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Current Biology

Dissociable cortical regions represent things and stuff in the human brain

Graphical abstract

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In brief

Using functional MRI, Paulun et al. reveal a double dissociation between the processing of rigid and non-rigid objects (things) and liquid and granular substances (stuff) within both the ventral and dorsal visual pathways.

Video abstract

Highlights

- fMRI is used to study the neural basis of perceiving nonsolid substances (stuff)
- Lateral occipital complex represents not only rigid shapes but also deformable materials
- "Frontoparietal physics network" represents not only things but also stuff
- Functional dissociation between stuff and things within dorsal and ventral streams

Paulun et al., 2025, Current Biology *35*, 1–9
September 8, 2025
https://doi.org/10.1016/j.cub.2025.07.027

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Article

Dissociable cortical regions represent things and stuff in the human brain

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https://doi.org/10.1016/j.cub.2025.07.027

SUMMARY

Extensive prior work has identified regions of the human brain associated with visual perception of objects (lateral occipital complex [LOC]) and their physical properties and interactions ("frontoparietal physics network" [FPN]). However, this work has nearly exclusively tested the response of these regions to rigid objects. Deformable or nonsolid substances, or "stuff," including liquids such as water or honey and granular materials such as sand or snow, are of similar importance in everyday life but have different physical properties and invite different actions. Little is known about the brain basis of stuff perception. Here, we scan participants with functional MRI (fMRI) while they view videos of rigid and non-rigid objects ("things") and liquid and granular substances (stuff). We find double dissociations between the processing of things and stuff within both the ventral and dorsal visual pathways. These findings suggest that distinct mental algorithms are engaged when we perceive things and stuff, as they are in artificial physics engines.

INTRODUCTION

When engaging with the world, we interact with an immense variety of substances and materials, from silk scarfs to steel knives, from porcelain plates to paper planes, and from roasted coffee beans to gooey honey. One of the most fundamental distinctions in our physical environment is whether something is a solid "thing" or liquid or granular "stuff." Things, like mugs, books, bananas, or rocks, are solid objects that move as single, coherent bodies, either rigidly or with some deformation. Stuff, i.e., liquids like water or shampoo and granular materials such as sand or snow, are collections of matter that do not move as cohesive bodies but deform constantly and may naturally divide into multiple disconnected and non-interacting sub-masses. Things and stuff bear fundamentally different affordances and we interact with them in distinct ways: things can be grasped, stacked, or thrown, whereas stuff has no constant shape to grasp or stack; instead, it flows, merges, drips, or oozes. Thus, we often use containers and tools to interact with and manipulate stuff. Even young infants 5 months of age have different expectations about the behavior of liquids and granular materials as distinct from rigid solids.[1,2] Yet, the question of how we perceive stuff has long been neglected in visual neuroscience[3] (note that stuff is often used synonymously with "material," i.e., a broader definition than what we consider here). Here, we ask whether distinct brain mechanisms are engaged in the visual perception of things, both rigid and deformable, and stuff, both liquid and granular.

Past research in visual neuroscience has almost exclusively focused on how the brain represents rigid objects, including their shape, location, physical properties, and relational attributes. For example, numerous studies have found that the lateral occipital complex (LOC) plays a role in extracting the 3D shape of rigid objects,[4,5] but it remains unknown whether LOC also represents deformable non-rigid objects or fluids without a constant shape. Similarly, previous work has identified a frontoparietal "physics network"[6,7] (FPN) that is engaged when participants make physical judgments about rigid objects, e.g., about the mass of an object[8] or stability of a block tower rather than descriptive (e.g., color) or other non-physical (e.g., social) judgments. However, because this network has never been tested on non-rigid objects, it remains unknown whether these brain regions reflect a general processor of physical information or a system specialized for rigid body physics in particular. Because of the distinct demands of simulating fluid vs. rigid body physics, computer programs usually simulate them using different engines and different forms of representation, i.e., 3D meshes for things and particles for stuff. Does the brain also employ different systems for representing stuff vs. things?

Previous research on material perception has addressed the related, yet conceptually distinct, questions of how we discriminate visual textures, recognize materials, and infer their physical properties. *Visual textures*, i.e., patterns of conjoint low-level features, like color, curvature, and spatial frequency, are properties of regions within an *image*—not necessarily of meaningful objects or substances. *Material recognition* refers to the higher-level determination of what something is made of (e.g., wood vs. clay vs. glass), which may be revealed from texture but also from shape and motion cues. *Physical properties* refer to attributes such as friction, viscosity, or elasticity, which can be inferred from observing the physical behavior even of unfamiliar materials. Previous psychophysical work has characterized behavior and developed computational models of visual

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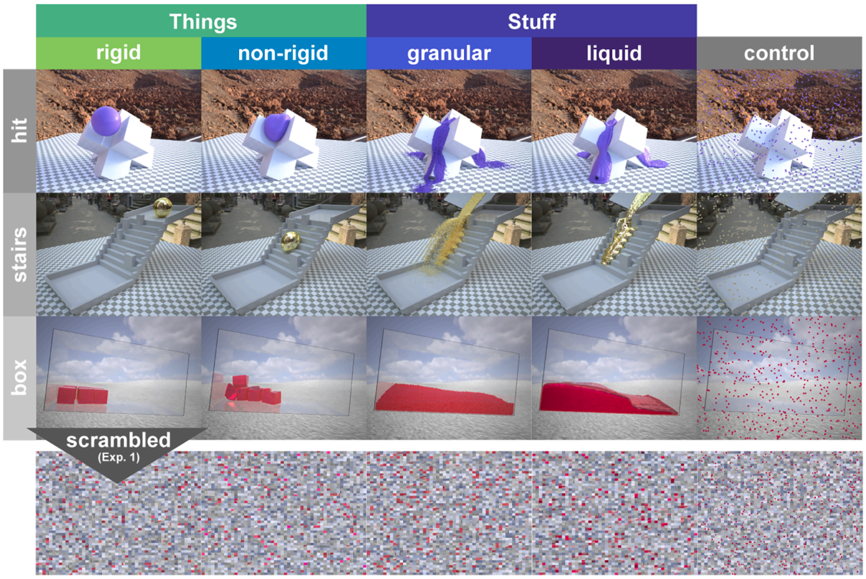

Figure 1. Stimuli and experimental design
Snapshots from video stimuli illustrating the experimental design in which we orthogonally varied the material (columns) and scenario (rows). The stimulus set contained 10 variations of each material × scenario combination, only one of which is shown here. In experiment 1, we additionally included a spatially scrambled version of each video (see last row) to create 30 conditions (5 materials × 3 scenarios × intact/scrambled). In experiment 2, we included a static version of each stimulus, consisting of four individual frames from the movies presented sequentially for 1 s each, to create 30 conditions (5 materials × 3 scenarios × dynamic/static). In both experiments, each experimental block consisted of five stimuli from one of the 30 conditions. Video S1 shows example stimuli.

perception of textures,[9–11] materials,[12–15] and physical properties.[16–23] Prior neuroimaging work has implicated early regions of the ventral visual pathway in the perception of textures (e.g., V1 and V4), more anterior regions in the collateral sulcus (CoS) in the perception of materials, and regions in the dorsal and ventral visual pathways in the perception of physical properties and material motion.[24] The hypothesis we test here is that the distinction between things and stuff serves as a major organizing principle of these higher-level regions in both pathways.

