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The mind's eyes: Distinct neural correlates of spatial and object imagery

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ABSTRACT

Mental imagery has long been central to understanding human cognition, yet its neural basis remains debated. Although neuroimaging studies often treat mental imagery as a unitary construct, behavioral research suggests a dissociation between object imagery (visualizing static objects in detail) and spatial imagery (visualizing dynamic transformations of objects and their relations). To test whether these forms of imagery rely on distinct neural systems, we conducted a pre-registered activation likelihood estimation (ALE) meta-analysis of 46 *f*MRI and PET studies ($N = 591$; 772 foci). Conjunction analyses revealed overlapping activity across the medial frontal gyrus, precuneus, and inferior parietal lobule, suggesting a common frontoparietal network underlying general imagery processes. However, contrast analyses revealed patterns of activation dependent on imagery type (object vs. spatial). While spatial imagery was associated with unique activation in bilateral superior parietal lobules, consistent with dorsal visual stream involvement, object imagery elicited unique activation in left-lateralized frontoparietal and ventral stream regions. These findings parallel the dual-stream model of visual processing, suggesting that object imagery, like object recognition, engages the ventral "what" stream, whereas spatial imagery, like spatial perception and transformation, engages the dorsal "where/how" stream. Theoretically, this distinction offers a new perspective on an old debate, namely, the extent to which mental imagery mirrors perception. Our findings suggest that the answer depends on the type of imagery engaged, pointing to task-specific alignment between imagery and perception. Practically, these results invite a reappraisal of how imagery relates to academic, occupational, and everyday behaviors, raising new questions about how different forms of imagery may support distinct cognitive processes.

1. Introduction

From ancient philosophy to modern-day neuroscience, mental imagery has been central to the effort to understand mind, brain, and behavior (MacKisack et al., 2016). Broadly construed as one's ability to 'see' with the 'mind's eye' and measured by asking people to visualize certain concrete objects (e.g., household items), visual mental imagery has been the subject of fierce philosophical and scientific debate. And not without good reason. For some scholars, visual mental imagery (hereafter referred to as mental imagery) lies at the heart of theories and models of intelligence, imagination, and creativity. For example, Aristotle ascribed critical importance to the mind's capacity to form mental images or *phantasia*: "The soul never thinks without a *phantasma*" (Aristotle, 1984, p. 431). Other scholars, such as Plato, cast serious doubt on the role of mental imagery in complex thought (MacKisack et al., 2016). Proponents of this view maintain that thought is fundamentally abstract and propositional. Mental images are epiphenomenal; a by-product of the brain's primary means of processing information through a syntactically structured system.

The advent of neuroimaging marked a critical advance in the 'imagery debate.' For the first time, researchers were able to test the extent to which perceiving an object and imagining an object relied on common brain regions. For example, does imagining an apple use the same brain regions as those used when actually viewing an apple? There is now considerable evidence that visual imagery and visual perception recruit at least partially overlapping neural structures. This has led some to conclude that "mental imagery functions as if it were a weak form of perception" (Pearson et al., 2015). These findings have given credence to ancient philosophical convictions, including those espoused by Hume, that there is no fundamental difference between something perceived and something imagined. Despite the many significant insights and affordances made possible through neuroimaging, including the ability

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to visualize visualization itself, many questions remain.

Different studies tend to report different neural correlates of mental imagery. For example, two recent meta-analyses on mental imagery revealed somewhat different overall findings, particularly with respect to the involvement of early visual cortex (see Spagna et al., 2021; Winlove et al., 2018). Whereas Winlove et al. (2018) identify a broadly distributed imagery network that overlaps with visual perception, Spagna et al. (2021) report no reliable evidence for early visual cortex involvement during visual mental imagery. Other reviews provide similar claims to Winlove et al. (2018), while also acknowledging considerable variability in the neural correlates reported between studies (Pearson, 2019; Pearson et al., 2015). Thus, despite broad agreement that mental imagery engages visual processing systems, the neural correlates of mental imagery remain underspecified and a topic of ongoing debate.

One reason for these inconsistencies may lie in how mental imagery is conceptualized. Is mental imagery best conceived as a unified central construct, or as multiple constructs serving different functions? Said differently, are there different types of mental imagery? A review of the literature suggests that mental imagery is commonly conceived as a unitary construct, with notable exceptions expanded on below. For example, in both meta-analyses mentioned above, the primary analysis collapses across a wide range of imagery tasks (e.g., imagery of objects, scenes, faces, and spatial transformations), which, arguably, differ in their cognitive demands and functional roles. By treating mental imagery as a unitary construct, we may be obscuring key functional differences between imagery types.

As argued below, there is reason to hypothesize two distinct forms of visual mental imagery; one that involves visualizing static images of an object or scene and another that involves visualizing and applying dynamic spatial transformations to an object or scene. While the first type of imagery is often referred to as object imagery, the second type of imagery is often referred to as spatial imagery. Returning the apple example above, might the neural correlates associated with imagining an apple in all its colour and detail differ from those involved in mentally cutting, rotating, or transforming it in some way? Decades of research provide reason to believe so, suggesting that object and spatial imagery form a central division in human cognition. Yet, this distinction is commonly ignored, with scholars routinely conflating object and spatial imagery as one and the same. The purpose of the present study is to test this hypothesis through an ALE meta-analysis, examining the extent to which object-based mental imagery is distinct from spatial mental imagery. In doing so, this review and meta-analysis aims to provide a theoretically and empirically differentiated account of the neural correlates of mental imagery.

Hereafter, we devote the majority of this Introduction to presenting an argument for why there is reason to suspect that object mental imagery and spatial mental imagery are dissociable, at least to some extent. We begin by reviewing the behavioral evidence in support of this view and then turn our attention to the neural evidence suggesting distinct neural networks. In doing so, we aim to offer an explanation for the discrepant findings of the neural correlates of mental imagery. Additionally, the implications of this work include new insights into contradictory findings of relations between mental imagery and a host of behavioral outcomes, including learning and performance in the Science, Technology, Engineering, and Mathematics disciplines (STEM).

2. Behavioral evidence for different types of mental imagery

Until relatively recently, it was assumed that mental imagery was a unitary, undifferentiated construct (see Blajenkova et al., 2006). The prevalence of this viewpoint can be seen in the myriad studies that have attempted to classify individuals as either ‘good’ or ‘bad’ imagers or measure it along a unidimensional continuum (Hollenberg, 1970; Paivio, 1983). Accordingly, as a behavioral trait, mental imagery was typically conceived as a single faculty. The mind’s eye (notably singular) was likened to vision itself and, as such, measured in terms of acuteness (e.g., see Paivio, 1971; Richardson, 1977). The widespread general use of the term *mental imagery* further speaks to its ubiquity as a unitary construct. According to Farah and colleagues (1988), “…imagery researchers have been misled by the use of a common term, ‘imagery,’ to label what are in fact two distinct types of representation.” However, such a distinction was not incorporated into the measurement of mental imagery until the early 21st century; it was only then that researchers began to measure mental imagery as multidimensional, distinguishing between imagery for objects and imagery for spatial transformations (e.g., see the Object-Spatial Imagery Questionnaire (OSIQ) developed by Blajenkova et al., 2006; see also Kozhevnikov et al., 2005).

In distinguishing between object and spatial imagery, researchers have since yielded convincing evidence in favour of this divide. For example, Kozhevnikov et al. (2005) found evidence of three distinct cognitive profiles; verbalizers, object imagers, and spatial imagers. Whereas the verbalizers (i.e., those preferring to process information through verbal-analytical means) performed at an intermediate level across imagery tasks, the visualizers (i.e., those preferring to process information visually) could further be divided into object and spatial imagers. While the object imagers scored poorly on spatial imagery tasks (e.g., mental rotation), they excelled on object imagery tasks (e.g., degraded pictures task). The opposite was true of spatial imagers, who excelled at spatial imagery tasks but performed poorly on the object imagery tasks. Based on these findings, the authors defined object imagers as those who tend to construct colourful, pictorial, and high-resolution images of individual objects and spatial imagers as those who tend to use imagery to schematize the spatial relations amongst objects and to transform and manipulate objects. Furthermore, while object imagers were found to encode and process images holistically, as a single perceptual unit, spatial imagers generated and processed images using a part-by-part analytical approach. Lastly, this study also found that while scientists and engineers excelled in spatial imagery, preferring spatial strategies, visual artists excelled in object imagery, preferring object-based strategies.

