Frontoparietal regions engaged in physical prediction are also involved in spatial working memory

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Abstract

Regions in the frontoparietal cortex respond when people make physical predictions, and when they deploy goal-directed attention. Is there a common neural substrate for intuitive physics and attentional demand, in individual people? We addressed this question in an open dataset in which human adults (N=28) engaged in two tasks involving (i) physical prediction and (ii) spatial working memory while undergoing functional MRI. Using pre-registered functional region-of-interest (fROI) analyses, we asked whether voxels most engaged during working memory (working memory ROIs) are also engaged during physical prediction, and vice versa for physics ROIs. We found that working memory ROIs responded equally during physical and social prediction, and therefore were not selective for physical processing. However, physics ROIs responded more during hard than easy working memory trials. These findings suggest that regions in the 'intuitive physics network' are also involved in spatial attention, and/or working memory.

Keywords: intuitive physics; multiple demand network; spatial working memory

Introduction

Every day, we engage with the physical world in sophisticated ways. What mental processes support this suite of abilities ('intuitive physics'), and what are their neural substrates? One hypothesis is that intuitive physics relies on computations from many cognitive and neural systems, including spatial reasoning, working memory, and action planning. Another hypothesis is that intuitive physics relies on specialized mechanisms that are irreducible to the sum of these other computations. Here, we used neuroimaging to study the relationship between two of these abilities (Mather, Cacioppo, & Kanwisher, 2013): physical prediction on the one hand, and spatial working memory on the other.

Prior research has revealed that regions in the frontal and parietal cortices (e.g. premotor cortex, somatosensory association cortex) are involved in intuitive physics; these regions respond when people make physical predictions and encode variables like object mass and stability (Fischer et al., 2016; Pramod et al., 2022; Schwettmann et al., 2019). However, in separate studies, the same regions also appear to support general attentional demand (e.g. spatial working memory, motor inhibition) (Fedorenko et al., 2013; Duncan, 2010; Assem et al., 2020). In one study, Fischer et al. (2016) scanned participants undergoing both working memory and physical prediction tasks, and found an overlap in 44.7% of the voxels engaged in both tasks, suggesting some overlap in these mental operations. At the same time, working memory and intuitive physics are not redundant mental processes: Mitko and Fischer (2020) found that correlations between individual performance in physical inference (e.g. judging which way an unstable tower of blocks will fall) and spatial abilities (e.g. mental rotation, spatial working memory) were low (range = 0.04-0.29), despite high split-half reliability within each task.

This prior work leaves open *where* these two functions overlap in cortical space, and *how* they are related. Is intuitive physics another function of the multiple demand network, or is attentional demand another function of the intuitive physics network, or both?

Methods

Here, we present a case study focused on the two abilities that were least correlated in individual subjects according to prior research (Mitko & Fischer, 2020): physical inference and spatial working memory. We pre-registered a set of functional region-of-interest (fROI) analyses to study whether the voxels most engaged during physical prediction (versus social prediction; "physics ROIs") are also engaged during demanding (vs less demanding) spatial working memory, and vice versa, for "working memory ROIs". All the fROI data and scripts required to reproduce the results and figures from this paper are openly available on OSF.

Dataset and Tasks

The open dataset we analyzed for this study can be found at https://openneuro.org/datasets/ds004934, and includes data from 28 adult participants (M age = 26.5y, 17 female, 50% White, 26 right-handed). In brief, each subject was scanned on two tasks over two runs: (i) social vs physical prediction and (ii) hard vs easy spatial working memory problems (see Liu, Lydic, Mei, & Saxe, 2024 for full task descriptions).

Overview of Analyses

We used fmriprep (Esteban et al., 2019) to pre-process the data: see here for a full description. We studied responses in 8 parcels, which we made by combining multiple demand parcels available at https://evlab.mit.edu/funcloc/ with parcels selective for physical reasoning from Liu et al. (2024): left and right precentral cortex, anterior parietal cortex, middle parietal cortex, and posterior parietal cortex (Figure 1B). We defined fROIs most engaged during physical (vs social) prediction and during difficult (vs easy) attentional demand from each run, for each subject, for each parcel, by taking the top 10% of voxels