Specifically, we test here whether things and stuff are processed by common or distinct brain mechanisms. In particular, we asked two questions: (1) are regions previously only shown to be engaged by rigid things (LOC and FPN) also engaged when observing non-rigid things and liquid and granular stuff and (2) do these or any other brain regions respond differentially to things (rigid and non-rigid) vs. stuff (liquid and granular)? To answer these questions, we created a large stimulus set of short (4 s) photo-realistic animations from physical simulations of rigid, non-rigid, liquid, and granular materials dynamically interacting in three basic scenarios (see Figure 1), as well as a control condition showing moving colored pixelated noise on the same backgrounds (the "background-only" control; far right column in Figure 1). Stimuli were presented to naive observers in two functional MRI (fMRI) experiments. In experiment 1, we presented intact versions of the videos using a blocked design and scrambled versions in which we spatially divided each video into a 50 × 50 grid and randomly rearranged the positions of the cells (see bottom row in Figure 1). Participants ($n = 14$) performed an orthogonal color change detection task while freely viewing the stimuli. The purpose of experiment 2 was 2-fold: first, to ask whether dynamic stimuli are essential for the activations observed, we presented intact videos as well as static snapshots from those videos in a blocked design. Furthermore, to exclude the possibility that the pattern of results may result from differential eye movement, participants in experiment 2 ($n = 14$) were asked to hold central fixation. In both experiments, two additional localizer tasks were performed to independently localize LOC and FPN on an individual level. All methods and analyses were preregistered unless labeled "exploratory." In both experiments, although both LOC and FPN respond to both things and stuff, we find dissociations in which some cortical regions within or adjacent to LOC and FPN respond preferentially to things and others respond preferentially to stuff.

RESULTS

To address our first research question—whether regions previously only shown to be engaged by rigid things are also engaged when observing non-rigid things and liquid and granular stuff—we first report the results of experiments 1 and 2 in LOC and FPN. Next, to address our second question, we report brain-wide analyses that test more broadly for any dissociations between neural responses to things and stuff.

The FPN is engaged by both things and stuff—but more by things

In experiment 1, the FPN responded more strongly to each of the four intact materials than to their scrambled-video controls and the background-only control (all $p < 0.05/4$, i.e., corrected for testing four materials; details see Table S1), see Figure 2A. Thus, the FPN is engaged not only by rigid things but also by non-rigid things and stuff. However, the FPN responded significantly more strongly to things (i.e., rigid and non-rigid: 0.73 ± 0.24) than to stuff (i.e., granular and liquid; 0.56 ± 0.22, $p < 0.05$).

Experiment 2 replicated these results (for intact materials) when participants were fixating, showing that our findings are not driven by differential eye movements. Specifically, the FPN responded (1) more strongly to each of the four dynamic materials than to the dynamic background-only control (all $p < 0.05/4$; Figure 2B) and (2) more strongly to dynamic things (0.46 ± 0.26) than dynamic stuff (0.39 ± 0.25, $p < 0.05$), although the effect size (Cohen's d = 0.29) was smaller compared with experiment 1 (Cohen's d = 0.71; exploratory analysis).

Experiment 2 further showed a significantly higher activation of the FPN for dynamic (0.37 ± 0.21) compared with static stimuli (0.27 ± 0.17, $p < 0.05$). Nonetheless, for all four materials, intact