Several follow-up studies provide additional support for the findings of Kozhevnikov et al. (2005). Not only is there evidence of two distinct forms of visualization, but these two forms tend to be negatively related to one another (Borst and Kosslyn, 2010; Kozhevnikov et al., 2010; Sokolowski et al., 2019). Those who report high spatial imagery tend to report low object imagery and vice versa. Critically, differences in self-report imagery preferences have been found to correlate with differences in more objective measures of visual vs spatial processing. For example, Borst and Kosslyn (2010) found correlations between spatial visualization skills (i.e., paper folding, paper form board test, and visual-spatial items on Raven’s Matrices) and a novel task assessing individual differences in spatial imagery. Conversely, spatial visualization skills shared essentially no correlation with object imagery. Kozhevnikov et al. (2010) reached a similar conclusion, finding that across five different age groups and various professional specializations (e.g., artists, scientists, architects), individuals with above-average spatial visualization skills (e.g., scientists) demonstrated below-average object visualization skills, with the opposite true for individuals with above-average object visualization skills (e.g., artists). In short, there appears to be a trade-off in object versus spatial visualization abilities, where a strength in one aspect of imagery tends to be accompanied by relative weakness and below-average performance in the other.

This fundamental difference in imagery type—object vs. spatial—may also help explain the inconsistent relations between self-report imagery vividness and its relation to a host of other behaviors, including performance in mathematics and science (Bates et al., 2021; Sokolowski et al., 2026). When imagery is measured according to object vs. spatial components, clear patterns of predictive relations emerge; namely, strong associations are observed between spatial imagery and STEM performance (Sokolowski et al., 2026), whereas objective imagery is correlated with visual skills, such as performance in the visual arts

(Kozhevnikov et al., 2010).

In summary, while mental imagery was once considered a general ability, there is increasing behavioral evidence indicating a key distinction between object and spatial imagery. This raises the intriguing possibility that object and spatial imagery rest on distinct neural underpinnings.

3. Neural evidence for different types of mental imagery

Although it remains common practice in neuroimaging studies, including meta-analyses, to collapse across object and spatial imagery (e.g., Spagna et al., 2021; Winlove et al., 2018), decades of research suggest that these forms of imagery are dissociable and underpinned by partially distinct neural systems (e.g., Pearson, 2019). Some of the earliest clues that the brain processed visual and spatial information differently came from lesion studies (e.g., see Levine et al., 1985; Farah, 1989). For example, one early case study revealed that a patient with brain damage to the posterior parietal region had difficulties determining the locations of objects from memory, but not the ability to describe their appearance from memory (Farah et al., 1988). For example, he was unable to recall the location of shops in his neighborhood or the layout of his furniture, but was able to give accurate and detailed descriptions of the appearances of objects from memory. Another patient, with brain damage to the bilateral inferior temporal, showed the opposite pattern. This patient was unable to draw or describe the appearances of objects from memory, but was able to accurately recall and describe the spatial locations of objects and landmarks from memory. Crucially, other case studies reported similar findings, leading to the highly influential dual-streams model of visual processing (Goodale and Milner, 1992; Milner and Goodale, 2006; Mishkin et al., 1983; Ungerleider and Mishkin, 1982).

Accordingly, this model posits a fundamental division in the visual system into two processing streams, one that runs ventrally and one that runs dorsally. The ventral pathway, sometimes referred to as the ‘what’ stream, runs from the occipital lobe to the temporal lobe, and processes the visual appearance of objects. The dorsal pathway, sometimes referred to as the ‘where/how’ stream, runs from the occipital lobe to the parietal lobes, and processes spatial information, such as the location of objects as well as object transformation (e.g., mental rotation). As described above, damage to the dorsal pathway results in compromised spatial processing, but not object recognition. Damage to the ventral pathway, on the other hand, results in compromised object recognition and the processing of visual features, but not spatial processing.

Critically, this double-dissociation does not only apply to perception (i.e., vision), but also to imagery (Farah et al., 1988; Pearson, 2019). For example, damage to the ventral stream often results not only in impaired recognition of common objects, but also the ability to imagine those same objects in the ‘mind’s eye.’ The opposite is true with damage to the dorsal stream, where one’s ability to visualize locations and perform various spatial transformations is impaired, but not their ability to visualize objects (e.g., see Farah et al., 1988; Farah, 1989). Taken together, evidence suggests that the structure of imagery may parallel the dual-streams structure of vision. Accordingly, we would expect on average, that spatial imagery tasks, such as those that involve mental rotation, would be associated with higher concentrations of activity in the parietal lobe, whereas object imagery tasks would be associated with higher activity in the temporal regions.

4. The present study

Although both behavioral and neuroscience research highlight a distinction between object and spatial imagery, their respective neural correlates have yet to be systematically examined. Even the most comprehensive reviews and meta-analyses on mental imagery fail to distinguish between these two forms (e.g., Spagna et al., 2021; Winlove et al., 2018). As argued above, this represents a key shortcoming of the literature and may help explain the inconsistent findings and interpretations regarding the neural basis of mental imagery. Moreover, while the dual-stream model of visual processing has been well established for visual perception, it remains unclear whether, and to what extent, mental imagery conforms to this same functional organization. If mental imagery does parallel the dual-stream model, this would provide further evidence for shared mechanisms between perception and imagery, contributing to the longstanding debate about whether imagery mirrors perception. From a more practical standpoint, evidence for distinct forms of mental imagery could not only inform our theoretical understanding of its cognitive correlates but also shed light on the mixed findings linking mental imagery to a range of behavioral outcomes, including performance in STEM disciplines.

Against this background, the present study was designed to test the extent to which object and spatial imagery converge and diverge in the human brain. To do so, we conducted a meta-analysis on the neural correlates of object vs. spatial imagery. For the purposes of this study, spatial imagery tasks were defined as those requiring mental rotation, a quintessential form of spatial transformation, whereas object imagery tasks were defined as those requiring individuals to form and recall static images of objects. We acknowledge the possibility that these categories may themselves be further subdivided. For example, mental rotation represents one form of dynamic spatial transformation, whereas other spatial tasks, such as mental paper folding, may engage partially distinct neural processes. Thus, our goal is not to suggest that spatial and object imagery are homogeneous in their makeup, but rather to test the broader claim that these two forms of imagery constitute a major first-order cognitive divide. Accordingly, activation likelihood estimation (ALE) meta-analyses were conducted separately for spatial and object imagery. To examine common and distinct neural substrates, we conducted a conjunction analysis to identify overlapping activation patterns and contrast analyses to determine regions selectively engaged by spatial versus object imagery. Based on theories of shared mechanisms between perception and imagery, we hypothesized that spatial imagery would primarily engage regions within the dorsal visual processing stream (the "where/how" pathway), supporting spatial transformations, while object imagery would preferentially engage regions within the ventral stream (the "what" pathway), supporting detailed visual representation.

5. Methods

The methods and analyses for the present study were pre-registered on the Open Science Framework (OSF-Preregistration) and all reported procedures adhere to this pre-registration. This study used data from and contributed data to the BrainMap database (https://brainmap.org/). All meta-analytic tools employed are registered with the Neuroimaging Informatics Tools and Resources Clearinghouse (NITRC) and the Neuroscience Information Framework (NIF).

5.1. Literature search

A systematic literature search was conducted using a stepwise approach. First, an initial search was performed using the PUBMED and PsycINFO databases. Core search terms applied to both the spatial and object imagery searches included: “PET,” “positron emission tomography,” “fMRI,” “functional magnetic resonance imaging,” “neuroimaging,” “imaging,” and “mental imagery.” Additional search terms were specific to each imagery type:

Spatial imagery/mental rotation: (mental rotation [Title/Abstract] OR mental imagery [Title/Abstract] OR visual-spatial [Title/Abstract] OR visuospatial [Title/Abstract] OR object rotation [Title/Abstract] OR mental transformation [Title/Abstract]) AND (fMRI [Title/Abstract] OR functional magnetic resonance imaging [Title/Abstract] OR PET [Title/Abstract] OR positron emission tomography [Title/Abstract] OR neuroimaging [Title/Abstract])

Object imagery: (visual imagery [Title/Abstract] OR object imagery [Title/Abstract] OR imagination [Title/Abstract]) AND (PET [Title/Abstract] OR positron emission tomography [Title/Abstract] OR fMRI [Title/Abstract] OR functional magnetic resonance imaging [Title/Abstract] OR neuroimaging [Title/Abstract] OR imaging [Title/Abstract] OR mental imagery [Title/Abstract]).

Second, reference lists of identified articles were manually reviewed to uncover additional relevant studies not captured in the initial search. Papers included in previous meta-analyses examining visual imagery (Spagna et al., 2021; Winlove et al., 2018) were also consulted for both included studies and cited references. This process was repeated iteratively until no further eligible articles were identified. All searches were performed by the second author in February 2024. The results pulled from the databases were reviewed by the third author to verify inclusion compatibility. Furthermore, all inclusions were independently verified by the BrainMap team to ensure they are appropriate for ALE whole-brain dataset analysis.

