = 0.05$). The same outlier analysis that was used in experiment 1 was also used here. The numbers of errors committed were also analysed with the above procedure, but an outlier analysis was not performed.

3.2.1 Form task. The main effect of condition (width: $M = 588$ ms; $SEM = 25$ ms; length: $M = 487$ ms, $SEM = 23$ ms) for response latency was significant ($F_{1,11} = 93.67$, $p < 0.001$, $MSE = 1304.04$). Again, this almost certainly reflects the fact that the difference in length was much more evident than the difference in width. In addition, the main effect of block type (baseline: $M = 504$ ms, $SEM = 21$ ms; filtering: $M = 572$ ms, $SEM = 27$ ms) was also significant ($F_{1,11} = 51.77$, $p < 0.001$, $MSE = 1079.03$). The interaction between condition and block type was also significant ($F_{1,11} = 34.01$, $p < 0.001$, $MSE = 412.15$). As in experiment 1, Bonferroni-corrected pairwise comparisons showed that, in the width condition, response latencies in the baseline blocks ($M = 537$ ms, $SEM = 22$ ms) were significantly faster than the response latencies in the filtering blocks ($M = 639$ ms, $SEM = 29$ ms) ($t_{11} = 8.01$, $p < 0.001$)—see figure 4a. Similarly, response latencies in the baseline blocks ($M = 470$ ms, $SEM = 21$ ms) of the length condition were significantly faster than those in the filtering blocks ($M = 504$ ms, $SEM = 26$ ms) ($t_{11} = 3.70$, $p < 0.004$).

In the analysis on the number of errors committed, the main effect of condition (width: $M = 3.42$, $SEM = 0.92$; length: $M = 1.50$, $SEM = 0.41$) reached significance ($F_{1,11} = 7.59$, $p < 0.02$, $MSE = 5.81$). The main effect of block type (baseline: $M = 1.54$, $SEM = 0.35$; filtering: $M = 3.38$, $SEM = 0.98$) was also significant ($F_{1,11} = 5.30$,
Results from experiment 2. Results are based on data from twelve participants, in a repeated-measures design. Bonferroni corrections were applied to control for Type I error rates. Error bars indicate 95% confidence intervals derived by using the mean square error term from the repeated-measures analyses of variance. (a) Results for participants’ response latencies in the form task (width and length) and the surface-properties task (texture and colour). *p < 0.001; **p < 0.004.  

The analysis on the number of errors yielded no significant results for the main effects of condition (colour: $M_{\text{baseline}} = 511$ ms, SEM = 13 ms; texture: $M_{\text{baseline}} = 502$ ms, SEM = 27 ms) or the texture condition (baseline: $M_{\text{baseline}} = 500$ ms, SEM = 28 ms; filtering: $M_{\text{baseline}} = 504$ ms, SEM = 26 ms; $t_{11} = 0.59$, $p > 0.56$).

The condition-by-block type interaction approached significance ($F_{1,11} = 3.87$, $p = 0.08$, MSE = 5.52). Because we expected to find significant differences between the baseline and filtering blocks in each condition, we carried out pairwise comparisons to investigate the interaction between condition and block type further (see figure 4b). As with response latency, participants committed significantly fewer errors in the baseline blocks ($M_{\text{baseline}} = 1.83$, SEM = 0.46) of the width condition than in the filtering blocks ($M = 5.00$, SEM = 1.56) ($t_{11} = 2.28$, $p < 0.05$). In the length condition, participants committed fewer errors in the baseline blocks ($M = 1.25$, SEM = 0.35) than in the filtering blocks ($M = 1.75$, SEM = 0.58), but this result did not reach significance ($t_{11} = 1.00$, $p > 0.33$).