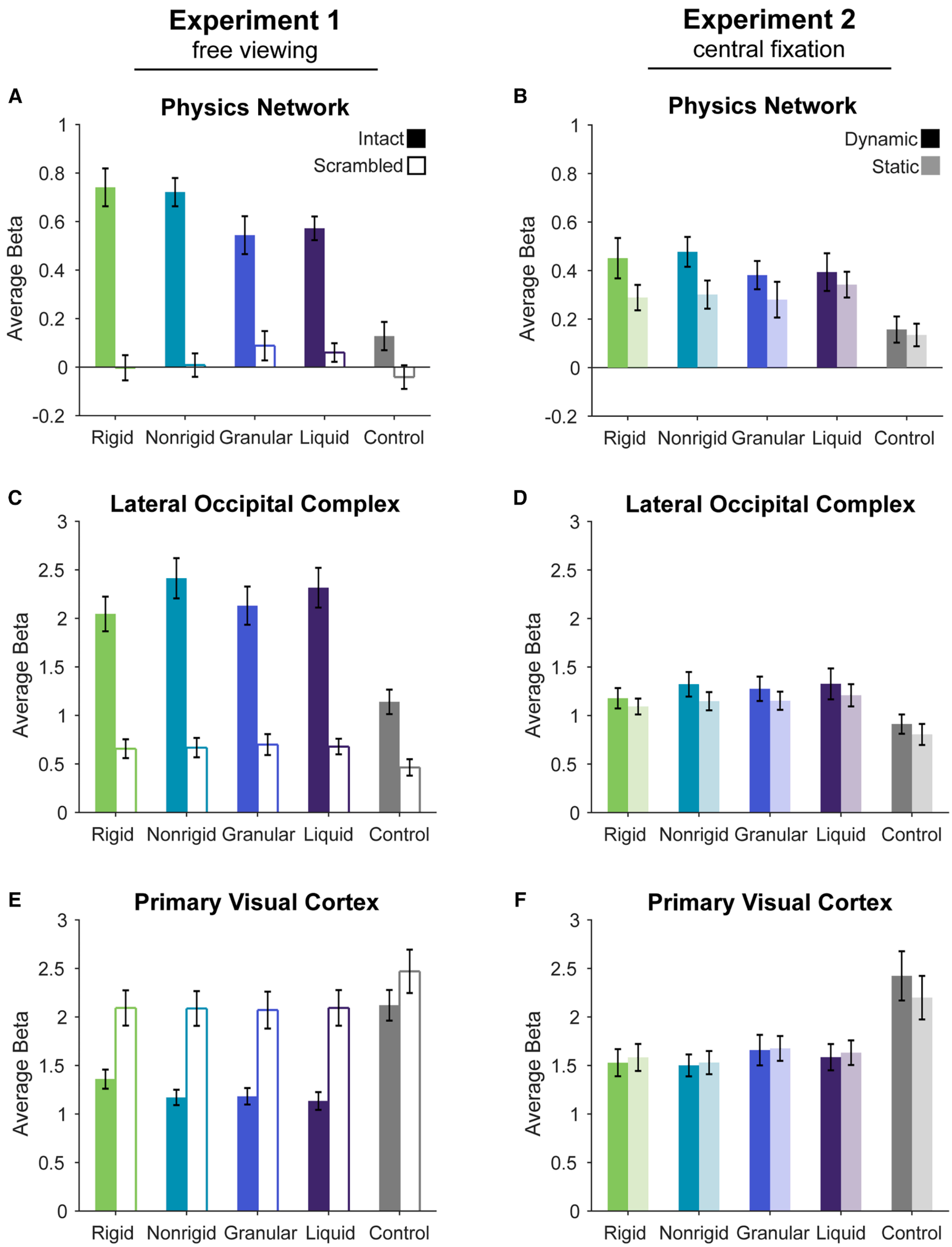

Figure 2. Average activation strength (beta) in fROIs

Results of the univariate analysis of experiment 1 (left column) and experiment 2 (right column) in the different fROIs (rows), FPN, LOC, and V1. Bars show the mean ± SEM beta for each condition averaged across subjects.

See also Tables S1–S3.

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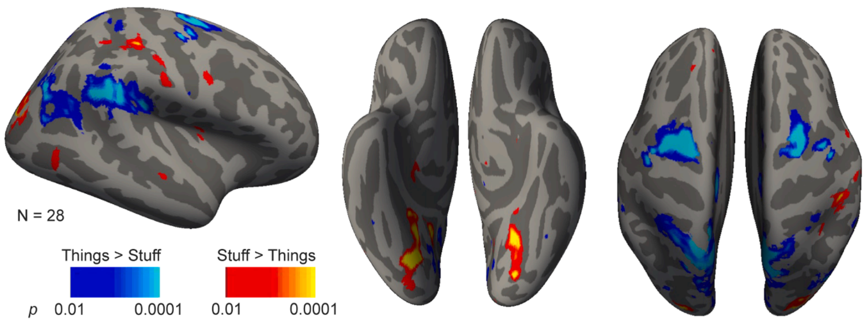

Figure 3. Stuff vs. things significance map
Significance map of the random-effects group analysis of the dynamic stuff vs. dynamic things contrast mapped onto the inflated average brain (FreeSurfer fsaverage). p values are uncorrected. Note that although the salient stuff > things activation visible in the posterior ventral occipital region resembles V4, this region did not respond more strongly to color than grayscale images, see Figure S1.

static stimuli produced a higher FPN response than did the static background-only control condition (all $p < 0.05/4$). However, the FPN did not respond significantly differently between static things and static stuff. Finally, responses in the FPN were larger when observers were freely viewing intact videos (experiment 1: 0.54 ± 0.21) compared with when they held central fixation while watching the same videos (experiment 2: 0.37 ± 0.21, $p < 0.05$).

Taken together, these results indicate that the FPN represents not only rigid objects but also deformable objects and fluid stuff, whether presented in videos or static snapshots from those videos. Yet, overall, the FPN responds more strongly to things (rigid and non-rigid) than stuff (granular and liquid). Furthermore, the FPN responds more strongly to dynamic videos than static snapshots and during natural free viewing compared with central fixation, matching the subjective impression of vividness in the dynamic natural viewing conditions.

The LOC responds to both things and stuff

Does LOC represent not just the 3D shape of rigid things, as suggested by previous research, but also the changing shapes of deformable things and stuff? In experiment 1, we found that LOC responded significantly more strongly to each of the intact materials than to their scrambled-video controls (all $p < 0.05/4$; Figure 2C; details, see Table S2) and more strongly to each of the intact materials compared with the background-only control (all $p < 0.05/4$). Unlike in FPN, we did not find a significant difference between things and stuff.

As we found for the FPN, experiment 2 replicated these results when participants were fixating, showing that our findings are not driven by differential eye movements. Specifically, we found that videos of each of the dynamic materials elicit a higher response in LOC than the background-only control videos (all $p < 0.05/4$), see Figure 2D.

LOC also resembled the FPN by showing a significantly greater response to (1) dynamic (1.20 ± 0.43) than static stimuli (1.08 ± 0.33, $p < 0.05$), (2) static materials than the static background-only control (all $p < 0.05/4$), (3) intact dynamic videos during free viewing (experiment 1, 2.01 ± 0.67) compared with fixation (experiment 2, 1.20 ± 0.43, $p < 0.05$), but (4) no significant difference between static things and stuff.

Taken together, our results show that LOC represents not only the 3D shape of rigid objects but also the changing shape of non-rigid things and stuff. The weaker responses to static images could be explained by fMRI adaptation[25] due to fewer frame-by-frame shape changes in this condition.

The primary visual cortex showed a different pattern of results from both LOC and FPN: we found stronger activation to the control conditions (both scrambled video and background only) than to intact videos or images of materials (Figures 2E and 2F; detailed stats in Table S3) and no higher response to dynamic than static stimuli. Taken together, these results in V1 show that the effects we found in LOC and FPN are unlikely to reflect simple low-level image or movie features.

Functional dissociations between things and stuff in the dorsal and ventral pathways

The analyses of the FPN and LOC described so far indicate that both regions respond to all material types, albeit with differences in the magnitude of response across material types. Might other regions show stronger differences in their response to things vs. stuff? To find out, we conducted a whole-brain random-effects analysis contrasting things and stuff, combining the data from the intact dynamic material conditions of experiment 1 and experiment 2 to maximize our statistical power, i.e., $N = 28$. Figure 3 shows the resulting significance map of this contrast on an inflated brain (FreeSurfer fsaverage). This analysis shows significant activations ($p < 0.0001$, uncorrected) for stuff > things in bilateral ventral and dorsal right hemisphere regions. For the reverse contrast (things > stuff contrast), we found strong activation bilaterally ($p < 0.0001$, uncorrected) in frontal and parietal regions resembling the FPN, as well as in a more medial region (T5 in Figure 4).