5.2. *Inclusion and exclusion criteria*

1. Studies must have included a spatial imagery and/or object imagery task.

   Spatial Imagery Task: Studies must have included a mental rotation task requiring participants to mentally rotate 2D or 3D stimuli.

   Studies involving the mental rotation of body parts (e.g., hands) or anatomical appendages were excluded due to specialized neural processing for faces and bodies (Downing et al., 2001; Tsao and Livingstone, 2008).

   Object Imagery: Participants must have been instructed to imagine concrete physical objects—real-world items with distinct and recognizable appearances (e.g., chair, spoon, basketball).

   For object imagery studies, tasks where participants were asked to imagine places, people, faces, monuments, or objects *in motion* were excluded to avoid confounds with autobiographical memory and dynamic spatial processing.

2. Studies must include a sample of healthy adult participants between 18 and 65 years of age.
3. Studies must report whole-brain group analyses with stereotactic coordinates in either MNI or Talairach/Tournoux space.

   Studies relying solely on ROI analyses or multivariate approaches were excluded due to potential inflation of regional significance (Müller et al., 2018). ROI focused studies were included if whole-brain results were separately reported and clearly labeled.

4. Neuroimaging must have been conducted using fMRI or PET.
5. Studies were included if they used *active* or *passive* control conditions.

   Active controls refer to tasks that kept participants mentally

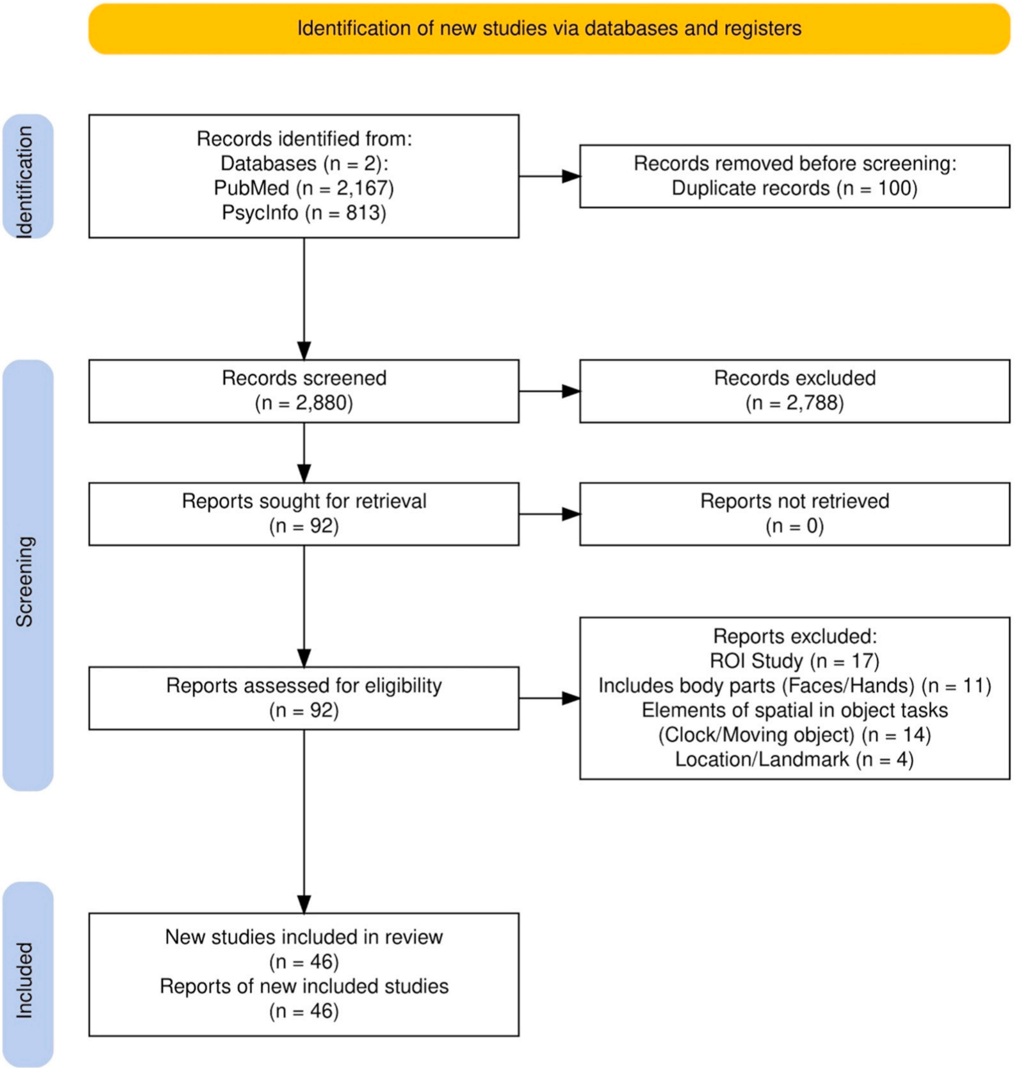

Fig. 1. PRISMA flow diagram illustrating the identification, screening, eligibility assessment, and inclusion of studies in the present meta-analysis.

engaged but did not require imagery (e.g., passive listening, abstract word presentation, simple motor responses).

Passive controls refer to rest or absence of task instructions.

Contrasts aimed at differentiating neural responses to specific object categories (e.g., tools vs. non-tools) were excluded.

6. Studies must have been published in English.

5.3. Included studies

Forty-six studies from the literature search met the inclusion/exclusion criteria and were included in the meta-analyses. Full details of the literature search and study selection process are provided in Fig. 1. All included studies contained either a spatial or object visual imagery task. Following study identification and screening for whether the study met inclusion criteria, BrainMap database was examined using Sleuth (version 3.0.4) to determine which studies were already pre-coded. Studies not yet available in the database were manually coded using Scribe (version 3.6; Fox and Lancaster, 2002) and submitted to the BrainMap team for validation and integration. The full set of eligible studies—both pre-coded and newly coded—was compiled using Sleuth. Together, these studies had a cumulative sample size of 591 healthy adult human participants and reported 772 activation foci. Activation foci were standardized to MNI space using BrainMap's tal2mni tool and extracted by subject group. Descriptive information for the included studies is reported in Tables 1 and 2.

5.4. Meta-analytic processing

Meta-analyses were conducted using the revised Activation Likelihood Estimation (ALE) algorithm implemented in GingerALE (version 3.0.2; Eickhoff et al., 2009, 2012, 2017; Turkeltaub et al., 2012). ALE assesses the convergence of reported activation peaks (foci) across independent studies by modeling stereotactic coordinates as three-dimensional Gaussian probability distributions. These distributions account for spatial uncertainty due to inter-subject and inter-template variability and are centered on the reported peak coordinates to generate modeled activation (MA) maps. MA maps from individual studies are then aggregated to compute ALE scores for each voxel, yielding a probabilistic map of activation convergence. To determine statistical significance, ALE scores are compared to null distributions generated by randomly redistributing the same number of foci across the brain. This approach controls for spurious convergence and tests whether observed clustering exceeds what would be expected by chance. The algorithm also incorporates sample size, by weighting the influence of each study by the number of participants (Eickhoff et al., 2012). Finally, in line with current recommendations, data were organized by subject group rather than by contrast to correct for within-group dependence, thus reducing bias from multiple contrasts derived from the same participants (Turkeltaub et al., 2012).

5.5. Single-file analyses

GingerALE (version 2.3.6) was used to compute single-file ALE meta-analyses for 1) all visual imagery (combining spatial and object imagery contrasts), 2) spatial imagery and 2) object imagery. All 46 empirical studies identified through the literature search and inclusion criteria were included to create the visual imagery (591 subjects, 100 contrasts, 772 foci), 27 studies were included in the spatial imagery map (350 subjects, 56 contrasts, 367 foci), and 19 studies were included in the object imagery map (241 subjects, 44 contrasts, 405 foci). Thus, all three meta-analyses met the criterion for adequate power, which is 17–20 experiments for each single dataset meta-analysis (Eickhoff et al., 2016). All single-file ALE analyses were thresholded using a cluster-level correction of 0.05 with a cluster-forming (uncorrected) threshold of $p < .001$, generated from 1000 threshold permutations, which is in line with recommendations for the optimal thresholding approach currently available (Eickhoff et al., 2012). The resulting single-condition ALE maps were subsequently used to perform conjunction analyses to identify regions commonly activated across spatial and object imagery, and contrast analyses to isolate regions selectively associated with each imagery type.