3.2.2 Surface-properties task. For response latencies, the main effect of condition (colour: $M = 511$ ms, SEM = 13 ms; texture: $M = 502$ ms, SEM = 27 ms) was not significant ($F_{1,11} = 0.26$, $p > 0.62$, MSE = 3664.58). In fact, the main effect of block type (baseline: $M = 506$ ms, SEM = 19 ms; filtering: $M = 506$ ms, SEM = 19 ms; $F_{1,11} = 0.001$, $p > 0.97$, MSE = 276.35) and the interaction between condition and block type ($F_{1,11} = 0.52$, $p > 0.48$, MSE = 480.87) were also not significant. Next, we conducted Bonferroni-corrected pairwise tests to shed light on the precise pattern of responses in the baseline and filtering blocks of the colour and texture conditions (see figure 4a). As it turns out, response latencies in the baseline and filtering blocks did not differ significantly in either the colour condition (baseline: $M = 513$ ms, SEM = 13 ms; filtering: $M = 508$ ms, SEM = 15 ms; $t_{11} = 0.56$, $p > 0.58$) or the texture condition (baseline: $M = 500$ ms, SEM = 28 ms; filtering: $M = 504$ ms, SEM = 26 ms; $t_{11} = 0.59$, $p > 0.56$).

The analysis on the number of errors yielded no significant results for the main effects of condition (colour: $M = 1.88$, SEM = 0.37; texture: $M = 1.67$, SEM = 0.30; $F_{1,11} = 0.258$, $p > 0.62$, MSE = 2.02), block type (baseline: $M = 1.58$, SEM = 0.30; filtering: $M = 1.96$, SEM = 0.37; $F_{1,11} = 0.88$, $p > 0.36$, MSE = 1.92), and the condition-by-block type interaction ($F_{1,11} = 0.47$, $p > 0.50$, MSE = 1.11). Again, no significant differences were observed in the number of errors committed in the baseline and filtering blocks for both the colour condition (baseline: $M = 1.58$, SEM = 0.38; filtering: $M = 2.17$, SEM = 0.49; $t_{11} = 1.25$, $p > 0.23$) and the texture condition (baseline: $M = 1.58$, SEM = 0.45; filtering: $M = 1.75$, SEM = 0.35; $t_{11} = 0.31$, $p > 0.76$; see figure 4b).
### 3.3 Discussion

The results of experiment 2 provide further evidence that width and length are integral dimensions of object form and cannot be processed independently. As in experiment 1, participants’ performance (both response latencies and accuracy) in the baseline blocks of both the width and length tasks was better than their performance in the filtering blocks, where both the relevant and irrelevant dimensions varied. This demonstrates that participants could not ignore changes to the irrelevant dimension while they were attending to changes to the task-relevant dimension. We can therefore conclude, with even more confidence, that the shape of an object is perceived holistically.

In sharp contrast, the results of experiment 2 demonstrate that colour and texture can be processed independently and can therefore be thought of as separable dimensions. That is, varying the colour of an object (between yellow and beige) had no effect on texture judgments (classifying objects as having a brick or wood texture), and varying the texture had no effect on colour judgments. More precisely, participants’ performance in the baseline blocks (where only the attended dimension varied) and filtering blocks (where both the attended and unattended dimensions varied) of each condition was virtually identical. This result would appear to suggest that colour and texture do not share common processing resources, and that the brain regions that have been associated with texture and colour processing, respectively, can function independently. At first blush, this interpretation may seem counterintuitive, as colour and texture are usually bound together to define part of an object’s surface properties in real-world objects. These findings are, however, consistent with our neuroimaging study, which demonstrated that the colour and texture of objects are processed in early-visual and late-visual areas, respectively (Cant and Goodale 2007). Although converging evidence is always appealing, there is another (more methodological) explanation why colour and texture did not show Garner interference. To examine whether this alternative account is correct, we conducted a third experiment.

### 4 Experiment 3

In experiment 2, colour and texture, which are two aspects of an object’s surface, did not interfere with each other in Garner’s speeded-classification task. One interpretation of this finding is that colour and texture do not share common processing resources. There are alternative interpretations for the lack of interference between colour and texture that are plausible, however. It is possible, for example, that colour and texture did not interfere with each other because of the nature of the stimuli and the required responses that we used in experiment 2. In the case of form, where the dimensions of length and width were integral, the two dimensions were continuous. In other words, one could progressively make the long object shorter until it equaled the short object in length. Moreover, the very responses that were used in the form task carry the notion of a continuous variable in which one response (wide) exists in relation to the other (narrow). The situation for the surface-property dimensions, however, was quite different. The colours (yellow and beige) and textures (brick and wood) we used are not so obviously continuous. This is particularly true for texture; there is no clear continuum between objects made out of wood and objects made out of brick. Moreover, for both colour and texture judgments, participants were required to use labels (“yellow” and “beige” or “brick” and “wood”), which impose a category judgment. Finally, the two colours and the two textures that we used in experiment 2 were very different. This, coupled with the categorical nature of the required response, might have made the task so easy that even if the irrelevant dimension demanded some attention, participants were doing so well that any minimal interference would not be reflected in response latency.
To test this idea, we manipulated the stimuli used in the two previous experiments so that both form and surface properties were now continuous variables. In fact, as figure 5 illustrates, the two colours and the two textures were much more similar. In addition, to minimise categorisation, we now asked participants to respond by saying “shade A’ or “shade B’ and “texture A’ or “texture B’. Although it was possible that these manipulations would produce interference between colour and texture, we still predicted, on the basis of the results of experiment 2, that the two dimensions would be independent.