Group analyses provide crude initial indications of where differential responses might be found in the brain, but they do not reveal the response profiles of any activated regions they discover and potentially blur responses of functionally distinct regions because of anatomical variability across participants.[26] We therefore conducted a group-constrained subject-specific (GSS) region of interest (ROI) analysis.[27] As for the random-effects analysis, here we combined data from the intact dynamic condition of both experiments to maximize statistical power. For the GSS analysis, we used half of the data (odd runs) to calculate a significance map of the stuff > things (or things > stuff, respectively) contrast for each subject and then identified "parcels," i.e., regions of overlap between subjects (see STAR Methods for details). We then functionally defined individual functional ROIs (fROIs) in each participant within those parcels (again using only the odd runs). Finally, we then used the held-out, i.e., independent, data of each subject (even runs) to measure and statistically compare response magnitudes for things and stuff in these fROIs.

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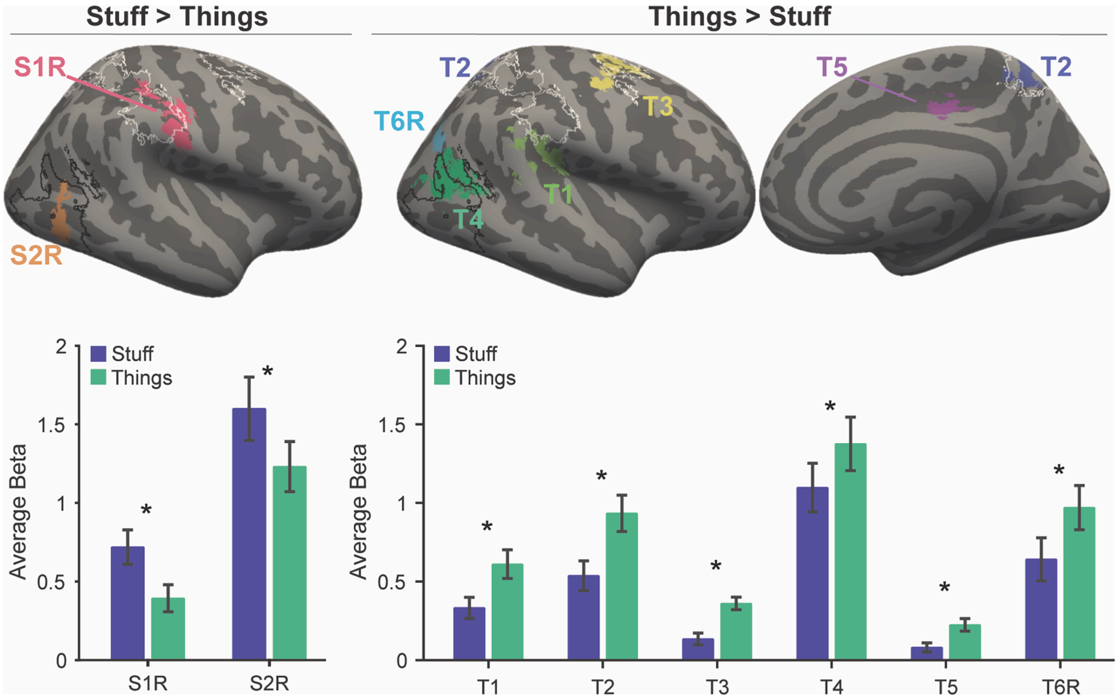

Figure 4. Results of the GSS analysis for the stuff > things and things > stuff contrasts

Inflated brains (FreeSurfer fsaverage) show the resulting group parcels, defined using one half of the data; bar plots below show the responses to stuff vs. things in the fROIs defined for individual subjects within those parcels, in the held-out data; blue bars show responses to stuff (liquid and granular) and green bars show responses for things (rigid and non-rigid). White outlines on the inflated brains show the group parcels of the FPN; black outlines show the group parcels of LOC. Parcels T1–5 were bilateral, and the corresponding bar plot shows the average activation across hemispheres. Asterisks indicate Bonferroni-corrected significance in a one-sided 10,000-fold permutation test ($p < .05$).

See also Figure S1 and Table S4.

This analysis yielded six parcels for the things > stuff contrast, five bilateral and one right-lateralized (i.e., 11 in total), all of which cross-validated to show a significant effect in held-out data, and two unilateral parcels for the stuff > things contrast, both cross-validated to show a significant effect in held-out data (detailed statistics in Table S4). Thus, this analysis revealed a functional dissociation between things and stuff in both the ventral and dorsal visual pathways, see Figure 4. Specifically, we found a functional subdivision within LOC, whereby a superior subregion showed a significantly stronger response to things > stuff (T4 in Figure 4) and a more inferior right-lateralized subregion showed the opposite response pattern (S2R in Figure 4). When mirroring the right-lateralized stuff parcel to the left hemisphere in an exploratory analysis, we found the same pattern of responses, i.e., a significant stuff > things effect also in the left hemisphere, indicating that the subdivision of LOC is bilateral.

We found a similar subdivision within the FPN: specifically, we found both an overall preference for things > stuff in the FPN regions (see T2 and T3 in Figure 4; consistent with the fROI and random-effects analyses described above) and an adjacent right-lateralized region with the opposite preference, stuff > things (see S1R in Figure 4), which also shows a significantly higher response to the physics task over the color task in the physics localizer. As we did for LOC, we tested whether the parietal stuff region was genuinely right lateralized or whether this region was also present in the left hemisphere but failed to reach significance in our GSS analysis. To find out, we mirrored the right hemisphere stuff parcel to the left hemisphere, identified fROIs within individual participants, and measured responses in held-out data (exploratory analysis). This analysis found a significant stuff preference (see SI), indicating that this pattern is bilateral. Thus, just like LOC, the brain's physics network shows a functional subdivision with at least one subregion showing a preference for stuff over things and several areas showing the opposite.

Outside the FPN, we found three further regions with a significant things > stuff response: one bilateral inferior of the parietal FPN (T1 in Figure 4), one bilateral medial (T5), and another posterior region in the right hemisphere (T6R). The parietal and posterior regions (T1 and T6R) resemble two regions previously reported by Fischer et al.[6] (P4 and P5R in Figure 4B of their paper) that showed higher responses to physics task > color task but a similar response to dots moving in a physical manner and dots moving in a social manner. Thus, these regions might respond to moving things, irrespective of whether the motion is attributed to physical or social causes. The medial things > stuff (T5) has not been reported before.

DISCUSSION

Extensive previous research has identified cortical areas involved in the representation of 3D shapes (LOC) and the representation of physical relations and properties (FPN)—but only for rigid, nondeformable things, such as block towers. How is stuff, such as milk, sugar, or mud, represented in the human brain? Our neuroimaging study yielded three key results: first, we found that the FPN is engaged when observing not just rigid body interactions but also physical interactions of a variety of substances, although it responded more to deformable and rigid things than liquid and granular stuff. Second, we found that LOC responds not only to things with constant shape but also to deformable objects and to liquid and granular stuff. Third, we found that both LOC and the physics network show distinct subregions, one with a preference for things and the other for stuff. Thus, our study reveals a functional double dissociation between the visual processing of stuff and things in both the ventral and dorsal streams of the human brain. We replicated these findings across two experiments while participants performed an orthogonal change detection task for both dynamic events and static snapshots of those events and during free viewing as well as central fixation.