5.6. Conjunction and contrast analyses

GingerALE (version 3.0.2) was used to compute conjunction and contrast analyses to identify regions of overlapping and distinct activation between spatial and object imagery. Conjunction analyses revealed areas of shared activation across the two imagery conditions, while contrast analyses identified regions showing significantly greater convergence for one condition relative to the other (Spatial Imagery > Object Imagery; Object Imagery > Spatial Imagery). All conjunction and contrast analyses were conducted using an uncorrected threshold of $p < .01$ with 10,000 permutation tests and a minimum cluster volume of 50 mm^3 . In line with prior meta-analyses (e.g., Hawes et al., 2019), an uncorrected threshold is considered appropriate in this context, as only clusters that passed the strict thresholding used for the single-condition ALE maps (cluster-level FWE $p < .05$, voxel-level $p < .001$) were included in these comparisons. The only alternative correction available for conjunction and contrast analyses is false discovery rate (FDR), which is not recommended for use with spatially smooth Gaussian data (Chumbley and Friston, 2009).

5.7. Visualizations

For the single-file maps, conjunction and contrast analyses, Mango (version 4.0.1; RII, 2013) was used to view the thresholded 3D ALE maps and extract MNI-specific anatomical labels for each significant cluster. Additionally, MATLAB was used in conjunction with the BrainNet Viewer toolbox (Xia et al., 2013) to generate three-dimensional renderings of the activation maps for presentation.

6. Results

6.1. Single-dataset meta-analyses

Single-dataset ALE meta-analyses were computed to examine converging foci for visual imagery (both spatial and object: $k = 46$, $N = 591$), spatial imagery ($k = 27$, $N = 350$) and object imagery ($k = 19$, $N = 241$).

6.2. Visual imagery (spatial and object)

The visual imagery single-file map, which included all contrasts reported in Tables 1 and 2, revealed convergent regions of brain activation across the bilateral frontal and parietal lobes, as well as the left occipital lobe (Fig. 2, Table 3).

6.3. Object imagery

The object imagery single-file map, which included all contrasts reported in Table 1 listed as 'object' under the column 'Map Inclusion', revealed activation in the left inferior parietal lobule, precuneus, precentral gyrus, middle frontal gyrus, fusiform gyrus, cingulate gyrus, subgyral regions, and claustrum; the right medial frontal gyrus; and bilaterally in the lingual gyrus (Fig. 2, Table 3). These findings indicate a predominantly left-lateralized frontoparietal activation pattern associated with object imagery.

6.4. Spatial imagery

The spatial imagery single-file map, which included all contrasts reported in Table 2 listed as 'spatial' under the column 'Map Inclusion',

Table 1
Summary of studies included in the object imagery meta-analysis.

1st Author	Year	Journal	N	Method	Age	Gender	Tasks	Contrast/s	Control
Amedi A.	2005	Neuron	9	fMRI	39	5 M 4 F	Imagined Objects/Scenes, Visual Object Identification	Visual Imagery Task (VI) vs Visual Objects Recognition Task (VO)	Passive
Boccia M.	2015	Human Brain Mapping	15	fMRI	25	8 M 7 F	Imagined Objects/Scenes	Visuo-spatial Imagination (Imagery)	Passive
D'Esposito M.	1997	Neuropsychologia	7	fMRI	28	7 M	Imagined Objects/Scenes, Passive Listening	Concrete > Abstract	Active
de Borst A. W.	2012	NeuroImage	10	fMRI	26	2 M 8 F	Imagined Objects/Scenes	Imagery vs Baseline	Passive
Formisano E.	2003	Neuron	6	fMRI	24	3 M 3 F	Imagined Objects/Scenes, Imagined Movement	Experimental	Passive
Gardini S.	2009	Psychological Research	13	fMRI	36	8 M 5 F	Imagined Objects/Scenes	Generating a general image	Active
							Imagined Objects/Scenes	Generating a specific image	
Gulyas B.	2001	Brain Research Bulletin	10	PET	32	10 M	Imagined Objects/Scenes	Alphabet Task (A) vs Rest (R)	Passive
							Passive Listening, Imagined Objects/Scenes	Alphabet Task (A) vs Internal Listing Task (L)	
							Imagined Objects/Scenes	Anthem Task (H) vs Rest (R)	
							Passive Listening, Imagined Objects/Scenes	Anthem Task (H) vs Internal Listing Task (L)	
							Imagined Objects/Scenes, Passive Listening	(A-L)-(R-L)	
							Imagined Objects/Scenes, Passive Listening	(H-L)-(R-L)	
Handy T. C.	2004	European Journal Of Cognitive Psychology	15	fMRI	24	5 M 10 F	Imagined Objects/Scenes	Picture recall > Rest	Passive
							Imagined Objects/Scenes	Noun recall > Rest	
Kosslyn S. M.	2005	Cognitive, Affective, & Behavioral Neuroscience	16	PET	22	16 M	Imagined Objects/Scenes, Finger Tapping/Button Press, Fixation	Verbal - Baseline	Active
Kosslyn S. M.	1995	Nature	12	PET	NS	12 M	Imagined Objects/Scenes	Small Images - Listening Baseline	Active
							Imagined Objects/Scenes	Medium Images - Listening Baseline	
							Imagined Objects/Scenes	Large Images - Listening Baseline	
Kosslyn S. M.	1997	Neuroimage	6	PET	23	6 M	Imagined Objects/Scenes, Visual Object Identification	(Imagery - Imagery Baseline) - (Noncanonical - Canonical)	Active
Kukolja J.	2006	Neuropsychologia	20	fMRI	25	20 M	Imagined Objects/Scenes, Visual Object Identification	Imagery vs. visual (RI + LI > RV + LV)	Active
							Imagined Objects/Scenes	Imagery vs. catch trials (RI + LI > 2CT)	
							Imagined Objects/Scenes	Left imagery vs. catch trials (LI > CT)	
							Imagined Objects/Scenes	Right imagery vs. catch trials (RI > CT)	
							Imagined Objects/Scenes	Left imagery vs. catch trials (LI > CT), masked with right imagery vs. catch trials (RI > CT)	
							Imagined Objects/Scenes	Right imagery vs. catch trials (RI > CT), masked with left imagery vs. catch trials (LI > CT)	
Mazard A.	2005	Cognitive Brain Research	15	fMRI	23	11 M 4 F	Imagined Objects/Scenes	Imagery - Baseline	Active
Mechelli A.	2004	Cerebral Cortex	5	fMRI	28	2 M 3 F	Imagined Objects/Scenes, Fixation	Imagery > Imagery-Control (Participant 1)	Passive
							Imagined Objects/Scenes, Fixation	Imagery > Imagery-Control (Participant 2)	
							Imagined Objects/Scenes, Fixation	Imagery > Imagery-Control (Participant 3)	
							Imagined Objects/Scenes, Fixation	Imagery > Imagery-Control (Participant 4)	
							Imagined Objects/Scenes, Fixation	Imagery > Imagery-Control (Participant 5)	
Mellet E.	1998	NeuroReport	8	PET	23	8 M	Imagined Objects/Scenes	Concrete Word Condition (CONC) - Rest (REST)	Passive
							Imagined Objects/Scenes, Passive Listening	Concrete Word Condition (CONC) - Abstract Words (ABST)	
Olivetti Belardinelli M.	2009	Acta Psychologica	9	fMRI	25	9 F	Imagined Objects/Scenes	Imagery (Visual) > Control (Abstract)	Passive
Trojano L.	2000	Cerebral Cortex	7	fMRI	27	4 M 3 F	Imagined Objects/Scenes	Imagery	Active
							Imagined Objects/Scenes	Imagery vs Baseline	
							Imagined Objects/Scenes, Counting/Calculation	Imagery vs Syllables	
							Imagined Objects/Scenes, Visual Object Identification	Imagery vs Perception	
Yomogida Y.	2004	Cerebral Cortex	43	fMRI	25	NS	Imagined Objects/Scenes	Word object imagery > Baseline	Passive
							Imagined Objects/Scenes	Word Synthesis > Baseline	
							Imagined Objects/Scenes	Picture Object imagery > Baseline	
							Imagined Objects/Scenes	Picture Synthesis > Baseline	
Zvyagintsev M.	2013	European Journal of Neuroscience	15	fMRI	25	8 M 7 F	Imagined Objects/Scenes, Counting/Calculation	Visual > Baseline	Active

Note. NS = not stated; Foci, number of foci reported in contrast; fMRI, functional magnetic resonance imaging; PET, positron emission tomography; N = sample size of each study; M = Male, F = Female

revealed convergent regions of brain activation in bilateral frontal and parietal lobes, as well as the left occipital lobe (Fig. 2, Table 3).

6.5. *Conjunction ALE map (Spatial and object imagery)*

A conjunction analysis was computed to identify which brain regions were activated by both spatial and object imagery single dataset ALE maps. Significant clusters of brain activation for spatial and object imagery converged in the left Inferior Parietal Lobule, Precuneus, Cingulate Gyrus and Sub-Gyral; bilateral Medial Frontal Gyrus (Fig. 3, Table 4). All brain regions reported in this conjunction analysis were significant at $p < .001$ with a minimum cluster size of 50.

