Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in
Behavioral
Sciences

Representing stuff in the human brain

Alexandra C Schmid[1] and Katja Doerschner[1,2]

Our experience of materials does not merely comprise judgments of single properties such as glossiness or roughness but is rather made up of a multitude of simultaneous impressions of qualities. To understand the neural mechanisms yielding such complex impressions, we suggest that it is necessary to extend existing experimental approaches to those that view material perception as a distributed and dynamic process. A distributed representations framework not only fits better with our perceptual experience of material qualities, it is commensurate with recent psychophysics and neuroimaging results.

Addresses
[1] Justus-Liebig-University Giessen, Germany
[2] Bilkent University, Turkey

Corresponding author: Doerschner, Katja
(Katja.Doerschner@psychol.uni-giessen.de)

Current Opinion in Behavioral Sciences 2019, **30**:178–185

This review comes from a themed issue on **Visual perception**

Edited by **Hannah E Smithson** and **John S Werner**

For a complete overview see the Issue and the Editorial

Available online 4th November 2019

https://doi.org/10.1016/j.cobeha.2019.10.007

Separate neural processing of material and shape properties?

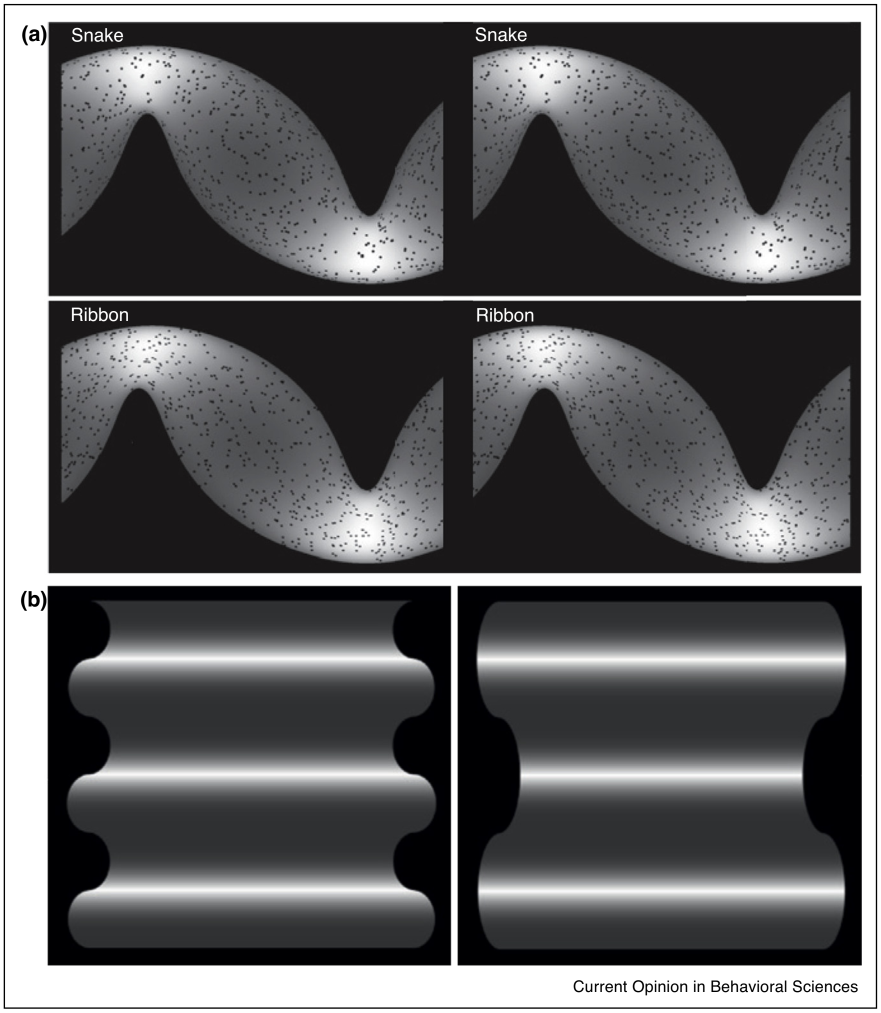
Our visual experience of the world is as much defined by the material qualities of objects as it is by their shape properties: keys look shiny, a tree trunk looks rough, and chocolate soufflé looks airy. Humans can easily and nearly instantaneously identify shapes [1,2] and properties of materials [3] through vision alone. Although much research has been dedicated to understanding the neural mechanisms underlying shape (e.g. Refs. [4–6,7••]) and — more recently — material perception [8], for the most part research on shape and material perception have not intersected substantially. In fact, most interpretations of human neuroimaging and monkey physiology research propose that shape and material properties may be processed independently along different parts of the ventral visual stream ([9–11] also see the review by Ref. [8]). In contrast, recent psychophysics work has shown that shape information can play quite a critical role in the perception of material properties, such as translucency ([12••], Figure 1a) or gloss ([13••], Figure 1b). In line with this, recent neuroimaging studies have found that shape sensitive cortical areas are, in fact, also sensitive to material properties such as surface gloss [14•]. Here, we take these recent findings of coupled shape-material computations as a departure point to highlight that our experience of materials comprises not only judgments of single properties such as glossiness or roughness; rather it consists of a multitude of simultaneous impressions of qualities (e.g. visual [15], haptic [16,17••], auditory [18,19], emotional, or motivational [20,21]). To understand the neural mechanisms yielding such complex impressions, we suggest that it is necessary to extend existing experimental paradigms to those that view material perception as a distributed and dynamic process. Specifically, we will discuss an alternative framework, inspired by recent neuroimaging work in object perception [22,23••,24••], that promises to better identify the neural correlates of our experience of material qualities. First, we will briefly review studies that investigate the neural sensitivity to material qualities and categories. We will then point out the potential limits of considering material quality as an independently and locally processed object property. Finally, we will discuss a potential alternative way of conceptualizing the neural representation of material properties in a distributed network involving direct and indirect associations.