Representation of things and stuff in the dorsal visual pathway

Our study builds on previous work implicating the FPN in intuitive physical reasoning. Specifically, the FPN has been shown to respond more when people make physical compared with non-physical judgments,[6] to respond to violations of physical expectations,[28] and to contain scenario-invariant information about object mass,[8] physical stability,[7] object contact relations,[29] and predicted future states.[29] These results highlight the role of the FPN in intuitive physical reasoning. Yet, these prior studies have tested only the response of the FPN to rigid things, leaving unexplored the multitude of different materials found in the world with vastly different properties and affordances, from rubber balls and plush toys to cottage cheese, maple syrup, and gravel. A true "physics engine," useful in the real world, must represent not just rigid things but also the fundamentally different properties and behavior of deformable things and stuff. Here, we show that, indeed, the FPN is engaged by these stimuli, providing further evidence for the frontoparietal network as the brain's physics engine. However, more interestingly, our results also indicate a functional division of labor, with some regions preferentially responding to things and other regions to stuff.

What is the function of the specialization of stuff- and things-preferring regions within the physics network? Although our study cannot answer this question, our results invite speculations about the underlying representations and computations. In artificial physics engines, e.g., those used in computer games, objects are usually represented as meshes, whereas fluids are simulated as particles. A similar approach has been used to model cognition: human predictions about solid objects have been modeled using an object-based representation,[30] whereas predictions of fluid flow were best modeled using a coarse, particle-based representation.[31] Thus, one hypothesis worth testing in future is that these apparently distinct mental algorithms are implemented in the respective things- and stuff-preferring cortical regions identified here. Further questions concern the information represented in the FPN (or its stuff-sensitive subregions). Do they contain invariant representations of stuff properties (such as viscosity or cohesion) or information about relations between different substances? Are they engaged in simulating future states of stuff, for example, whether tea is about to brim over a mug or cereal over the rim of the bowl?

Representation of things and stuff in the ventral visual pathway

3D shape processing in the LOC

Many studies have highlighted the role of LOC in extracting the 3D shape of rigid objects from different cues, such as lightness, motion, and texture.[4,5] But what about non-rigid substances? By definition, a fluid can take on any shape, and even non-rigid objects can show drastic changes in their 3D shape, so one possibility was that LOC would not respond to these stimuli because they do not have fixed shapes. But, here, we find that LOC represents not only the fixed 3D shape of rigid things but also the changing shapes of deformable things and stuff. LOC also showed higher activation to dynamic scenes compared with static snapshots of the same scenes. This might result, in part, from fMRI adaptation because a larger number of different shapes are represented in a given time period for dynamic stimuli. Another hypothesis is that LOC is tuned not to shape but to shape *changes*, much as visual motion area MT is tuned to motion (i.e., position *changes*).

The fact that LOC is sensitive to deformations suggests that it might play a role in identifying the kind of substance in front of us. Several behavioral studies show that people use shape deformation when judging the physical properties of liquids and objects, such as viscosity or stiffness,[16,17,21,22] and, in many cases, such dynamic information outweighs other cues such as texture.[17,23] Imagine distinguishing water from liquid soap, based not on the label on the bottle but on the way it flows out of the bottle. Its sensitivity to shape changes makes LOC a prime candidate brain region for such inferences. Future work should test the exact role of LOC in inferring materials from shape and deformation. How do shape and deformation interact with texture and other cues to material perception? What is the relation between material motion and other (non-physical) forms of non-rigid motion, such as biological motion?

Here, we found a functional dissociation between stuff and things within LOC, mirroring the dissociation we found in FPN. A speculative interpretation of these findings is that the brain might have two coherent networks, each spanning both pathways, one preferentially processing things and the other stuff. Consistent with this possibility, previous work identified a large "material motion network"[24] spanning both the dorsal and ventral visual streams by contrasting point-light displays of non-rigid materials physically deforming (e.g., cloth flapping in the wind) with rigidly rotating structure-from-motion displays of the same objects (i.e., non-physical motion). Although the point-light displays elegantly eliminated potential low-level confounds, their design did not contrast whether stuff and things (or different types of materials more generally) are processed by the same or distinct brain mechanisms. Thus, their study does not provide evidence for (or against) the speculation of two distinct networks. Another possibility is that although we find a similar-looking dissociation in each visual stream, their origins may differ according to the distinct functions of the two pathways (recognition/identification in the ventral pathway vs. world modeling and simulation in the dorsal pathway). Thus, the observed dissociation in LOC might reflect the different shape features of things and stuff (rather than different representational formats, such as particles).

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Material and texture processing in ventromedial regions

We found an additional bilateral region with a stuff > things preference in the ventromedial cortex (see middle panel of significance map in Figure 3 and GSS parcel S4 in Figure S1) in the region of the CoS, V4, and the parahippocampal place area (PPA). Previous research has reported these regions to be sensitive to textures[32–36] (both in object surfaces and from object ensembles), color,[37] scenes,[38] and material classes[39] (e.g., wood and metal). However, the GSS analysis revealed that our stuff-sensitive region does not respond more strongly to materials than to the background-only control (with an overlaid texture of moving dots), to color than to grayscale images, or to scenes than to objects (see Figure S1). Thus, we hypothesize that the ventromedial stuff > things response might reflect mid-level features (like texture) rather than physical properties of stuff and things. Granular materials inherently show a grainy texture, and liquids might exhibit a specific texture-like flow of highlights even when they are rendered with the same optical properties as objects. Future research should disentangle the role of different areas in the ventromedial cortex in the perception of the conceptually related stuff, textures, ensembles, and other visual non-objects, such as grass or clouds.