Figure 5. Examples of the stimuli used in experiment 3. The stimuli could vary along two form dimensions (width and length), and two surface-property dimensions (colour and texture). In this experiment the stimuli were rendered so that variations in the two surface-property dimensions were continuous, rather than categorical.

4.1 Methods
4.1.1 Participants. Twelve right-handed individuals (six male, six female; mean age 24.4 years, range 20 – 30 years) participated in this experiment. The participants were selected with the use of the same inclusion/exclusion criteria as those in experiments 1 and 2.

4.1.2 Stimuli and apparatus. As in the previous two experiments, the stimuli used in this experiment consisted of computer-rendered rectangular blocks which varied along two form (width and length) and two surface-property (colour and texture) dimensions (see figure 5). With respect to the form dimensions, the stimuli were rendered in two different widths (wide, 30 mm; narrow, 24 mm) and two different lengths (long, 56 mm; short, 48 mm). To ensure that texture, in particular, was now a continuous variable, we selected only the brick texture and eliminated the wood texture used previously. Both stimuli were rendered in brick textures at two levels of resolution, labeled ‘texture A’ and ‘texture B’, respectively. We also selected two shades of red, labeled ‘shade A’ and ‘shade B’, respectively, which varied slightly in hue but not luminance. The apparatus used in this experiment was identical to that of the previous two experiments.

4.1.3 Procedure. The procedure used in this experiment was identical to that used in experiment 2.
4.2 Results
The analysis used in this experiment was identical to that used in experiment 2.

4.2.1 Form task. The main effect of condition (width: $M = 559$ ms, SEM = 38 ms; length: $M = 642$ ms, SEM = 52 ms) for response latency was significant ($F_{1,11} = 12.49$, $p < 0.005$, MSE = 6606.19). In addition, the main effect of block type (baseline: $M = 567$ ms, SEM = 38 ms; filtering: $M = 634$ ms, SEM = 51 ms) was also significant ($F_{1,11} = 13.90$, $p < 0.003$, MSE = 3846.67). The interaction between condition and block type did not reach significance ($F_{1,11} = 0.92$, $p > 0.35$, MSE = 1629.60). To confirm our predictions, we conducted Bonferroni-corrected pairwise comparisons. In the width condition, response latencies in the baseline blocks ($M = 587$ ms, SEM = 47 ms) were significantly faster than the response latencies in the filtering blocks ($M = 32$ ms) for response latency was significant ($t_{11} = 2.26$, $p < 0.05$)—see figure 6a. Similarly, response latencies in the baseline blocks ($M = 603$ ms, SEM = 47 ms) of the length condition were significantly faster than those in the filtering blocks ($M = 681$ ms, SEM = 59 ms) ($t_{11} = 4.45$, $p < 0.001$).

In the analysis on the number of errors committed, the main effect of condition (width: $M = 1.63$, SEM = 0.38; length: $M = 3.46$, SEM = 1.10) came very close to reaching significance ($F_{1,11} = 4.69$, $p = 0.053$, MSE = 8.61). The main effect of block type (baseline: $M = 2.21$, SEM = 0.68; filtering: $M = 2.88$, SEM = 0.75), however, did reach significance ($F_{1,11} = 7.65$, $p < 0.02$, MSE = 70). The condition-by-block type interaction was not significant ($F_{1,11} = 0.66$, $p > 0.43$, MSE = 3.17). We conducted a posteriori pairwise comparisons using the logic outlined above (see figure 6b). This analysis failed to return any significant results. Participants’ accuracy in the baseline and filtering blocks of the width condition did not differ significantly (baseline: $M = 1.08$, SEM = 0.38; filtering: $M = 2.17$, SEM = 0.56; $t_{11} = 1.82$, $p > 0.09$). Similarly, the number of errors committed by participants in the baseline and filtering blocks of the length condition did not differ significantly (baseline: $M = 3.33$, SEM = 1.17; filtering: $M = 3.58$, SEM = 1.09; $t_{11} = 0.46$, $p > 0.65$).