Neural mechanisms in material perception

A processing hierarchy in the ventral visual pathway

Investigations into the neural mechanisms underlying the perception of material qualities have started out only recently. From this work a few candidate areas have emerged as being particularly sensitive to changes in material properties: for example, in human fMRI studies, stronger responses to glossy objects (compared to matte) have been found from early (e.g. V1, V2) to late visual areas in the ventral stream (e.g. posterior fusiform) [25,26]). Similarly, regions along the medial ventral visual cortex (e.g. Collateral Sulcus CoS, Parahippocampal gyrus PHG, Lingual Gyrus LG, Fusiform Gyrus FG, Parahippocampal Place Area PPA) show a preference for texture information (e.g. granite and tree bark) over shape, color, or orientation [27,9,11,28–33]. Ventral stream areas also seem to be important for the processing of material categories (e.g. wood, stone, fabric) and their properties (e.g. FG, CoS, or PHG, see [34–36]). In light of these results it is perhaps not surprising that a general interpretation is that 'visual information about materials and surface qualities are processed and represented mainly through a hierarchy of the ventral visual pathway' [8], where lower-level image statistics that differentiate materials are represented in earlier visual areas, while later areas reflect differences in higher-level

Figure 1



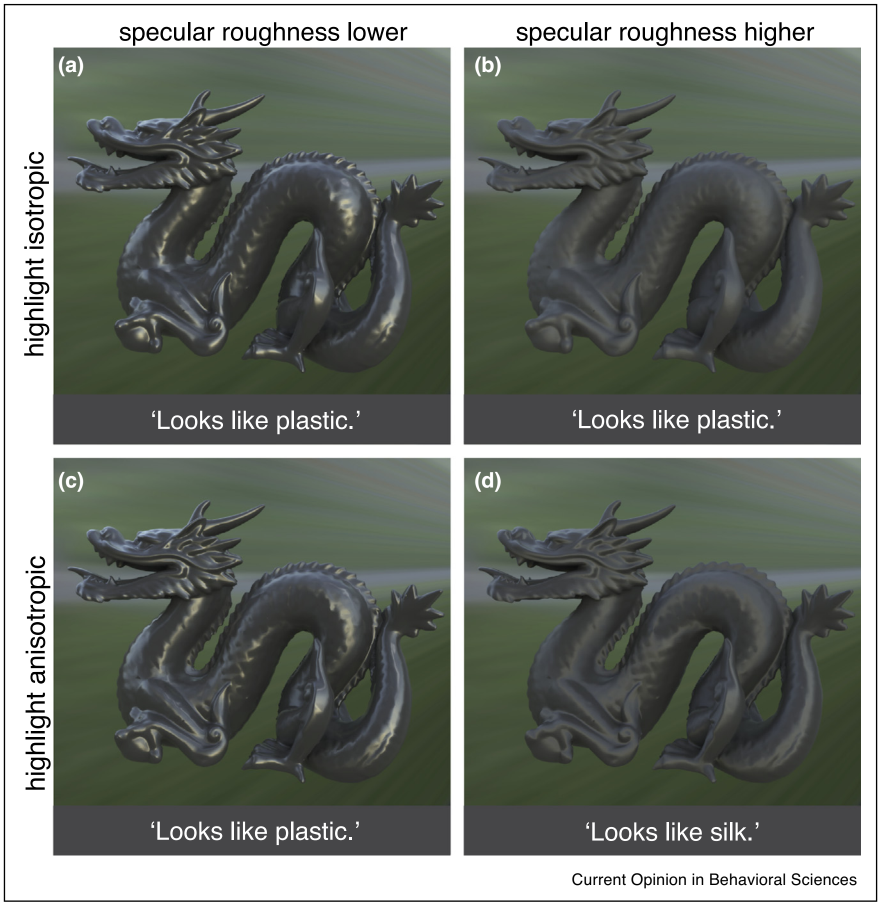
Examples for joint computations of shape and material quality.
(a) Depending on the stereoscopic shape interpretation (snake or ribbon) the same luminance gradient appears as a translucent volume illuminated from within, or as an opaque surface reflecting light from above (left and right images are set up for cross-fusion). Figure adapted from Ref. [12••] (with permission from authors). **(b)** Another example that material perception depends on perceived three-dimensional shape: the luminance gradients in the left and right images are the same, however the different contours, induce different percepts of three-dimensional shape, and material (matte on the left and shiny on the right). Figure adapted from Ref. [13••] (with permission from authors).

representations of the perceived quality and category of materials [35].

Cooperative computations and interactions

Although this late-combination-of-cues idea certainly has a computational appeal [37] and has guided neuroimaging research (e.g. Refs. [38,7••,8]), the processing of material properties might not be neatly localized to one cortical vicinity with, say, the processing of shape to another. In fact, recent psychophysics results have strongly suggested that at least some computations of material quality occur together with computations of shape. For example, perceived 3D shape and surface properties like lightness, gloss and translucency can mutually constrain one another [12••,13••,39–45], implying that it is computationally unlikely that they are processed separately. Marlow *et al.* [13••,41] showed that the same luminance gradient — even with the same bounding contour — can be perceived as matte shading or glossy shading (i.e. *different materials*) depending on the perceived 3D shape (Figure 1b). Moreover, recent neuroimaging studies have found that putative shape-specialized regions are also sensitive to changes in material properties (e.g. V3b/KO [25,46,14•], LOC, [35], or V4 [47]), and, conversely, that putative material specialized-regions can process shape information (e.g. CoS, [33,35], or FG

Figure 2



Categorical shifts in material appearance.