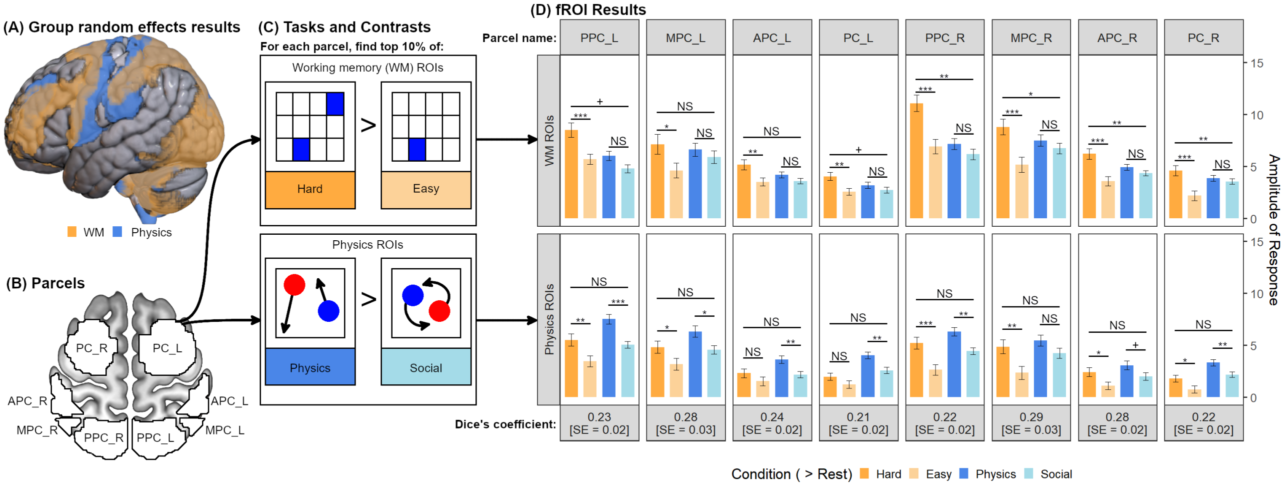

Figure 1: (A) Whole-brain map of the contrasts hard > easy (WM, orange) and physics > social (blue), non-parametric group random effects analysis, thresholded at $p < 0.05$, applying a threshold free cluster enhancement (TFCE) family-wise correction. (B) Parcels in premotor and parietal cortex (PC = precentral; APC = anterior parietal; MPC = middle temporal; PPC = posterior parietal) (C) Tasks and contrasts used for fROI selection. (D) Results for WM and physics fROIs within each parcel, and Dice's Coefficient (overlap between fROIs). NS indicates $p > .1$; + $< .1$; * $< .05$; **$< .01$; *** $< .001$, two-tailed

that responded to physics > social prediction trials, and hard > easy working memory trials. See Figure 1 (Figure 1C). This procedure resulted in 16 fROIS: 8 physics fROIs, 8 working memory fROIs, with one fROI per run.

To test whether physics and working memory fROIs were selective for the task upon which they were defined, we fit a linear mixed effects model in R (using the lme4 package: Bates et al., 2015) per fROI with an interaction between task (working memory or physical prediction) and condition (preferred vs dis-preferred, i.e. hard vs easy for working memory; physics vs social for physical prediction), and a random intercept for participant. The responses of an fROI involved in both physical prediction and working memory would result in a main effect of condition (preferred > dis-preferred), with no interaction between task and condition. In contrast, responses in an fROI that is selective for the task it was defined on would lead to an interaction of condition and task, such that the fROI shows a preferred response only for its matching task. We also measured the extent of overlap between fROIs by computing Dice's Coefficient (Wilson et al., 2017) between each pair of fROIs within each parcel.

Results

Figure 3 shows the two main results. First, we found a low-moderate (Dice's Coefficient = 0.21-0.28; Wilson et al., 2017) degree of overlap between working memory and physics ROIs within each parcel. Second, we found an asymmetry in regions in the frontoparietal cortex most engaged by working memory and physical prediction. Working memory fROIs were not specifically engaged during physical processing, and responded during both physical and social prediction, especially in the right hemisphere (Figure 1D; top row). By contrast, all physics fROIs showed a main effect of condition, and 6 out of 8 fROIs responded more during hard than easy spatial working memory trials. Cortical regions engaged in physical processing are involved in spatial working memory, but not vice versa.

Discussion

The most appealing hypothesis relating the multiple demand and intuitive physics networks, *a priori*, is that intuitive physics is yet another function of the domain-general multiple demand network. Yet the current findings turn this idea on its head. Using the gold-standard method for identifying the MD network in individual participants (Fedorenko, 2021), we found that the frontoparietal portions of this network were not specifically engaged for physical processing. Using the same method to identify frontoparietal physics fROIs, we found that in contrast, physics fROIs were also engaged when people deploy spatial attention. This is striking because our physics ROIs were not defined based on spatial attention or attentional demand; both the social and physical conditions of the task used for localization required people to track and predict the movements of objects, and were matched for difficulty (accuracy: physical M(SD) = 80.0(9.15)% vs social M(SD) = 81.1(12.5)%; p = .55).

One interpretation of this finding is that frontoparietal physics regions are not selective for intuitive physics. A second is that these regions are specialized for physical reasoning, but physical reasoning depends on spatial attention. To adjudicate between these accounts, future research can ask whether physics fROIs are responsive during other tasks that ado not involve spatial attention (e.g. motor inhibition). In asking questions about shared vs distinct functions of cortical regions, our results suggest that spatial overlap between regions engaged in different tasks does not necessarily entail symmetrically shared function.

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