6.6. *Contrast ALE maps (Spatial > Object imagery; Object > Spatial imagery)*

Contrast analyses that compared the spatial versus object imagery single dataset ALE maps were conducted to reveal which brain regions were specifically activated by different types of visual imagery. Contrasting spatial > object imagery resulted in activation in the left precuneus and right Superior Parietal Lobule, while contrasting object > spatial imagery resulted in specific activation in the left Fusiform Gyrus, Inferior Frontal Gyrus, Precentral Gyrus, Angular Gyrus, Cingulate Gyrus, Precuneus, Sub-lobar Insula and Sub-lobar Claustrum; bilateral Lingual Gyrus (Fig. 3, Table 4). All brain regions that were significantly associated with these contrast analyses were significant at $p < .001$ with a minimum cluster size of 50.

7. Discussion

Up to this point, neuroimaging research has largely treated object and spatial imagery as equivalent. To imagine an apple is to imagine an apple, regardless of whether the apple is visualized as a static, high-definition picture or dynamically rotated and transformed in space. The current findings challenge this longstanding view of mental imagery as a unitary, undifferentiated construct. Instead, our meta-analysis demonstrates that the neural substrates of imagery depend critically on the nature of the task. By systematically distinguishing between two forms of imagery—object-based visualization of static, pictorial details and spatial-based manipulation of objects and their relations—we identified both distinct and overlapping neural networks across 46 *f*MRI studies. Spatial imagery was associated with unique activation in bilateral superior parietal lobules, consistent with the dorsal visual stream. In contrast, object imagery elicited unique activation in left-lateralized frontoparietal and ventral stream regions. Regions of convergence included the medial frontal gyrus, precuneus, and inferior parietal lobule. These findings parallel the dual-stream model of visual processing, suggesting that object imagery, like object recognition, engages the ventral "what" stream, whereas spatial imagery, like spatial perception and transformation, engages the dorsal "where/how" stream. From a theoretical standpoint, this distinction offers a new perspective on an old debate, namely, the extent to which mental imagery mirrors perception. Our findings suggest that the answer depends on the type of imagery engaged, pointing to task-specific alignment between imagery and perception. From a practical standpoint, these results invite a reappraisal of how imagery relates to academic, occupational, and everyday behaviors, raising new questions about how different forms of imagery may support distinct cognitive processes.

8. Evidence for distinct neural substrates for object vs. spatial imagery

Results of our contrast analyses indicate that spatial and object imagery are subserved by partially dissociable neural networks. In the present study, spatial imagery was measured by mental rotation, a well-established measure of both mental imagery and spatial ability (Hawes et al., 2019). In line with prior studies, mental rotation was associated with frontoparietal activity (Hawes et al., 2019). However, after taking object imagery into account, mental rotation was uniquely related to activity in the left precuneus/superior parietal lobe and right superior parietal lobe. Although these regions have been shown to underlie a wide variety of cognitive tasks, including a key role in the default mode network (Fransson and Marrelec, 2008), these regions have been extensively linked to spatial processing, including mental rotation (see Hawes et al., 2019). Moreover, these regions are associated with the dorsal stream.

In contrast, object imagery, which was measured through tasks requiring the visualization of static objects, was uniquely related to areas of the ventral stream, including the left fusiform gyrus, bilateral lingual gyri, and inferior frontal regions; regions typically involved in high-resolution visual encoding and object recognition (Milner and Goodale, 2006). Notably, the left fusiform cluster identified here closely overlaps with the "imagery node" reported by Spagna et al. (2021). Together, these findings reinforce this region's involvement in object imagery, while also suggesting that this region may play less of a role during spatial imagery. These regions, particularly the left fusiform gyrus, have also been shown to play an important role in semantic processing, including tasks that involve naming, categorization, and feature verification of visually presented objects (Binder et al., 2009; Dehaene and Cohen, 2011). The present results present the possibility that object imagery may also involve semantic processing.

Taken together, our findings indicate that the dual-streams model of vision may also apply to mental imagery. Indeed, spatial imagery recruited dorsal-stream regions commonly involved in spatial processing and transformation, while object imagery activated ventral-stream regions commonly implicated in visual encoding and object recognition. These findings provide support that visualization processes rely on task-specific neural circuits that mirror those involved in visual perception.

In addition to the dual-streams account, our findings align with a recent proposal that likens mental simulation to the architecture of video/computer game engines, arguing for a fundamental split between physical simulation and graphical rendering (Balaban and Ullman, 2025). Accordingly, while spatial transformations, such as mental rotation, are posited to rely primarily on simulation-based computations (i.e., a "physics engine"), imagery for visual details is said to be analogous to graphics rendering (i.e., a "graphics engine"). In this model, the proposed dichotomy parallels the object-spatial distinction, but extends it by suggesting that spatial imagery should be broadened to also encompass "physical imagery", including all information necessary for reasoning about motion, interaction, *and* object properties, such as spatial extent. Thus, the authors suggest that "physical-spatial" imagery is preferred to spatial imagery in describing the computations that underlie simulation-based reasoning. This proposal provides a promising avenue for future research, as it makes specific predictions about which systems or "engines" are at play during mental imagery while also offering a computational model of imagery (see Balaban & Ullman, 2025, for details). The extent to which this model maps onto the object vs. spatial dichotomy presented here remains an open question for future research.

9. Regions of overlap between object and spatial imagery

In addition to the distinct activations associated with object and spatial imagery, conjunction analyses revealed regions common to both imagery types. Specifically, shared activation was observed in the left

Table 2
Summary of studies included in the spatial imagery meta-analysis.

1st Author	Year	Journal	N	Method	Age	Gender	Tasks	Contrast/s	Control
Barnes J.	2000	Neuropsychologia	6	fMRI	34	4 M 2 F	Mental Rotation	Rotational Transformation vs. Rotational Reference	Active
Ecker C.	2006	NeuroImage	10	fMRI	25	10 F	Mental Rotation, Finger Tapping/Button Press	100 ° angular disparity > Baseline	Passive
							Mental Rotation, Finger Tapping/Button Press	100 ° angular disparity > 20 ° angular disparity	
							Mental Rotation, Finger Tapping/Button Press	60 ° angular disparity > 0 ° angular disparity	
Gauthier I.	2002	Neuron	15	fMRI	NS	8 M 7 F	Mental Rotation	Large-Small Rotations	Active
Halari R.	2006	Experimental Brain Research	19	fMRI	26	9 M 10 F	Mental Rotation, Finger Tapping/Button Press	Rotation > Rest (Men)	Active
							Mental Rotation, Finger Tapping/Button Press	Rotation > Control (Men)	
							Mental Rotation, Finger Tapping/Button Press	Rotation > Rest (Women)	
							Mental Rotation, Finger Tapping/Button Press	Rotation > Control (Women)	
Hugdahl K.	2006	Neuropsychologia	11	fMRI	30	6 M 5 F	Mental Rotation, Finger Tapping/Button Press	3D experimental > 2D control	Active
Johnston S.	2004	Neuroscience Letters	9	fMRI	26	5 M 4 F	Mental Rotation, Visual Object Identification	Different Orientation - Same Orientation	Active
Jordan K.	2001	NeuroImage	9	fMRI	21	1 M 8 F	Mental Rotation, Finger Tapping/Button Press	3D > Rest	Passive
							Mental Rotation, Finger Tapping/Button Press	Abstract > Rest	
							Mental Rotation, Finger Tapping/Button Press	3D > Control	
							Mental Rotation, Finger Tapping/Button Press	Abstract > Control	
							Mental Rotation, Finger Tapping/Button Press	Letter > Control	
							Mental Rotation, Finger Tapping/Button Press	Mental Rotation > Control	
Jordan K.	2002	Neuropsychologia	24	fMRI	26	10 M 14 F	Mental Rotation	Women (Rotation vs. Control)	Active
							Mental Rotation	Men (Rotation vs. Control)	
Kawamichi H.	2007	Brain Research	12	fMRI	NS	12 M	Mental Rotation	3D rotation with large angular difference (3DL) > Rest	Passive
							Mental Rotation	3D rotation with small angular difference (3DS) > Rest	
							Mental Rotation	2D rotation with large angular difference (2DL) > Rest	
							Mental Rotation	2D rotation with small angular rotation (2DS) > Rest	
							Mental Rotation	3DL - 3DS	
							Mental Rotation	2DL - 2DS	
Keehner M.	2006	NeuroImage	14	fMRI	NS	7 M 7 F	Mental Rotation	Mental rotation > 0 ° rotation	Active
Kosslyn S. M.	2001	Neuroreport	8	PET	24	8 M	Mental Rotation, Finger Tapping/Button Press	EA > Baseline	Active
							Mental Rotation, Finger Tapping/Button Press	IA > Baseline	
Kosslyn S. M.	1998	Psychophysiology	12	PET	20	12 M	Mental Rotation	Cubes vs. Cubes Baseline	Passive
Levin S. L.	2005	Evolutionary Psychology	11	fMRI	21	6 M 5 F	Mental Rotation, Visual Object Identification	Spatial vs. Same (when collapsing across sex)	Active
							Mental Rotation, Visual Object Identification	Spatial vs. Different (collapsed across sex)	
Ng V. W. K.	2001	Journal of Cognitive Neuroscience	12	fMRI	29	12 M	Mental Rotation	Mental Rotation: Activation - Baseline	Active
Podzebenko K.	2005	Journal of Cognitive Neuroscience	16	fMRI	31	8 M 8 F	Mental Rotation	Rotating Alphanumerics - Rest	Passive
							Mental Rotation	Rotating Alphanumerics - Stationary Alphanumerics	
							Mental Rotation, Passive Viewing	Rotating Abstracts - Stationary Abstracts	
Schendan H. E.	2007	NeuroImage	13	fMRI	22	6 M 7 F	Mental Rotation	Mental rotation task: Rotation > Control	Passive
Seurinck R.	2005	NeuroImage	24	fMRI	23	24 F	Mental Rotation	Tools, Fixed-Paced	Active
							Mental Rotation	Tools, Self-Paced	
Suchan B.	2006	Neuroscience	11	fMRI	27	6 M 5 F	Mental Rotation	Simultaneous matrix rotation > Simultaneous 3-D cube rotation	Active
							Mental Rotation	Simultaneous 3-D cube rotation > Simultaneous matrix rotation	
							Mental Rotation	Successive matrix rotation > Successive 3-D cube rotation	