Four panels show the same object illuminated by the same light field. We manipulated the specular roughness (between left and right images) and specular highlight anisotropy (between top and bottom images). We found that while Figures **(a)**–**(c)** have a somewhat 'plastic-like' appearance (with more or less gloss), panel **(d)** not only looks rougher but also changes the material category, that is, it looks like silk to most observers [54]. This illustrates that certain combinations of visual cues evoke specific material qualities and categories. Investigations of the neural processing of material properties need to be able to account for these association effects.

[32]) which supports the idea of (neural) joint computations of material quality and shape.[3]

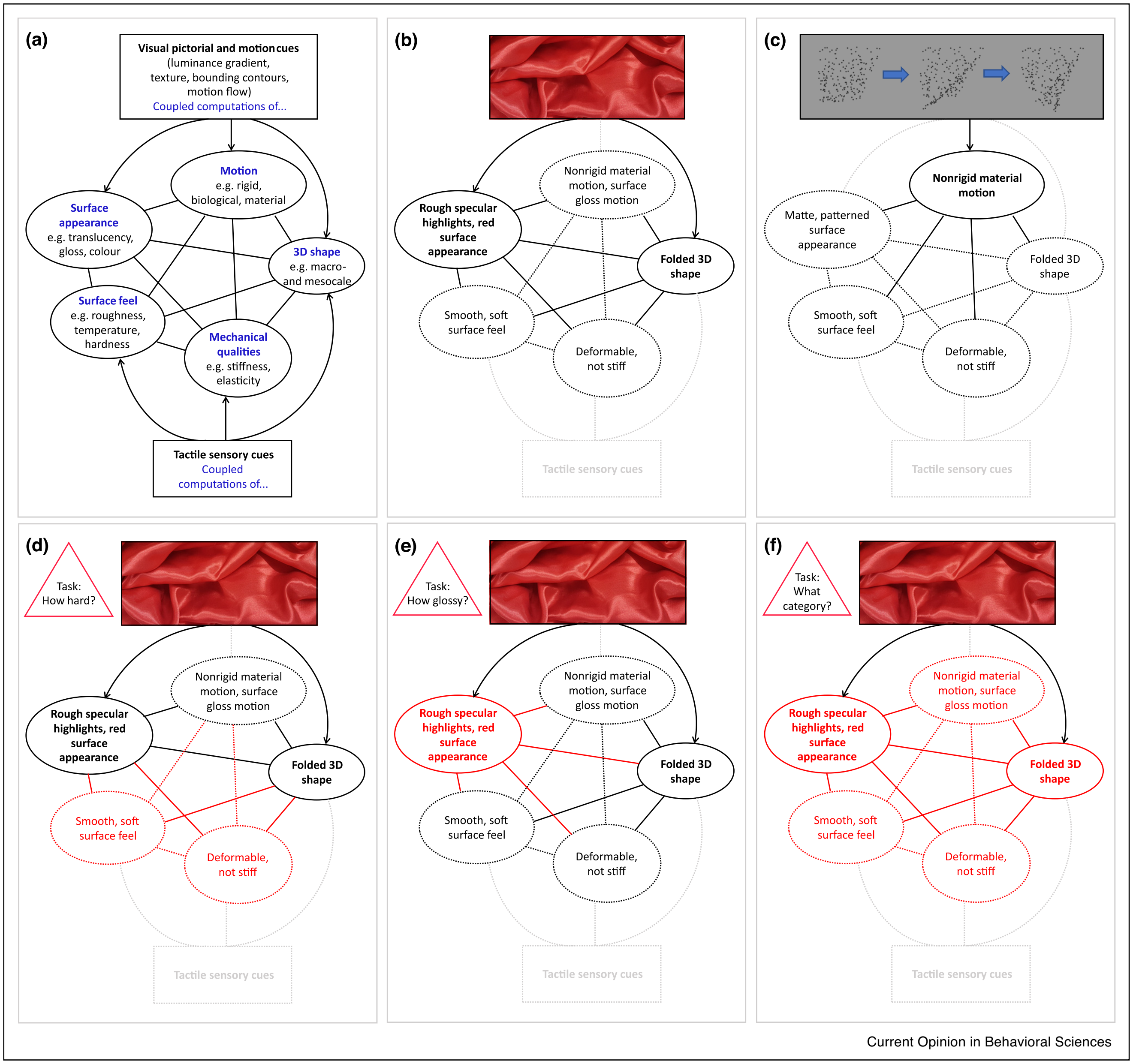
Shape and material properties do not just mutually constrain one another, they also interact in a non-linear manner when observers judge perceptual qualities of objects. For example, in [48] soft substances that fell on the ground looked runnier when they were transparent and glossy (as opposed to matte), whereas harder substances looked equally non-runny regardless of their surface optics. In addition, certain combinations of shape and material evoke specific material qualities [48] and categories (see Figure 2, [49,50]), suggesting that our perception of materials is not limited to the processing of image features to determine whether a surface is glossy or translucent [51]; our perception also *includes* these associated material qualities (e.g. see Figure 2, [52]). In fact, such associations extend beyond our visual experience: seeing an image of silky stuff evokes a vivid sensation of what it would feel like to run our hands through the material (e.g. Refs. [53,48]). These associations may also be related to task demands: judging the softness of a visually presented material will mostly rely on associations with tactile properties (Figure 3d).