Future directions

Here, we have identified brain regions that are differentially engaged during perception of things vs. stuff, opening up a broad landscape of new questions. Our study shows that these regions are engaged when observing physical interactions of stuff and things, but what information is extracted and what computations are conducted in these regions? Previous work has shown that regions like FPN, LOC, and CoS represent the physical properties of things, such as mass[8,40] or softness.[33,41] Do stuff-sensitive regions represent stuff properties, like viscosity or cohesion? Do they only represent the *visual* properties of stuff (and things) or are they multimodal; e.g., are they engaged when listening to the sounds of things, e.g., balls bouncing or glasses clinking, and the sounds of stuff, e.g., water splashing or mud sloshing? The division of physical matter into stuff and things is also reflected in linguistics, e.g., as mass and count nouns. What is the relation between stuff-/things-selective regions and linguistics, and how does this relate to cross-linguistic differences?[42] In our study, participants performed an orthogonal task that did not require processing of physical material properties, indicating that the brain processes this distinction even when not required by the task but leaving unanswered exactly how automatic the engagement of those regions is. More importantly, it remains to be tested what role those regions play, not only in perception but also in extracting physical properties, predicting what will happen next, and planning actions on things and stuff. Testing the causal role of these brain regions for behavior will also be crucial for our understanding of how the brain represents and interacts with the physical world.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Vivian Paulun (paulun@wisc.edu).

Materials availability

This study did not generate new unique reagents.

Data and code availability

- All experimental stimuli have been deposited at Zenodo at https://doi.org/10.5281/zenodo.15786346 and are publicly available as of the date of publication.
- De-identified human fMRI data (beta values) have been deposited at Zenodo at https://doi.org/10.5281/zenodo.15786346 and are publicly available as of the date of publication.
- This paper does not report original code.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

ACKNOWLEDGMENTS

This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation; project PA 3723/1-1 to V.C.P.), NIH grant EY033843 to N.K., and NSF Science and Technology Center—Center for Brains, Minds, and Machines grant NSF CCF-1231216.

AUTHOR CONTRIBUTIONS

Conceptualization, V.C.P. and N.K.; methodology, V.C.P., R.R.T.P., and N.K.; software, V.C.P. and R.R.T.P.; formal analysis, V.C.P. and R.R.T.P.; investigation, V.C.P. and R.R.T.P.; resources, N.K. and J.B.T.; data curation, V.C.P.; writing – original draft, V.C.P.; writing – review and editing, V.C.P., R.R.T.P., N.K., and J.B.T.; visualization, V.C.P.; supervision, N.K.; and funding acquisition, V.C.P., N.K., and J.B.T.

DECLARATION OF INTERESTS

The authors declare no competing interests.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.cub.2025.07.027.

A video abstract is available at https://doi.org/10.1016/j.cub.2025.07.027#mmc3.

Received: February 23, 2025
Revised: June 23, 2025
Accepted: July 8, 2025

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Please cite this article in press as: Paulun et al., Dissociable cortical regions represent things and stuff in the human brain, Current Biology (2025), https://doi.org/10.1016/j.cub.2025.07.027

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
fMRI beta values	This paper	https://doi.org/10.5281/zenodo.15786346
Stimuli	This paper	https://doi.org/10.5281/zenodo.15786346
Software and algorithms		
Realflow 10 (v. 10.5.3.0189)	NextLimit Technologies	www.nextlimit.com/realflow/
Matlab (v. 2018b)	MathWorks	https://www.mathworks.com
Psychophysics Toolbox (v. 3)	Brainard,[43] Pelli,[44] and Kleiner et al.[45]	http://psychtoolbox.org
Freesurfer (v. 6.0.0)	Fischl[46]	https://freesurfer.net/
Other		
Preregistration Experiment 1	This paper	https://doi.org/10.17605/OSF.IO/8XN2K
Preregistration Experiment 2	This paper	https://doi.org/10.17605/OSF.IO/UVHRT

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAIL

The methods and analyses presented in this paper have been preregistered unless stated otherwise (i.e., marked as exploratory analyses). Fifteen subjects (ages 22–37; 5 male, 10 female) participated in Experiment 1. Following our preregistration, the data of one participant was excluded from the analysis because we were not able to localize one of our ROIs (FPN). Seventeen participants (ages 20-37; 5 male, 11 female, 1 non-binary) participated in Experiment 2. Following our preregistration, the data of three participants was excluded from the analysis: for one participant we were not able to localize one of our ROIs (LOC), two participants did not show up for the second scan session and thus we did not obtain the minimal number of six runs of our main experiment. All participants had normal or corrected-to-normal vision. All participants gave informed consent before participation. All experiments were approved by the Massachusetts Institute of Technology Institutional Review Board.

METHOD DETAILS

Preregistration

All of the experimental methods and main analyses were pre-registered and are available on the Open Science Framework (see key resources table). Results of analyses that were preregistered but were not reported in the final version of this paper, can be found on OSF next to the preregistration.

Stimuli

We used RealFlow's (version 10.5.3.0182, Next Limit Technology) Dyverso particle-based physics engine to simulate short (4 sec) interactions of four different material types, i.e., liquid, granular, non-rigid, and rigid, each appearing in three different kinds of scenarios flowing/rolling/bouncing down stairs ('Stairs'), falling onto an obstacle ('Hit'), and moving inside a tilting transparent container ('Box'). The different scenarios introduced variability to the stimuli that was orthogonal to our variable for interest, materials. For each scenario, we created 10 different variations, by varying the 3D shapes of the stairs, obstacle, or box, the motion path of the box, the camera position, and the amount of material (i.e. number of solid objects, amount of liquid). We simulated all four materials within each of the 30 unique scenes. The simulations were rendered using RealFlow's built-in Maxwell rendering engine. For each of the 30 unique scenes, we randomly chose one of 10 different high dynamic range (HDR) images as backgrounds and one of 5 different appearances for the materials. The optical material appearances varied in color (blue, purple, red, yellow, green) and surface appearance (opaque and glossy, shiny and metallic, translucent) to have high realism but not evoke specific prior expectations about the physical properties of specific materials. For each of the 30 unique scenes, we created a 'no material' control condition that showed the same background scene and objects, but no material was physically interacting with the scene. Instead, a pixelated noise pattern, that randomly changed position every 6 frames, was overlaid onto the image. Thus, we created 150 unique videos: 5 materials x 3 scenarios x 10 variations. For each video, we created a 'scrambled control' by spatially dividing it into a 50 x 50 grid and randomly rearranging the positions of the cells to use as a control condition in Experiment 1. From each video, we selected 4 frames to use in the static condition of Experiment 2. The frames were selected to show static snapshots of the physical interaction between the target material and the environment.

General procedure

In Experiment 1, every subject completed one MRI session including 1) a high-resolution anatomical scan, 2) two runs of a physics localizer,[6–8] 3) one run of a dynamic object localizer,[47] 4) six to ten runs of the main experiment—as many as we could collect within a 2h scan session. All experiments were run in Matlab using the Psychophysics Toolbox[43–45] extensions.