(*continued on next page*)

Table 2 (*continued*)

Thomsen T.	2000	Medical Science Monitor	11	fMRI	NS	6 M 5 F	Mental Rotation	Main Effect of Stimulus	Active
							Mental Rotation	3D Drawings vs. 2D Control, Males	
							Mental Rotation	3D Drawings vs. 2D Control, Females	
Logie R. H.	2011	Neuropsychologia	21	fMRI	NS	7 M 14 F	Mental Rotation, Finger Tapping/Button Press	Mental rotation > Control	Active
Vanrie J.	2002	Neuropsychologia	6	fMRI	25	3 M 3 F	Mental Rotation	Invariance - Control	Active
							Mental Rotation	Rotation - Control	
Vingerhoets G.	2001	NeuroImage	10	fMRI	26	5 M 5 F	Mental Rotation	Figures Rotation - Figures Control	Active
							Mental Rotation	Rotations - Controls	
Vingerhoets G.	2002	NeuroImage	12	fMRI	29	12 M	Mental Rotation	Rotated Tools > Non-Rotated Tools	Active
Weiss E. M.	2003	Neuroscience Letters	20	fMRI	NS	10 M 10 F	Mental Rotation	Rotated Images vs. Control, Men and Women	Active
Wilson K. D.	2006	Perception	7	fMRI	NS	3 M 4 F	Mental Rotation	Letter mental rotation (LMR)	Active
							Mental Rotation	Object mental rotation (OMR)	
Wraga M.	2003	Brain and Cognition	16	PET	NS	16 M	Mental Rotation	Object - Object Baseline	Active
							Mental Rotation	Object - Object Baseline	
Wraga M.	2005	Neuropsychologia	11	fMRI	NS	7 M 4 F	Mental Rotation	Object Task, Activations	Active

Note. NS = not stated; Foci, number of foci reported in contrast; fMRI, functional magnetic resonance imaging; PET, positron emission tomography; N = sample size of each study; M = Male, F = Female; Loc = location; NR = Not Reported

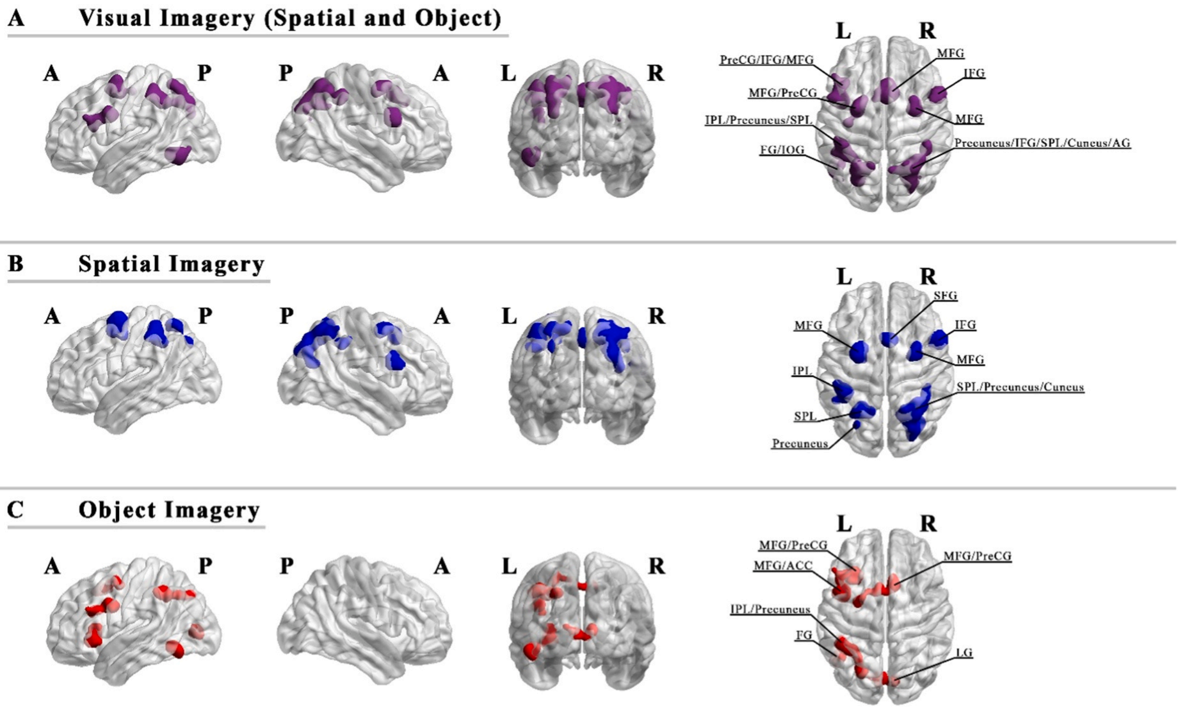

Fig. 2. *Single dataset ALE maps of visual imagery, spatial imagery, and object imagery.* Note. These maps were generated using a cluster-level correction of 0.05 with 1000 threshold permutations and a cluster-forming (uncorrected) threshold of $p < .001$. Significant clusters of convergent brain clusters are reported in Table 3. ACC = Anterior Cingulate Cortex, FG = Fusiform Gyrus, IFG = Inferior Frontal Gyrus, IPL = Inferior Parietal Lobule, LG = Lingual Gyrus, MFG = Middle Frontal Gyrus, PreCG = Precentral Gyrus, SFG = Superior Frontal Gyrus, SPL = Superior Parietal Lobule.

inferior parietal lobe, left precuneus, and bilateral medial frontal gyri. These regions are part of a frontoparietal network commonly implicated in attentional control, working memory, and mental simulation (e.g., Bartolomeo and Malkinson, 2019; Jonikaitis and Moore, 2019; Pearson, 2019; Petersen and Posner, 2012; Spagna et al., 2021). Importantly, these regions may also play a key role in the early stages of image formation. That is, before any spatial transformation takes place or there is a need to add further visual details.

This interpretation aligns with the proposal of a top-down, reverse hierarchy, model of mental imagery (e.g., see Pearson, 2019; Spagna et al., 2021), which posits that the mental actions required to create a mental image are first initiated in the frontal cortex. From there, increasingly posterior regions, such as the medial temporal areas, support the retrieval of stored memories, which then help to form the sensory and spatial representations of the imagery content. If the imagery requires movement or spatial locations, other areas, such as the parietal lobes, are also recruited.

Our findings offer a slight extension to this model, suggesting that following the early stages of image formation, a key division in labor may occur in which subsequent neural recruitment is determined by whether images require object- or spatial-based processing. Accordingly, mental imagery may 'start off' on a similar path but then 'later' diverge depending on whether the image requires visual processing or spatial processing, at which point the ventral or dorsal stream become involved, respectively. Future studies that combine neuroimaging with time-sensitive measures, such as MEG or EEG, may offer a means to test

Table 3
Single dataset analyses (visual imagery, spatial imagery, object imagery).