We propose that interactive processing of image features and associations should be considered when studying the neural mechanisms of our perceptual experience of material qualities. Paradigms that focus on identifying what areas process a specific object property or image feature may miss out on

---

[3] It has been proposed that the involvement of a cortical region in a certain perceptual computation (shape or material) might depend on the task that the visual system is performing ([31,35]). Task demands can be incorporated into a distributed representation of material qualities as illustrated in Figure 3.

Figure 3



Current Opinion in Behavioral Sciences

A distributed networks framework for material perception.

An example of how the perception of material qualities might arise from distributed network activity. This toy network encompasses the coupled computations of different properties (such as 3D shape and material) from visual sensory cues (or cues from other modalities, e.g. tactile; arrows from rectangles to ellipses), and it also considers how associated properties might influence or activate each other (connections between ellipses). Rectangles show example sensory cues that are processed by the network, ellipses denote specific object and material properties (3D shape, surface appearance, surface feel) that may be evoked directly by sensory cues or associated properties (solid) or indirectly via other routes (dotted). Light gray dotted lines imply neither direct nor indirect processing via a given route. Panel **(a)** shows our hypothetical network and its potential connections. **(b)** Static image cues are directly associated with representations of surface appearance and 3D shape (solid black lines), as well as indirectly associated (dotted black lines) with surface feel, mechanical qualities and potential image motion (nonrigid, specular motion). **(c)** Looking at moving dot patterns of a cloth blowing in the wind [82] changes the pattern of direct and indirect associations. Note, however, that similar properties are activated as in b. Panel **(d)** illustrates how task demands influence which aspects of the network are drawn upon. Red colors mean that properties of connections are relevant for a given task (solid and dotted lines denote direct and indirect associations, respectively). In this case estimating the hardness (a tactile judgment) of the material in the image cannot be achieved directly from the visual input (no direct connections from visual input to the red ellipses) but has to occur via 3D cues to shape, or optical properties of the material (direct routes, red solid) or via indirect routes that become activated by association shape and optical cues with a specific material category that has characteristic nonrigid motion properties. Panels **(e)** and **(f)** show properties drawn upon when judging an optical property and while performing a categorization task, respectively. Note that highlighting a component does not imply that these units are activated per se: it is the important aspects of material perception. In fact, there appears to be a consensus among most researchers whose work we have cited that knowing which cortical areas preferentially respond to one object property over another does not necessarily reveal the underlying computations carried out by these regions (e.g. Ref. [34]). In order to make progress towards understanding the computations performed by the brain in material perception we suggest, in the next section, that it may be fruitful to look towards developments in the object and scene recognition neuroimaging literature. Specifically, we suggest that the computations that make up our complex perceptual experience of materials are unlikely to be executed by separate specialized cortical areas, but instead must be jointly computed and realized by sufficiently complex and distributed, interacting neural hardware.

Moving to a distributed representations framework

Research investigating the mechanisms underlying object and scene perception has started turning to the idea that neural representations should reflect the dynamic nature of tasks and goals; that is, recognition, interaction, navigation, and prediction (e.g. Refs. [55–57]). There is a growing body of literature suggesting that object and scene representations are distributed in distinct but highly interactive networks or circuits that extend beyond the ventral pathway ([22,23••,58–60,45,57,61] also see Box 1), and that property representations (such as what an object looks like, how it moves, how it is used) are grounded in the activity of such networks (e.g. Ref. [24••]). The implications for material perception are that the processing of properties such as surface appearance, form, motion, tactile properties, and even action-related properties such as 'graspable' are intricately intertwined (e.g. Ref. [62], for a review see Ref. [24••]), rather than being processed separately and then integrated downstream. Under this framework, representations of such properties (e.g. wobbling motion) can be activated and affected by other associated properties (e.g. Jell-O shaped, green, glossy, translucent), associated conceptual knowledge (e.g. 'dessert'), and task demands (e.g. asking 'how gelatinous is this object?') (see Figure 3 for another example). Furthermore, representations of such properties are not modality-specific [63]: they can potentially be activated through visual, tactile, and auditory input. For example, somatosensory and auditory cortices respond when viewing pictures of graspable objects [64] and sound-implying objects [65], respectively. Importantly, object and material representations, including both category and material quality representations, *are* the distributed activation of associated properties and concepts (see Figure 3 for an illustration of this framework).

Box 1 Distributed representations of object, material, and scene properties

What evidence is there for distributed representations over the conception of the ventral and dorsal pathways as serial staged hierarchies?

- A distributed representations framework better reflects evidence about structural and functional connections that have been found in the brain. There is anatomical and functional evidence that ventral and dorsal streams give rise to multiple distinct pathways, where regions from putative early and late stages of the hierarchy communicate directly [22,23••].
- Resting state fMRI reveals several interconnected networks of brain regions (e.g. Ref. [58]).
- Common areas are activated for both perceptual and conceptual tasks, suggesting that object properties are represented in a modality-independent manner (e.g. Refs. [60]).
- There are examples of task-based effects on visual processing (e.g. Refs. [80,57,73]).
- There is evidence that behavior does not correlate with patterns of activity in putative object/scene-selective brain regions (e.g. Ref. [59,81]).