In Experiment 2, every subject completed two scan sessions. Across both sessions, every participant completed 1) a high-resolution anatomical scan, 2) two runs of a physics localizer,[6–8] 3) four runs of a static object localizer and 4) six to ten runs of the main experiment (as many as we can collect within the time given). In the second scan session, we recorded our participant's eye movements during up to six runs of the main experiment to ensure they held central fixation as instructed. We did not attempt to record eye movements in both sessions, because the time it took to adjust and calibrate the eye tracker within the constraints of the MRI bore would have substantially decreased the number of runs that we completed with each participant.

fMRI data acquisition

All imaging was performed on a Siemens 3T Prisma scanner with a 32-channel head coil at the Athinoula A. Martinos Imaging Center at MIT. For each subject, we collected a high-resolution T1-weighted anatomical image (MPRAGE: TR = 2.53 s; TE = 3.57 ms; a = 9°; FOV = 256 mm; Matrix = 256x256; Slice thickness = 1 mm; 176 slices; Acceleration factor = 2; 24 reference lines; BW=190Hz/pix) in the first scanning session. The whole-brain functional data was collected using a T2*-weighted echo planar imaging pulse sequence (TR = 2 s; TE = 30 ms; a = 90°; FOV = 204 mm; Matrix = 102 x 102; Slice thickness = 2 mm; Voxel size = 2 x 2 mm in-plane; Slice gap = 0 mm; 66 slices).

Design main experiment

Experiment 1

The main experiment had a blocked design of 30 conditions: 5 materials (liquid, granular, non-rigid, rigid, no material control) x 3 scenarios (stairs, hit, container) x scrambled vs. intact. Figure 1 shows example snapshots from the experimental conditions.

Each block consisted of videos from one condition. More specifically, each block showed 5 movie clips of the same material x scenario x intact/scrambled combination with a 300 ms interstimulus interval, i.e., each stimulus block was 21.2 sec long. For each block, the stimuli were chosen pseudorandomly: The ten possible stimuli of each condition were shuffled randomly and divided into two blocks. This procedure was repeated until all blocks in the design matrix were populated with stimuli. Thus, no stimulus appeared twice in a block and all stimuli of a condition appeared (on average) equally often.

Each run consisted of 20 stimulus blocks and three fixation blocks, one at the beginning, middle, and end of each run. The fixation blocks lasted 20 sec and showed a white cross in the center of a gray screen. For each subject, we created a palindromic order of conditions within each run and each run started with a block of a different condition. The order of runs was then shuffled pseudorandomly so that it was (a) different for each subject and (b) so that each material x scenario x intact/scrambled combination would appear once within every three runs. This strategy was intended to ensure that (a) we would sample an equal number of blocks for all conditions even if subjects did not complete all runs of the design, and (b) across participants, each condition would happen equally often in each serial position within a run. Every participant completed six to ten runs of the main experiment, whereby every material x scenario x intact/scrambled combination appears at least four times within 6 runs, and ten runs correspond to the whole design matrix.

To ensure subjects were paying attention to the materials, they performed an orthogonal color change detection task. For this purpose, the material (or no material control) in one of the stimuli (randomly chosen) in each block changed its color slightly during the second half of the video. Participants were asked to press a button whenever they detected a color change. We did not inform participants about the frequency of color changes.

Experiment 2

The design of the main experiment was the same as in Experiment 1 with two exceptions: (1) Instead of scrambled conditions, there were static conditions. The static condition consisted of static images from the movies used in the dynamic condition. Specifically, for each stimulus, we selected four snapshots of the physical interactions, e.g. moments of collisions. The four frames were shown for 1 sec each and in a random temporal order. In each block, there was one stimulus for which 1 or 2 frames showed the color switch that subjects had to detect and respond to. (2) In both conditions (static and dynamic) we presented an optimized fixation target[48] in the center of the screen to help subjects fixate throughout the experiment. To verify that participants maintained fixation, we attempted to measure eye movements using an in-scanner eye tracker for at least half of the runs of each subject.

Functional ROI localization

We used standard and established methods to functionally localize our three ROIs, i.e., frontoparietal physics network (FPN), lateral occipital complex (LOC), and primary visual cortex (V1) in each subject individually. Specifically, we intersected the subject-specific localizer contrast map with group-level or anatomical parcels. If, for a given subject, there were fewer than 100 voxels (pooled across both hemispheres and in case of FPN across frontal and parietal parcels) in the fROI, we reduced the significance threshold from p <.001 to p <.05 (uncorrected). If the fROI still contained fewer than 100 voxels we excluded the subject from further analysis (in case of FPN or LOC) or excluded the fROI from further analysis (V1).

Physics Localizer

To functionally localize the FPN in the same way as Fischer et al., every participant in Experiments 1 and 2 completed two runs of the 'intuitive physics' localizer task that was previously described.[6–8] Specifically, on each trial, participants saw a short movie clip (~6 s) depicting a 360°; view of an unstable block tower composed of blue and yellow rigid blocks. While viewing the movies, participants were asked to perform one of two tasks: (1) a 'physical reasoning task' in which they had to indicate whether the block tower was more likely to fall towards one or the other side (marked by a different floor color) and (2) a 'color task' in which they had to indicate whether there were more blue or more yellow blocks in the block tower. Participants were cued which task they would have to do in the upcoming trial through an instruction screen preceding the movie. Participants gave their responses using a button box. To avoid any potential confounds due to specific motor responses, participants switched the hand with which they pressed the buttons between runs 1 and 2. Each run consisted of 23 blocks (18 s), three fixation blocks as well as 10 blocks each of the physics and the color tasks. We used the physics task > color task contrast to functionally localize the frontoparietal physics system in each subject individually. Specifically, we intersected each subject's significance map ($p < 0.001$, uncorrected) with the previously published anatomical constraint parcels for the physics network.[7,8]

Dynamic objects localizer

In Experiment 1, the LOC was functionally localized using a dynamic face, object, scenes, scrambled objects (dynFOSS) localizer.[47] One run of the localizer consisted of 21 blocks (18 s), i.e., 5 fixation blocks as well as four blocks of each category showing five short (3 s) video clips of that category. Participants were instructed to perform a 1-back task and press a button whenever a video was repeated. Every participant completed one run of the dynFOSS localizer. To functionally localize LOC in each subject individually, we intersected the significance map of the objects > scrambled objects contrast ($p < 0.001$, uncorrected) with previously published anatomical constraint parcels for LOC.[47] V1 was also defined using the dynFOSS localizer. We identified V1 by intersecting the anatomical V1 voxels (using FreeSurfer labels) with the *all* > *fixation* contrast ($p < 0.001$, uncorrected), thus only considering voxels from the V1 region that responded significantly to visual stimulation.