4.2.2 Surface-properties task. In the surface-properties task, the main effect of condition was significant, with participants responding faster overall in the colour condition ($M = 479$ ms, SEM = 16 ms), than in the texture condition ($M = 599$ ms, SEM = 35 ms) ($F_{1,11} = 29.35$, $p < 0.001$, MSE = 5881.33). This result, however, was the only significant result obtained in this analysis. The main effect of block type was not significant, as
participants’ response latencies in the baseline (M = 538 ms, SEM = 25 ms) and filtering blocks (M = 540 ms, SEM = 25 ms) were extremely similar (F_{1,11} = 0.13, p > 0.72, MSE = 293.33), and the interaction between condition and block type was also not significant (F_{1,11} = 0.74, p > 0.40, MSE = 527.33).

Next, we conducted Bonferroni-corrected pairwise comparisons to confirm the prediction that colour and texture would not interfere with each other (see figure 6a). As it turns out, response latencies in the baseline and filtering blocks did not differ significantly in both the colour condition (baseline: M = 481 ms, SEM = 17 ms; filtering: M = 477 ms, SEM = 16 ms; t_{11} = 0.59, p > 0.45) and the texture condition (baseline: M = 595 ms, SEM = 35 ms; filtering: M = 603 ms, SEM = 37 ms; t_{11} = 0.77, p > 0.56). Indeed, there was no hint of any difference.

The analysis on the number of errors committed yielded no significant results for the main effect of condition (colour: M = 0.83, SEM = 0.25; texture: M = 1.38, SEM = 0.34; F_{1,11} = 1.45, p > 0.25, MSE = 2.43). For the main effect of block type, however, participants committed significantly fewer errors in the baseline blocks (M = 0.75, SEM = 0.21) than in the filtering blocks (M = 1.46, SEM = 0.26) (F_{1,11} = 6.48, p < 0.03, MSE = 0.93). The condition-by-block type interaction was not significant (F_{1,11} = 0.01, p > 0.91, MSE = 1.84). When colour and texture were examined independently, however, no significant differences were observed in the number of errors committed in the baseline and filtering blocks for the colour condition (baseline: M = 0.50, SEM = 0.15; filtering: M = 1.17, SEM = 0.41; t_{11} = 1.88, p > 0.08) or the texture condition (baseline: M = 1.00, SEM = 0.39; filtering: M = 1.75, SEM = 0.49; t_{11} = 1.30, p > 0.22)—see figure 6b.

**4.3 Discussion**

The results of experiment 3 provide further evidence that width and length are integral dimensions of object form. Thus, these results again suggest that the perception of the shape of an object is holistic—and that it is impossible to attend to length and width independently. It is interesting to note, however, that in this case the response latencies for length were actually longer than the response latencies for width, a pattern that was different from that obtained in experiments 1 and 2. Exactly why this was the case is not clear. In experiment 3, the stimuli were much more two dimensional than was the case in the earlier experiments. Moreover, the difference in length in experiment 3 was much smaller than in the other two experiments, whereas the difference in width remained quite similar.