Thinking about materials and their properties in terms of distributed activations, rather than as emerging from separate cortical areas specialized for processing individual properties, will help to connect neural representations of materials with our complex and multifaceted visual experience of the world and the objects in it: Through visual information alone we simultaneously recognise objects holistically (chair, spoon, cat) at different levels of abstraction (my cat, pet, animate being); we recognise the materials that things are made from (wood, fur, glass, plastic); experience multisensory material qualities (hard, cold, fluffy); and we automatically access associated semantic concepts and affordances ('can grasp', 'is eaten', 'can sit on'). A distributed representations framework not only fits better with our perceptual experience of materials, it is commensurate with recent psychophysics and neuroimaging results. For example, [66] found that when people visually discriminated photographs of different fabrics, combinations of the surface properties and folding patterns that were present in the stimuli influenced how tactile stimuli would be matched. This crossmodal association between visual and tactile properties is reflected in neuroimaging results that show that tactile discriminations can activate and be decoded in visual areas [67–72], and reciprocally, visual discrimination of rough and smooth surfaces can be decoded in somatosensory cortex (even when controlling for the effects of imagery, memory, and non-tactile visual characteristics, [14•]). Sun *et al.* [14•] describe their results as 'compatible with an anticipatory system that extracts surface properties from visual information'. Indeed, touching and grasping objects is something that typically occurs after object identification,

(Figure 3 Legend Continued) aspect of the representation that the brain 'pays attention to' when performing the task. As [24••] puts it: 'the regions comprising a circuit do not come online in piecemeal fashion as they are required to perform a specific task, but rather seem to respond in an automatic, all-or-none fashion as if they were part of the intrinsic, functional neural architecture of the brain.' [24••]. Other modalities (e.g. auditory input), and cognitive and emotional states that are not shown in this toy diagram may also interact with the processing of material qualities.

so such effects could reflect a priming for future action [24••]. It is difficult to account for cross-modal interactions in visual and somatosensory areas if properties are processed in separate, independent streams before being integrated.

Outlook

The aim of this article was to use recent findings that highlight the multifaceted aspects of experiencing material qualities to spark a paradigm shift in related neuroimaging research. The question remains about *how* our representations of material properties are grounded in these distributed networks. That is, what are the local computations performed in ventral and dorsal regions that give rise to these representations [73••]? It has been suggested that the important computational goals of the visual system likely reflect our experience, that is, the perceptual scission of a scene into different causal 'layers': shape, pigment, gloss, translucency, and illumination effects [74••]. These local computations, as suggested in Section 2, are likely to occur coupled (Figure 1). Therefore, just as important as searching for areas where certain cues (e.g. texture statistics, motion flow, binocular disparity) are processed is an understanding of how our holistic impressions emerge, that is, the neural substrates associated with combining these cues to conjointly compute shape, material, illumination, and so on. Investigating this requires moving from univariate designs and analyses, where one type of stimulus or attention to one stimulus dimension leads to greater activity than another stimulus/attended dimension, to multivariate designs and analyses ([75,76•] see Ref. [77] review for a comprehensive comparison of univariate and multivariate techniques, but see Ref. [78] for limitations of multivariate techniques). For example, using multivariate pattern analysis (MVPA), Sun and colleagues identified a region that potentially integrates cues to 3D structure (V3B/KO, [25,46,14•,7••]). Such multivariate methods allow for the identification of regions where activity reflects unique or joint representations. Furthermore, new techniques have been developed to combine fMRI decoding with MEG decoding [79], which could help reveal the underlying spatio-temporal dynamics — a representation at a certain time point (MEG) correlates with (has the same representational structure as) neural activation at particular regions (fMRI) — which could help to unravel when and where different representations emerge. Results yielded by multivariate techniques may thus play a key role in deepening our understanding of the neural processes involved in material perception because they have the potential to reveal distributed patterns of activity that underlie joint computations of properties and their associations.

Conflict of interest statement

Nothing declared

Acknowledgements

Sofja Kovalevskaja Award ('Perceiving Material Qualities - Brain Mechanisms and Dynamics') by the Alexander von Humboldt Foundation, endowed by the German Federal Ministry of Education and Research.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Thorpe S, Fize D, Marlot C: **Speed of processing in the human visual system**. *Nature* 1996, **381**:520-522.

2. VanRullen R, Thorpe SJ: **Is it a Bird? Is it a Plane? Ultra-rapid visual categorisation of natural and artifactual objects**. *Perception* 2001, **30**:655-668.

3. Sharan L, Rosenholtz R, Adelson EH: **Accuracy and speed of material categorization in real-world images**. *J Vis* 2014, **14**:1-24.

4. Handa T, Mikami A: **Neuronal correlates of motion-defined shape perception in primate dorsal and ventral streams**. *Eur J Neurosci* 2018, **48**:3171-3185.

5. Georgieva SS, Todd JT, Peeters R, Orban GA: **The extraction of 3D shape from texture and shading in the human brain**. *Cereb Cortex* 2008, **18**:2416-2438.

6. Dodd JV, Krug K, Cumming BG, Parker AJ: **Perceptually bistable three-dimensional figures evoke high choice probabilities in cortical area MT**. *J Neurosci* 2001, **21**:4809-4821.

7. •• Welchman AE: **The human brain in depth: how we see in 3D**. *Annu Rev Vis Sci* 2016, **2**:345-376.

Excellent review on studies of binocular disparity and its combination with other depth cues. Suggests that the dorsal visual cortex processes 3D information and also integrates signals to represent the structure of viewed surfaces, whereas the ventral cortex may store representations of object configurations and the features required for task performance.