Static objects localizer

In Experiment 2, LOC was functionally localized using a static food, objects, and color (statFOC) localizer. We used this localizer (and not the same as in Exp. 1) because, in addition to localizing LOC, this localizer includes a color > greyscale contrast that allowed us to test whether ventral regions with a preference for Stuff>Things overlap with color-sensitive regions, e.g., V4, see Figure S1. Briefly, one run of the localizer consisted of 19 blocks, i.e., 3 fixation blocks and 16 stimulus blocks. Each stimulus block showed 20 images from one stimulus category, i.e., a combination of food/non-food objects X color/grey-scale X intact/scrambled. Each image was presented for 750 ms with a 250 ms ISI. (Note that food vs nonfood object conditions were included in this localizer to test an unrelated hypothesis not discussed here. Participants were instructed to perform a 1-back task and press a button whenever an image was repeated. Every participant completed four runs of this localizer. We identified LOC in each subject individually using the objects (food and nonfood) > scrambled objects (food and nonfood) contrast across color/greyscale ($p <0.001$, uncorrected). We intersected this significance map with previously published anatomical constraint parcels for LOC.[47] V1 was also defined using the statFOC localizer. Specifically, we identified V1 by intersecting the anatomical V1 voxels (using FreeSurfer labels) with the *all* > *fixation* contrast ($p < 0.001$, uncorrected), thus only considering voxels from the V1 region that responded significantly to visual stimulation.

Eye movement recordings and analysis

To ensure that none of the effects we found in Experiment 1 were driven by differential eye movement patterns, we asked participants to fixate on the center of the screen, marked by a fixation target, throughout Experiment 2. We used an EyeLink 1,000 Eye-Tracker (SR Research) inside the scanner in the second scan session of Experiment 2. We were able to record eye movement data from 10 out of 14 participants, i.e., we could not record eye movements for four participants due to technical difficulties. Of the remaining 10 subjects, we recorded eye movements for 1–6 runs, i.e., on average 44% of runs per subject. We verified that our participants held fixation and that there were no differences in terms of the number, velocity, amplitude, and duration of remaining saccades, as well as the duration of fixations, see Figure S2.

QUANTIFICATION AND STATISTICAL ANALYSIS

fMRI data preprocessing

The fMRI data preprocessing was done using Freesurfer[46] (version 6.0.0) in Matlab and included alignment to the T1-weighted anatomical scan, motion correction, slice-time correction, linear fit to detrend the time series, and spatial smoothing with a Gaussian kernel (FWHM = 5 mm). For the univariate analyses, we derived the response magnitude of each voxel to each condition using a general linear model (GLM) which included experimental conditions except scenario (i.e., materials x intact/scrambled in Exp. 1 and materials x dynamic/static in Exp. 2) and 6 nuisance regressors based on the motion estimates (x, y, and z translation; roll, pitch, and yaw of rotation). All analyses were performed in each subject's native volume.

fMRI data analyses

Univariate fROI analysis

In Experiment 1, we first tested whether LOC and FPN are engaged when observing dynamic materials, manifested by a higher activation for intact videos than for scrambled controls as well as a higher activation for intact materials than the intact background-only control. This was done for each of the four materials independently. We tested whether we find the opposite pattern in V1. Next, we tested whether our fROIs respond with equal magnitude to all types of materials (HU0) or respond differentially between materials. Specifically, we used paired comparisons to test whether the response magnitude might be different for each material (HU1a), whether it is different for Things (rigid and nonrigid) vs Stuff (liquid and granular; HU1b), or whether the response magnitude might be different for rigid vs deformable (non-rigid, liquid, granular) materials (HU1c). To test these hypotheses, we used 10,000-fold non-parametric permutation tests in each ROI. Statistical tests were performed on the average responses to each condition in every subject (i.e., averaged across all voxels within an fROI). We corrected for multiple comparisons wherever appropriate, i.e., when comparing the four materials to control conditions and in paired comparisons between materials.

We conducted the same tests in Experiment 2 (except the comparison to the scrambled control, as there was no scrambled control), but separately for dynamic and static conditions. Additionally, we tested whether any of our fROIs responds differently to static compared to dynamic videos (main effect). Finally, we tested the hypothesis that we find the same pattern of response magnitudes to different materials for the dynamic condition of Experiment 2 (while participants were fixating) that we found for the intact condition of Experiment 1 (while participants were free viewing), i.e. that controlling eye movements will not make a difference.

Univariate whole brain analysis

In addition to the above-mentioned ROI analyses, we conducted two types of whole-brain analyses for the Stuff vs. Things and the Deformable vs. Rigid contrast: (1) traditional random effects analysis and (2) Group-Constrained Subject-Specific (GSS) analysis.[27] To increase the statistical power of both, we combined data from the intact dynamic conditions of Experiments 1 and 2 (note that this was preregistered only for Experiment 2 as we did not know about the second experiment yet when preregistering Experiment 1). Both types of analyses were performed in the volumetric space (not on the surface).

For the random effects, we used all runs of the Stuff and Things conditions for every participant. First, we projected each participants' individual contrast effect size map into FreeSurfer's fsaverage space. Then, we used FreeSurfer's "mri_glmfit" function to run a standard group-level random-effects analysis across all 28 subjects.

Following the GSS method of Fedorenko et al.,[27] we divided each participants data in even and odd runs and calculated two independent significance maps for Stuff vs Things for each subject. Next, both significance maps of each subject were projected into FreeSurfer's fsaverage space. We then used half of the data (odd runs) to find regions of overlap between subjects for a given contrast, e.g., Stuff > Things. Specifically, each individual's significance map was thresholded at p <.01 (uncorrected) and we identified voxels that showed an overlap of at least 3 participants. Next, we used a watershed algorithm to subdivide the group overlap map into discrete parcels. The resulting parcels were projected back into each participant's voxel space. To define each participant's fROI, we then selected the top 10% of voxels with the highest significance in the relevant contrast (again using the odd runs). Crucially, we then used the held-out, i.e. independent, data of each subject (even runs) to validate the effect, e.g. a significant Stuff>-Things or Stuff>Things response. We only considered parcels for further analysis if the effect was validated in held-out data. Furthermore, to ensure that the resulting fROIs were meaningful and represented something about the physical nature of the materials, e.g., Stuff vs Things, we employed three additional criteria: (1) significantly greater response to intact materials > intact control, (2) no significant difference between scrambled and intact version of the contrast (e.g., scrambled Stuff > scrambled Things), and (3) the fROI had a size of at least 10 voxels on average across participants. We only considered parcels relevant if they met those additional criteria. There were only two bilateral parcels (for the Stuff > Things contrast) that did not meet these additional criteria. Their location and response profile are shown in Figure S1. Of the remaining parcels we combined those of a given contrast that were directly adjacent to each other.