Hemisphere	Brain Area	BA	X	Y	Z	ALE	VOL/mm^3
Visual Imagery Map (Spatial and Object)							
L	Inferior Parietal Lobule	40	-42	-46	44	0.03934047	13320
L	Precuneus	19	-26	-72	42	0.03460521	
L	Inferior Parietal Lobule	40	-42	-38	52	0.03323519	
L	Inferior Parietal Lobule	40	-34	-50	42	0.03122573	
L	Superior Parietal Lobule	7	-28	-66	52	0.02446556	
L	Precuneus	31	-26	-74	30	0.02369522	
L	Superior Parietal Lobule	7	-28	-56	62	0.02184593	
L	Precuneus	7	-18	-62	52	0.02161318	
L	Precuneus	7	-14	-60	58	0.02127878	
R	Precuneus	7	26	-60	58	0.03578037	12872
R	Precuneus	7	22	-70	42	0.03511838	
R	Inferior Parietal Lobule	40	40	-42	44	0.02986361	
R	Superior Parietal Lobule	7	34	-54	52	0.02749115	
R	Precuneus	7	8	-64	56	0.02212626	
R	Cuneus	18	26	-82	34	0.02117265	
R	Angular Gyrus	39	32	-58	36	0.02012886	
R	Angular Gyrus	39	32	-54	36	0.01960785	
R	Precuneus	31	34	-70	24	0.01749393	
L	Precentral Gyrus	6	-42	6	30	0.03565687	5288
L	Inferior Frontal Gyrus	9	-46	16	24	0.0244649	
L	Middle Frontal Gyrus	9	-40	24	24	0.0240789	
L	Middle Frontal Gyrus	9	-50	30	28	0.02005042	
L	Middle Frontal Gyrus	6	-26	0	60	0.03579937	4128
L	Precentral Gyrus	4	-36	-16	54	0.02207927	
R	Medial Frontal Gyrus	32	6	12	48	0.04698878	3712
L	Medial Frontal Gyrus	6	2	22	42	0.02281383	
R	Middle Frontal Gyrus	6	30	-2	54	0.04715217	3312
L	Fusiform Gyrus	37	-48	-58	-12	0.03405798	3120
L	Inferior Occipital Gyrus	19	-42	-74	-4	0.01736968	
R	Inferior Frontal Gyrus	9	52	10	26	0.03034654	1248
Object Imagery Map							
L	Inferior Parietal Lobule	40	-34	-50	42	0.02646871	4568
L	Inferior Parietal Lobule	40	-42	-46	44	0.02394939	
L	Precuneus	19	-24	-74	42	0.02080066	
L	Precuneus	7	-26	-62	42	0.0165496	
L	Precentral Gyrus	6	-40	6	32	0.02734664	3560
L	Middle Frontal Gyrus	9	-38	24	24	0.01867143	
L	Middle Frontal Gyrus	9	-46	20	28	0.01574596	
L	Middle Frontal Gyrus	9	-52	28	28	0.01486237	
R	Medial Frontal Gyrus	32	8	14	48	0.02552737	2680
L	Cingulate Gyrus	24	-6	12	48	0.01723925	
L	Middle Frontal Gyrus	6	-26	-2	52	0.01723113	
L	Cingulate Gyrus	24	-10	6	52	0.01703073	
L	Sub-Gyral	6	-24	0	58	0.01540589	
L	Sub-Gyral	6	-18	8	56	0.01336747	
L	Fusiform Gyrus	37	-48	-56	-12	0.03099402	2632
R	Lingual Gyrus	18*	8	-82	6	0.01937745	1680
L	Lingual Gyrus	18	-6	-78	6	0.01785945	
L	Lingual Gyrus	18	-16	-76	10	0.01410897	
R	Lingual Gyrus	18	4	-84	-2	0.01279795	
L	Sub-lobar Claustrum	13*	-30	24	-2	0.02017341	984
Spatial Imagery Map							
R	Superior Parietal Lobule	7	28	-60	54	0.028991	10816
R	Precuneus	7	32	-52	54	0.02498705	
R	Precuneus	7	24	-70	46	0.02172881	
R	Cuneus	19	32	-76	34	0.01796577	
R	Cuneus	7	28	-78	38	0.01751446	
R	Precuneus	31	34	-70	24	0.01740245	
L	Superior Parietal Lobule	7	-28	-58	62	0.02098183	5104
L	Precuneus	19	-28	-72	44	0.02005324	
L	Superior Parietal Lobule	7	-14	-60	60	0.01885678	
L	Precuneus	31	-24	-76	32	0.01312736	
L	Inferior Parietal Lobule	40	-42	-38	54	0.02859733	3168
L	Inferior Parietal Lobule	40	-48	-48	42	0.01428696	
R	Middle Frontal Gyrus	6	28	-4	56	0.02891624	2872
R	Sub-Gyral	6	32	4	58	0.02313024	
L	Middle Frontal Gyrus	6	-26	0	62	0.02745856	2440
L	Middle Frontal Gyrus	6	-24	-6	50	0.01410393	
R	Inferior Parietal Lobule	40	40	-40	44	0.02437919	1600
R	Superior Frontal Gyrus	6	4	12	50	0.02826257	1448
R	Inferior Frontal Gyrus	9	54	10	24	0.01879122	1016

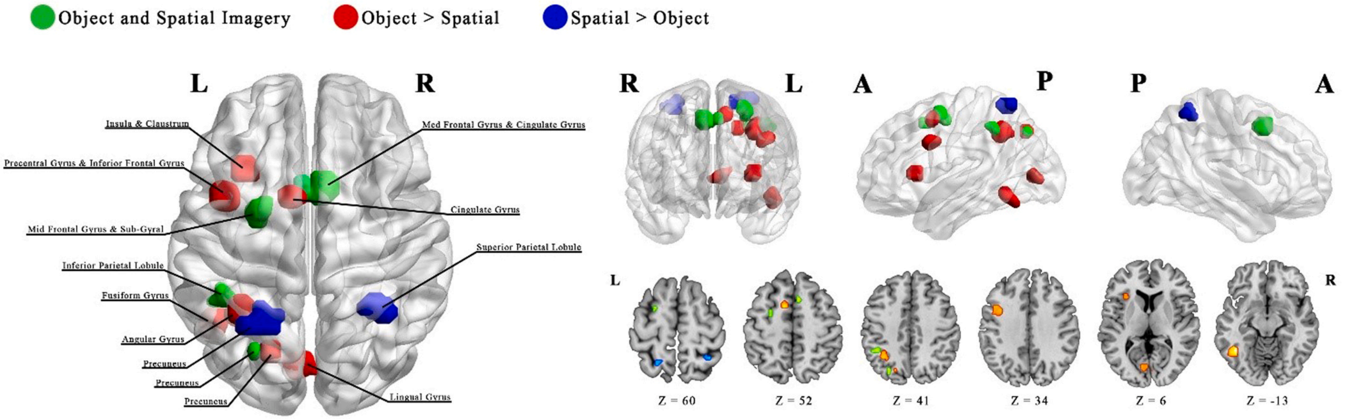

Fig. 3. *ALE maps from the conjunction and contrast analyses.* Note. The ALE conjunction analysis revealed significant clusters of convergence between spatial and object imagery (green). ALE contrast analyses reveal specific activation for spatial > object imagery (blue) and object > spatial imagery (red/orange). All conjunction and contrast analyses were conducted using an uncorrected p < .01 with 5000 permutations and a minimum volume of 50 mm3. All maps are shown in MNI space. Significant clusters from the conjunction and cluster analyses are reported in Table 4.

Table 4
Conjunction and contrast analyses (spatial imagery, object imagery).

Hemisphere	Brain Area	BA	X	Y	Z	ALE	VOL/mm^3
Spatial and Object Imagery (Conjunction)							
L	Inferior Parietal Lobule	40	-40	-44	44	0.01660396	856
L	Inferior Parietal Lobule	40	-48	-48	42	0.01428696	
R	Medial Frontal Gyrus	32	6	12	48	0.02216905	560
L	Sub-Gyral	6	-24	0	58	0.01540589	400
L	Precuneus	19	-26	-72	42	0.016613	296
L	Medial Frontal Gyrus	32	-4	14	48	0.01293085	40
L	Cingulate Gyrus	24	-2	10	48	0.01238009	
Spatial > Object Imagery (Contrast)							
L	Precuneus	7	-21	-55	64	2.9888823	456
R	Superior Parietal Lobule	7	34	-50	60	3.0114536	272
Object > Spatial Imagery (Contrast)							
L	Fusiform Gyrus	37	-43.4	-56.2	-14.2	3.8905935	1776
L	Fusiform Gyrus	37	-48.7	-57.6	-14.9	3.7190173	
L	Precentral Gyrus	6	-36	7	32	3.0114536	928
L	Precentral Gyrus	9	-44	12	34	2.8627362	
L	Inferior Frontal Gyrus	6	-45	5	35	2.5971532	
L	Lingual Gyrus	18	-10	-74	8	3.0902321	920
L	Lingual Gyrus	18*	-10	-80	4	2.7821505	
L	Lingual Gyrus	18	-2.5	-76.5	6	2.5556161	
R	Lingual Gyrus	18	2	-82	0	2.5556161	
R	Lingual Gyrus	18	4	-82	6	2.5426989	
L	Angular Gyrus	39	-34	-56	40	3.5400841	848
L	Cingulate Gyrus	24	-9.3	4	50.7	3.8905935	352
L	Sub-lobar Insula	13	-32	22	10	2.894304	264
L	Sub-lobar Claustrum	13*	-28	20	6	2.794376	
L	Precuneus	7	-18	-72	42	3.0356722	112

this model, helping to clarify how shared and task-specific processes unfold throughout the imagery process.