8. Komatsu H, Goda N: **Neural mechanisms of material perception: quest on Shitsukan**. *Neuroscience* 2018, **392**:329-347.

9. Cant JS, Goodale MA: **Attention to form or surface properties modulates different regions of human occipitotemporal cortex**. *Cereb Cortex* 2007, **17**:713-731.

10. Cant JS, Large ME, McCall L, Goodale MA: **Independent processing of form, colour, and texture in object perception**. *Perception* 2008, **37**:57-78.

11. Cavina-Pratesi C, Kentridge RW, Heywood CA, Milner AD: **Separate processing of texture and form in the ventral stream: evidence from fMRI and visual agnosia**. *Cereb Cortex* 2010, **20**:433-446.

12. •• Marlow PJ, Kim J, Anderson BL: **Perception and misperception of surface opacity**. *Proc Natl Acad Sci U S A* 2017, **112**:13840-13845.

Demonstrates that perceived surface gloss depends on perceived 3D shape. Suggests that perceived shape constrains the computation of material qualities.

13. •• Marlow PJ, Todorović D, Anderson BL: **Coupled computations of three-dimensional shape and material**. *Curr Biol* 2015, **25**:221-222.

Demonstrates that perceived translucency depends on perceived 3D shape. Suggests that perceived shape constrains the computation of material qualities.

14. • Sun H-C, Di Luca M, Ban H, Muryy A, Fleming RW, Welchman AE: **Differential processing of binocular and monocular gloss cues in human visual cortex**. *J Neurophysiol* 2016, **115**:2779-2790.

Identifies brain areas that preferentially respond to glossy objects. Also finds activations related to gloss in the posterior fusiform (pFs) and in area V3B/KO, which are areas known to play a role in shape perception. Suggests that these areas integrate information related to shape and surface properties, and might be candidate areas for joint computations of shape and material properties.

15. Fleming RW, Wiebel CB, Gegenfurtner KR: **Perceptual qualities and material classes**. *J Vis* 2013, **13**:1-20.

16. Adams WJ, Kerrigan IS, Graf EW: **Touch influences perceived gloss**. *Sci Rep* 2016, **6**:21866.

17. •• Sun H-C, Welchman AE, Chang DHF, Di Luca M: **Look but don't touch: visual cues to surface structure drive somatosensory cortex**. *Neuroimage* 2016, **128**:353-361.

Shows that visual material qualities activates somatosensory cortex. Suggests that visual cues to an object's surface properties (especially those relevant for grasping, such as roughness) evoke activity in neural circuits associated with tactile stimulation.

18. Klatzky RL, Pai DK, Krotkov EP: **Perception of material from contact sounds**. *Presence Teleoperators Virtual Environ* 2000, **9**:399-410.

19. Fujisaki W, Goda N, Motoyoshi I, Komatsu H, Nishida S: **Audiovisual integration in the human perception of materials**. *J Vis* 2014, **14** 12–12.

20. Fujisaki W, Tokita M, Kariya K: **Perception of the material properties of wood based on vision, audition, and touch**. *Vis Res* 2015, **109**:185-200.

21. Drewing K, Weyel C, Celebi H, Kaya D: **Systematic relations between affective and sensory material dimensions in touch**. *IEEE Trans Haptics* 2018, **11**:611-622.

22. Kravitz DJ, Saleem KS, Baker CI, Mishkin M: **A new neural framework for visuospatial processing**. *Nat Rev Neurosci* 2011, **12**:217-230.

23. •• Kravitz DJ, Saleem KS, Baker CI, Ungerleider LG, Mishkin M: **The ventral visual pathway: an expanded neural framework for the processing of object quality**. *Trends Cogn Sci* 2013, **17**:26-49.

Proposes that the ventral pathway is best understood as a recurrent occipitotemporal network containing neural representations of object quality both, utilized and constrained by distinct cortical and subcortical systems. Each system serves its own specialized behavioral, cognitive, or affective function. This framework contrasts with the idea of the ventral visual pathway as a largely serial staged hierarchy culminating in singular object representations and more parsimoniously incorporates attentional, contextual, and feedback effects.

24. •• Martin A: **GRAPES—grounding representations in action, perception, and emotion systems: how object properties and categories are represented in the human brain**. *Psychon Bull Rev* 2016, **23**:979-990.

Proposes that concepts should be viewed as the products of highly interactive neural circuits grounded in the action, perception, and emotion systems. The nodes of these circuits are defined by regions representing specific object properties (e.g. form, color, and motion) and thus are property-specific, rather than strictly modality-specific. This view breakes away from the view that concepts could be housed in primary sensory and motor cortices and that an object concept could be stored in a single brain region.

25. Kam T-E, Mannion DJ, Lee S-W, Doerschner K, Kersten DJ: **Human visual cortical responses to specular and matte motion flows**. *Front Hum Neurosci* 2015, **9** p. 579.

26. Wada A, Sakano Y, Ando H: **Human cortical areas involved in perception of surface glossiness**. *Neuroimage* 2014, **98**:243-257.

27. Baumgartner E, Gegenfurtner KR: **Image statistics and the representation of material properties in the visual cortex**. *Front Psychol* 2016, **7**:1-13.

28. Cant JS, Xu Y: **Object ensemble processing in human anterior-medial ventral visual cortex**. *J Neurosci* 2012, **32**:7685-7700.