Importantly, the results of experiment 3 provide additional evidence that colour and texture are separable dimensions and can be processed independently of each other. Varying texture had no effect on the speed with which participants made colour judgments, and vice versa. (The texture discrimination was clearly more difficult than the colour discrimination in this experiment, but even so, varying colour had no effect on performance in the texture-discrimination task.) The fact that no interference in response latency was observed between colour and texture when these variables were both categorical (experiment 2) and continuous (experiment 3) provides further validity for the claim that colour and texture do not share common processing resources. Again, this confirms the earlier conclusion that the separate brain regions involved in the processing of colour on the one hand and texture on the other are at some level at least truly independent in their processing of visual input. It is true that more errors were committed in the filtering blocks than in the baseline blocks for colour and texture together, but the error rate was so low and variable that it is likely that this difference does not reflect a real effect. Typically, response latency is a much more sensitive measure than error rate, and there was no hint of any Garner interference between colour and texture on this measure.
5 General discussion

Taken together, these experiments clearly demonstrate that the length and width of an object cannot be perceived separately. Evidence from all three experiments showed that participants could not ignore length while attending to width, and vice versa. These findings are entirely consistent with those from many previous experiments which have shown, by means of the Garner paradigm, that width and length are integral dimensions of object shape (Felfoldy 1974; Dykes and Cooper 1978; Macmillan and Ornstein 1998; Ganel and Goodale 2003). In other words, the visual perception of object shape depends on ‘configural’ or ‘holistic’ processing in which a given dimension cannot be perceptually isolated from the other dimensions of the object. There is a wealth of evidence from neuroimaging experiments and neuropsychological studies that the perception of the shape of an object (which includes, of course, its length and width) is mediated by area LO in the ventral stream.

In contrast, accumulating evidence from both neuroimaging and neuropsychological studies is suggesting that the perception of the surface properties of an object, such as its colour and texture, is processed by neural mechanisms in more medial and anterior regions of the ventral stream (James et al 2003; Peuskens et al 2004; Cant and Goodale 2007). Nevertheless, it was important to establish that the processing of visual information in these different regions could be carried out independently. In other words, that, in the Garner task, participants could attend to the width (or length) of an object without being affected by changes in colour or texture, and vice versa. This is exactly what we found in experiment 1. Despite the presence of robust Garner interference between length and width, there was absolutely no interference between form and surface properties in either direction.

This last point highlights the importance of using behavioural evidence for establishing whether or not the demonstration of separate brain regions in fMRI means that the processing carried out in one region is truly independent from the processing carried out in the other. After all, the fact that attending to form results in a different pattern of regional activation than attending to surface properties does not mean that these anatomically separate regions are functionally independent (Cant and Goodale 2007). In fact, these regions might be heavily interconnected and share common processing resources. To show true independence of processing (parallel processing), it is necessary to examine the behavioural performance when people attend to one dimension while the other varies. In our experiments the results are clear: discriminating the form of objects is not disrupted by changes in surface properties, and vice versa. It would appear that the separate brain regions activated for form and surface properties do reflect some sort of parallel processing of visual input. Finally, it should be noted that behavioural evidence for parallel processing of stimulus dimensions does not mean (at least at the resolution of fMRI) that different brain regions will always be revealed in imaging studies. Of course, as imaging resolution improves, one would expect that differences in behavioural performance will map onto differences in patterns of activation. A case in point is the recent demonstration of separate functional regions within the fusiform face area, a brain region that until recently has been treated as a single functional area (Schwarzlose et al 2005; Grill-Spector et al 2006). At present, the final arbiter of whether or not the processing of one stimulus attribute shares the same neural circuitry as the processing of another is behavioural performance. For this reason, tasks like the Garner speeded-classification task play a critical role in this endeavour.

Aside from the obvious differences in the computational demands of form perception and surface-property perception, there are other ecological considerations that might have promoted a separation in the neural processing systems that deal with these two aspects of an object. For example, when the shape of an object is occluded by
other objects, observers can rely on surface cues, such as diagnostic colour and texture, to identify that object. An everyday example would be looking for an orange in a bowl of fruit where other fruit on top obscure the boundaries of the orange. Form is sometimes uninformative. Identification of ripe fruit, for example, is often possible only by examining the colour (and sometimes the texture) of the skin. This is not the only example. Many objects have roughly the same shape, and often the most efficient way to identify (or classify) such objects is on the basis of their surface (ultimately, their material) properties. Indeed, in the natural world, identifying the material from which something is made is often as important as recognising its geometric form. Geometric structure may be important in the realm of manufactured objects, but in the world of the hunter gatherer, surface properties are equally important. In Adelson's (2001) words, 'stuff' is as important as 'things'. Clearly, the analyses of form and surface cues have to be integrated at some point, but perhaps it is more efficient to separate them initially since they are derived to some degree from rather different low-level visual input.