10. Individual differences in imagery style

Our results add to a growing body of behavioral research suggesting key differences in object and spatial imagery. While most individuals can engage in both, people often exhibit a relative preference or strength in one over the other, and these abilities are typically negatively correlated (Blajenkova et al., 2006; Sokolowski et al., 2019). This distinction is nontrivial, as imagery preference is associated with a host of meaningful real-world outcomes. For example, spatial imagers are more likely to pursue and excel in STEM fields, while object (or visual) imagers tend to gravitate toward the arts (Blajenkova et al., 2006; Kozhevnikov et al., 2005; 2010). Moreover, imagery preferences have also been associated with clinical diagnoses including post-traumatic stress disorder (PTSD) and depression, as well as with the development and efficacy of imagery-based treatments for these conditions (e.g., see Brewin and Holmes, 2003; Holmes et al., 2005; 2009; Ji et al., 2017; Pearson et al., 2015). Thus, an improved understanding of when, why, and how these biases in mental imagery arise, and the specialization of neural networks that support them, presents an important area of research with real-world implications.

Central to this aim is to better understand the factors that drive these individual differences in imagery preference and skill. One possibility is that experiences bias individuals toward using one form of imagery over another (e.g., engagement in visual arts vs. mathematics). Another possibility is that individuals are genetically predisposed to favor either object or spatial visualization. Supporting the latter view, Kozhevnikov et al. (2010) found no evidence that age or domain-specific experience influenced the trade-off between object and spatial imagery, suggesting a biological basis. However, this conclusion is based on a single cross-sectional study, and much remains unknown about the malleability and underlying neural correlates of these preferences.

The integration of neuroimaging with behavioral research offers a promising path forward. For example, given behavioral evidence of a trade-off between imagery preference and ability, how might these differences be reflected at the neural level? One possibility is that individuals high in spatial imagery will demonstrate greater activity in dorsal stream regions during spatial tasks, while object imagers will show greater activation in the ventral stream regions for object-based tasks. Alternatively, greater neural activity may signal greater cognitive effort rather than efficiency. From this perspective, high object imagers might show less activation for object imagery tasks (due to more efficient processing), but more activation for spatial tasks (due to higher effort demands), with the opposite pattern for spatial imagers. It is also possible that individual differences arise not only from stream-specific activation, but also from differential recruitment of shared neural regions, such as the frontoparietal regions noted above.

Importantly, several lines of research challenge the notion that individuals are inherently skilled in one type of imagery but not the other. The first line of research comes from the spatial training literature, which shows that spatial visualization, including mental rotation, is a highly malleable skill (e.g., see Hawes et al., 2022; Uttal et al., 2013), with emerging evidence that improvements in spatial skill transfer to STEM performance (Hawes et al., 2022). These findings suggest that imagery skill is malleable and sensitive to experience. However, the relationship between imagery preference, imagery skill, training outcomes, and the extent to which such changes are accompanied by measurable neuroplasticity, remains unexplored. For example, do gains in spatial visualization ability correspond to increased activation in regions found to be uniquely associated with spatial imagery, such as the right superior parietal lobe and left precuneus, as revealed in the present meta-analysis? The second line of evidence comes from biographical studies of prominent scientists and mathematicians. According to the trade-off account, individuals who excel in STEM should demonstrate strong spatial imagery abilities but relatively weaker object imagery. Yet in many cases, highly creative scientists, including Louis Pasteur, Frederick Banting, and Michael Faraday, have also shown considerable talent in the visual arts (e.g., Paivio, 1983; Root-Bernstein, 1985). One notable example comes from Ramón y Cajal, widely regarded as the father of modern neuroscience, whose interest and talents in the visual arts was central to his work:

It is an actual fact that, leaving aside the flatteries of self-love, the garden of neurology holds out to the investigator captivating spectacles and incomparable artistic emotions. In it, my aesthetic instincts found full satisfaction at last. Like the entomologist in pursuit of brightly coloured butterflies, my attention hunted, in the flower garden of the gray matter, cells with delicate and elegant forms, the mysterious butterflies of the soul (Cajal, 1937, p. 155–156).

Such examples raise the possibility that the object/spatial trade-off does not apply uniformly. In some individuals, the capacity to flexibly engage both object and spatial imagery may, in fact, serve as a source of creativity and divergent thinking. Whether this flexibility represents a rare exception or a more general, but under-recognized capacity, remains an open and important question for future research.

A related question concerns cases in which both object- and spatial-based processes may be simultaneously engaged, as may occur during scene imagery. For example, imagining walking through one's childhood home requires representing the spatial layout of the environment while also recalling object-specific detail (e.g., the colour and intricacies of a clock on the wall). Research on the neural correlates of scene construction suggests the involvement of an integrated network that supports the representation of objects within a spatial framework (Hassabis and Maguire, 2007; Zeidman and Maguire, 2016). Accordingly, scene imagery provides but one example of how, depending on task demands, object and spatial imagery processes may operate in concert rather than in isolation. Future efforts are needed to further examine how the partially distinct neural networks identified here are coordinated across tasks that require both detailed object representation and spatial transformation.

11. Limitations and future directions

Like other ALE meta-analyses, this study is not without limitations. In providing a 'big picture' view of object vs. spatial imagery, some of the study and task-specific nuances are lost and obscured as a result of averaging across studies. As such, one major shortcoming of the present analysis was the variability permitted between imagery types. Whereas our spatial imagery condition was confined to a relative isolated type of imagery, mental rotation, the same was not true of the object imagery condition, which by nature, included more variability between studies. For example, studies included in the spatial maps, predominantly involved rotating abstract stimuli, such as 3D block figures, whereas studies included in the object imagery maps included imagining a wide assortment of everyday objects. Thus, both the range of objects to visualize as well as the degree of familiarity may have influenced the results. These differences, especially the variability in the object condition, may explain, in part, the more disparate and widespread activation unique to object imagery relative to spatial imagery.

Along these lines, by restricting spatial imagery to mental rotation, we may be observing a particular case of spatial visualization, which may or may not be representative of spatial visualization at large. To be sure, spatial visualization includes a wide assortment of spatial imagery tasks, including mental paper folding, mental cross-sectioning, spatial perspective taking, composition/decomposition of shapes and objects, and mechanical reasoning to name but a few examples (e.g., see Hawes and Ansari, 2020; Wai et al., 2009; Uttal et al., 2013). Crucially, despite being classified as measures of spatial visualization, these measures are not isomorphic. For example, Hegarty and Waller (2004) found evidence suggesting that mental rotation and spatial perspective taking, although highly related to one another, are dissociable cognitive processes. This is relevant to the current findings given that spatial perspective taking may more directly align with the dorsal stream's role in spatial location, orientation, and visually guided action (Goodale and Milner, 1992; Milner and Goodale, 2006). Thus, while we have interpreted our findings as support for a dual-streams model of imagery (mirroring the dual-streams model of vision), caution is warranted as it remains possible that our findings may be specific to mental rotation and not spatial imagery more broadly. Moving forward, it will be necessary to further test the dual-streams model of mental imagery by including a wider assortment of spatial visualization tasks and systematically mapping their neural correlates. The same can be done with object imagery tasks to more fully understand and delineate the general and specific boundaries of applying the dual-streams model to mental imagery.

12. Conclusion

The present findings indicate a key distinction between object and spatial imagery. While object imagery was associated with left-lateralized regions implicated in processing visual details, such as object recognition, spatial imagery was associated with bilateral parietal regions commonly engaged in tasks requiring spatial processing. These results parallel the ventral "what" and dorsal "where/how" streams of visual perception, suggesting that both imagery and vision rely on similar task-specific neural systems. This distinction between object and spatial imagery is nontrivial, offering both a reinterpretation of prior findings and a more refined model of imagery to guide future research.

Declaration of Competing Interest

We have no conflict of interest to disclose.

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