29. Cant JS, Xu Y: **The impact of density and ratio on object-ensemble representation in human anterior-medial ventral visual cortex**. *Cereb Cortex* 2015, **25**:4226-4239.

30. Cant JS, Xu Y: **The contribution of object shape and surface properties to object ensemble representation in anterior-medial ventral visual cortex**. *J Cogn Neurosci* 2016, **29**:398-412.

31. Cant JS, Arnott SR, Goodale MA: **fMR-adaptation reveals separate processing regions for the perception of form and texture in the human ventral stream**. *Exp Brain Res* 2009, **192**:391-405.

32. Cavina-Pratesi C, Kentridge RW, Heywood CA, Milner AD: **Separate channels for processing form, texture, and color: evidence from fMRI adaptation and visual object agnosia**. *Cereb Cortex* 2010, **20**:2319-2332.

33. Peuskens H, Claeys KG, Todd JT, Norman JF, Van HP, Orban GA: **Attention to 3-D shape, 3-D motion, and texture in 3-D structure from motion displays**. *J Cogn Neurosci* 2004, **16**:665-682.

34. Cant JS, Goodale MA: **Scratching beneath the surface: new insights into the functional properties of the lateral occipital area and parahippocampal place area**. *J Neurosci* 2011, **31**:8248-8258.

35. Hiramatsu C, Goda N, Komatsu H: **Transformation from image-based to perceptual representation of materials along the human ventral visual pathway**. *Neuroimage* 2011, **57**:482-494.

36. Jacobs RHAH, Baumgartner E, Gegenfurtner KR: **The representation of material categories in the brain**. *Front Psychol* 2014, **5** p. 146.

37. Landy MS, Maloney LT, Johnston EB, Young M: **Measurement and modeling of depth cue combination: in defense of weak fusion**. *Vis Res* 1995, **35**:389-412.

38. Welchman AE, Deubelius A, Conrad V, Bülthoff HH, Kourtzi Z: **3D shape perception from combined depth cues in human visual cortex**. *Nat Neurosci* 2005, **8**:820-827.

39. Knill DC, Kersten D: **Apparent surface curvature affects lightness perception**. *Nature* 1991, **351**:228-230.

40. Schmid AC, Anderson BL: **Perceptual dimensions underlying lightness perception in homogeneous center-surround displays**. *J Vis* 2017, **17** p. 6.

41. Marlow PJ, Anderson BL: **Material properties derived from three-dimensional shape representations**. *Vis Res* 2015, **115**:199-208.

42. Marlow PJ, Anderson BL: **Motion and texture shape cues modulate perceived material properties**. *J Vis* 2016, **16**:1-14.

43. Marlow PJ, Mooney SWJ, Anderson BL: **Photogeometric cues to perceived surface shading**. *Curr. Biol.* 2019, **29**:306-311.

44. Mooney SWJ, Anderson BL, Taylor G, Building A: **Specular image structure modulates the perception of three-dimensional shape**. *Curr Biol* 2014, **24**:2737-2742.

45. Norman JF, Todd JT, Orban GA: **Perception of three-dimensional shape from specular highlights, deformations of shading, and other types of visual information**. *Psychol Sci* 2004, **15**:565-570.

46. Sun H-C, Ban H, Di Luca M, Welchman AE: **fMRI evidence for areas that process surface gloss in the human visual cortex**. *Vis Res* 2015, **109**:149-157.

47. Kim T, Bair W, Pasupathy A: **Neural coding for shape and texture in macaque area V4**. *J. Neurosci.* 2019, **39**:4760-4774.

48. Schmid AC, Doerschner K: **Shatter and splatter: the contribution of mechanical and optical properties to the perception of soft and hard breaking materials**. *J Vis* 2018, **18**:1-14.

49. van Assen JJR, Fleming RW: **Influence of optical material properties on the perception of liquids**. *J Vis* 2016, **16**:1-12.

50. Aliaga C, O'sullivan C, Gutierrez D, Tamstorf R: **Sackcloth or silk? The impact of appearance vs dynamics on the perception of animated cloth**. *Proc. of the ACM Symposium on Applied Perception* 2015:41-46.

51. Chadwick AC, Kentridge RW: **The perception of gloss: a review**. *Vis Res* 2015, **109**:221-235.

52. Fleming RW: **Material perception**. *Annu Rev Vis Sci* 2017, **3**:365-388.

53. Baumgartner E, Wiebel CB, Gegenfurtner KR: **Visual and haptic representations of material properties**. *Multisens Res* 2013, **26**:429-455.

54. Schmid AC, Doerschner K: **Chocolate, chrome, or cloth? The appearance of specular highlights determines perceived material category**. *J. Vis., 19th Annual Vision Sciences Society Conference (VSS)*; *St Pete Beach, FL, USA: 2019*.

55. Fischer J, Mikhael JG, Tenenbaum JB, Kanwisher N: **Functional neuroanatomy of intuitive physical inference**. *Proc Natl Acad Sci U S A* 2016, **113**:5072-5081.

56. Groen IIA, Silson EH, Baker CI: **Contributions of low-and high-level properties to neural processing of visual scenes in the human brain**. *Philos Trans R. Soc B* 2017, **372**:1-11.

57. Hebart MN, Bankson BB, Harel A, Baker CI, Cichy RM: **The representational dynamics of task and object processing in humans**. *eLife* 2018, **7**:1-21.

58. Simmons WK, Martin A: **Spontaneous resting-state BOLD fluctuations reveal persistent domain-specific neural networks**. *Soc Cogn Affect Neurosci* 2012, **7**:467-475.