Another way in which the identification of material properties plays a critical role in behaviour is the control of object-directed actions. For example, the selection of an appropriate grip posture and the calibration of the initial forces that one applies to an object depend crucially on identifying the density, compliance, and friction coefficient of the material from which the object is made. This reliance on surface properties to yield information regarding an object's material properties (ie expected weight) was shown very nicely in an experiment where participants lifted cubes of equal size and weight that were made of balsa wood, mahogany, aluminium, brass, and steel (Harshfield and DeHardt 1970). [Weights had been added to the inside of the objects to make them all weigh the same.] Participants lifted each cube and then ranked its weight. Under these conditions, the balsa wood object was ranked heaviest and the steel object the lightest, with mahogany, aluminium, and brass falling in between in descending order. A separate group of participants ranked the weight of the same cubes visually (without lifting) and, in this case, reported the reverse order, exactly in line with what one would expect on the basis of the apparent density of each material (wood the lightest and steel the heaviest). This so-called 'density–weight' illusion illustrates the importance of the identification of the material properties of objects when interacting with them.

Having established that form and surface cues are processed independently, we went on to examine whether or not the processing of colour and texture can be dissociated. Here we were less certain about the outcome of the experiments. On the one hand, in the real world, colour and texture are often highly correlated. But, on the other hand, our imaging data (Cant and Goodale 2007) suggest that the processing of these two surface properties may be somewhat independent. As it turned out, the results of experiments 2 and 3 clearly demonstrated that colour and texture were separable dimensions in the Garner sense; that is, participants were able to ignore changes in colour while attending to changes in texture, and vice versa. Moreover, it is unlikely that the lack of interference found between colour and texture can be attributed to the nature of the required response or particular stimuli we used. In experiment 3 we deliberately avoided the use of a categorical response and used stimulus dimensions that varied along a continuum (in the same way as length and width do). Thus, we used different shades of red and different densities of the same texture rather than brick versus wood or yellow versus beige as we did in experiment 2. Nevertheless, these manipulations had no effect on the results of the experiment. In short, whether the dimensions of colour and texture (or the responses) were categorical (experiment 2) or continuous (experiment 3), the processing of these two dimensions did not interfere with one another.
At first blush, the lack of interference between colour and texture may seem counter-intuitive. After all, we observed strong interference between width and length, which are two aspects of an object’s form. Why shouldn’t the same be true for colour and texture, which are two aspects of the surface properties of an object? The answer to this is not straightforward and there are a number of factors at work. As discussed earlier, length and width are not simply two different aspects of form; they are so fundamentally integrated that changes in one dimension actually affect the perception of the other (Ganel and Goodale 2003). Indeed, the width and length of objects are essentially arbitrary labels, even though by convention the shorter dimension is typically called the width. What is critical for object recognition, however, is the overall shape of the object. Thus, it is not surprising that changes in length interfere with judgments of object width, and vice versa. The same cannot be said for colour and texture where the labels are not arbitrary but, instead, are fundamentally different aspects of the surface properties of an object. To investigate this observation further, one might ask how similar (or different) two attributes of an object have to be in order to demonstrate Garner interference. In other words, is there a psychophysical threshold which determines the degree of interference observed (or not) between two stimulus dimensions (e.g., width and length)? These are important issues in the context of the Garner speeded-classification task, but our use of width and length in these experiments was to establish the validity and reliability of the particular version of the Garner task that we used.

5.1 What’s in a surface?

Although colour and texture are separable aspects of the surface properties of objects, it remains a question which of the two aspects plays the more critical role in flagging the identity of objects. An argument can be made that texture is the more important cue to object identity—in part because it provides a more immediate route to material properties. For example, we might have little difficulty recognising a black-and-white close-up of a strawberry for what it is, but we would have much more difficulty identifying a strawberry from a textureless patch of strawberry red. By the same token, you might even identify a blue strawberry from a close-up of its skin but the same blue patch of colour without the strawberry texture would never be associated with a strawberry. Black-and-white films work because texture cues (along with form) provide almost all the information one needs to have a rich experience of the depicted scene. Form and colour might work for cartoons, but the experience is a much more diminished one.