59. Groen II, Greene MR, Baldassano C, Fei-Fei L, Beck DM, Baker CI: **Distinct contributions of functional and deep neural network features to representational similarity of scenes in human brain and behavior**. *eLife* 2018, **7**:1-26.

60. Hsu NS, Frankland SM, Thompson-Schill SL: **Chromaticity of color perception and object color knowledge**. *Neuropsychologia* 2012, **50**:327-333.

61. Almeida J, Mahon BZ, Nakayama K, Caramazza A: **Unconscious processing dissociates along categorical lines**. *Proc Natl Acad Sci U S A* 2008, **105**:15214-15218.

62. Chouinard PA, Goodale MA: **Category-specific neural processing for naming pictures of animals and naming pictures of tools: an ALE meta-analysis**. *Neuropsychologia* 2010, **48**:409-418.

63. Mahon BZ: **What is embodied about cognition?** *Lang Cogn Neurosci* 2015, **30**:420-429.

64. Smith FW, Goodale MA: **Decoding visual object categories in early somatosensory cortex**. *Cereb Cortex* 2015, **25**:1020-1031.

65. Meyer K, Kaplan JT, Essex R, Webber C, Damasio H, Damasio A: **Predicting visual stimuli on the basis of activity in auditory cortices**. *Nat Neurosci* 2010, **13**:667-668.

66. Xiao B, Bi W, Jia X, Wei H, Adelson EH: **Can you see what you feel? Color and folding properties affect visual–tactile material discrimination of fabrics**. *J Vis* 2016, **16**:1-34.

67. Amedi A, von Kriegstein K, van Atteveldt NM, Beauchamp MS, Naumer MJ: **Functional imaging of human crossmodal identification and object recognition**. *Exp Brain Res* 2005, **166**:559-571.

68. Lacey S, Sathian K: **Visuo-haptic multisensory object recognition, categorization, and representation**. *Front Psychol* 2014, **5**:1-15.

69. Man K, Damasio A, Meyer K, Kaplan JT: **Convergent and invariant object representations for sight, sound, and touch**. *Hum Brain Mapp* 2015, **36**:3629-3640.

70. Podrebarac SK, Goodale MA, Snow JC: **Are visual texture-selective areas recruited during haptic texture discrimination?** *Neuroimage* 2014, **94**:129-137.

71. Sathian K *et al.*: **Dual pathways for haptic and visual perception of spatial and texture information**. *Neuroimage* 2011, **57**:462-475.

72. Stilla R, Sathian K: **Selective visuo-haptic processing of shape and texture**. *Hum Brain Mapp* 2008, **29**:1123-1138.

73. •• Bracci S, Daniels N, Op de Beeck H: **Task context overrules object- and category-related representational content in the human parietal cortex**. *Cereb Cortex* 2017, **27**:310-321.

Human fMRI study that shows that human parietal cortex does not preferentially represent particular object properties irrespective of task, but together with frontal areas is part of a multiple-demand and content-rich cortical network representing task-relevant object properties. The results paints a more detailed picture of the roles of ventral and dorsal stream in the processing of object properties.

74. •• Anderson BL: **Visual perception of materials and surfaces**. *Curr Biol* 2011, **21**:978-983.

This primer summarizes the challenges in material perception, understanding how mid level vision organizes image measurements into a coherent representation of surfaces and materials. It suggests that a simple linear, progressive flow from low-level feature detection to high-level scene analysis fails to capture the massive recurrence that occurs throughout the visual system. Here, 'mid-level vision' refers to the collective processes that are involved in making information about surfaces and materials explicit, rather than a particular region of cortical processing.

75. Haxby JV, Gobbini MI, Furey ML, Ishai A, Schouten JL, Pietrini P: **Distributed and overlapping representations of faces and objects in ventral temporal cortex**. *Science* 2001, **293**:2425-2430.

76. • Kriegeskorte N, Mur M, Bandettini P: **Representational similarity analysis - connecting the branches of systems neuroscience**. *Front Syst Neurosci* 2008, **2**:1-28.

An approach growing in popularity for investigations of object and scene representations is to explore multivariate stimulus spaces, for example, using stimulus sets that vary in multiple dimensions and comparing the similarity structure of neural activation spaces with those derived from different features about the stimulus space, or human behavior.

77. Hebart MN, Baker CI: **Deconstructing multivariate decoding for the study of brain function**. *Neuroimage* 2017, **180**:4-18.

78. Ritchie JB, Kaplan DM, Klein C: **Decoding the brain: neural representation and the limits of multivariate pattern analysis in cognitive neuroscience**. *Br J Philos Sci* 2017, **70**:1-27.

79. Cichy RM, Pantazis D, Oliva A: **Similarity-based fusion of MEG and fMRI reveals spatio-temporal dynamics in human cortex during visual object recognition**. *Cereb Cortex* 2016, **26**:3563-3579.

80. Harel A, Kravitz DJ, Baker CI: **Task context impacts visual object processing differentially across the cortex**. *Proc Natl Acad Sci U S A* 2014, **111**:962-971.

81. King ML, Groen IIA, Steel A, Kravitz DJ, Baker CI: **Similarity judgments and cortical visual responses reflect different properties of object and scene categories in naturalistic images**. *Neuroimage* 2019, **197**:368-382.

82. Schmid AC, Boyaci H, Doerschner K: **Differential fMRI responses to material motion compared to other motion types**. *Perception* 2019, **48**:205-206 http://dx.doi.org/10.1177/0301006618824879.