Of course, we are not positing that texture, or colour for that matter, are better predictors of object identity than form is. Form is a very powerful predictor of identity, independent of both colour and texture. This is why people can easily identify line drawings, which completely lack inner details, such as colour and texture. The point here is that when form information is occluded, which can often be the case in our environment, texture may be a better predictor of the identity of an object than colour is. Moreover, texture is a much better predictor of material properties than form.

In light of the above discussion, one could reasonably ask what type of information the colour of objects signals. Perhaps colour is very useful when it comes to identifying and parsing objects from their surroundings. Indeed, some researchers have theorised that the evolution of colour vision enabled primates to discriminate fruits from the backdrop of densely coloured foliage (Mollon 1995; Osorio and Vorobyev 1996). In addition, surface properties can be used to judge the palatability of food, such as if a banana is ripe or rotten (Allman 2000). It is up for debate whether colour or texture would be a more useful cue in this latter situation.
5.2 Future directions
Perhaps we did not find interference between colour and texture in these experiments because these dimensions were not diagnostic to the recognition of the stimuli we used. It is possible that if we had used different fruits as our stimuli, rather than bricks and wood (where colour and texture information may not be as diagnostic to recognition), we might have observed interference between colour and texture. We could, for example, occlude form information and use square patches of strawberries and square patches of raspberries rendered in two slightly different shades of red. Appealing to the point that colour and texture are inextricably linked in natural classes of objects (eg fruits, vegetables), manipulating cues that are diagnostic for object recognition may provide the greatest chance of finding interference between colour and texture. Here, of course, the interference would almost certainly be more of a top–down phenomenon (if we did find it), compared to the kinds of effects that we observed with length and width in the present experiments.

Finally, one thing we have not discussed is the role of texture in revealing the form of objects. Texture gradients, for example, clearly play an important role in revealing the shape of an object. Here one might expect interference between form defined by contour and form defined by texture in a Garner-type experiment. The way in which different brain regions responsible for extracting texture interact with known object recognition areas such as area LO also remain to be explored.

References
Boucart M, Humphreys G W, 1997 “Integration of physical and semantic information in object processing” Perception 26 1197 – 1209
Cant J S, Goodale M A, 2007 “Attention to form or surface properties modulates different regions of human occipito-temporal cortex” Cerebral Cortex 17 713 – 731
Dick M, Hochstein S, 1988 “Interactions in the dimensions and absolute judgments of orientation and length” Perception 17 177 – 189
Felfoldy G L, 1974 “Repetition effects in choice reaction time to multidimensional stimuli” Perception & Psychophysics 15 453 – 459
Gegenfurtner K R, Rieger J, 2000 “Sensory and cognitive contributions of color to the recognition of natural scenes” Current Biology 10 805 – 808
Large M-E, Aldcroft A, Vils T, 2005 “Perceptual continuity and the emergence of perceptual persistence in the ventral visual pathway” Journal of Neurophysiology 93 3453 – 3462
Livingstone M S, Hubel D H, 1987 “Physiological evidence for separate channels for the perception of form, color, movement, and depth” Journal of Neuroscience 7 3416 – 3468
Macmillan N A, Ornstein A S, 1998 “The mean-integral representation of rectangles” Perception & Psychophysics 60 250 – 262
McKeefry D J, Zeki S, 1997 “The position and topography of the human colour centre as revealed by functional magnetic resonance imaging” Brain 120 2229 – 2242
Oliva A, Schyns P G, 1997 “Coarse blobs or fine edges? Evidence that information diagnostically changes the perception of complex visual stimuli” Cognitive Psychology 34 72 – 107
Reis A, Faisca L, Ingvar M, Petersson K M, 2006 “Color makes a difference: Two-dimensional object naming in literate and illiterate subjects” Brain and Cognition 60 49 – 54
Schwarzlose R F, Baker C I, Kanwisher N, 2005 “Separate face and body selectivity on the fusiform gyrus” *Journal of Neuroscience* 25 10555–11059
Shechter S, Hochstein S, 1992 “Asymmetric interactions in the processing of the visual dimensions of position, width, and contrast bar stimuli” *Perception* 21 297–312
Tarr M J, Kersten D, Cheng Y, Doerschner K, Rossion B, 2002 “Men are from Mars, women are from Venus: Behavioral and neural correlates of face sexing using color” *Journal of Vision* 2 598a
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