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Visual cognition: A new perspective on mental rotation

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Manipulating an object in one's mind has long been thought to mirror physically manipulating that object in allocentric three-dimensional space. A new study revises and clarifies this foundational assumption, identifying a previously unknown role for the observer's point-of-view.

Look at the images in Figure 1A: are the two blue objects the same three-dimensional shape appearing at different orientations? Or are they genuinely different shapes? Now try the same exercise for the two red objects: same, or different? Though you can probably determine the answer in both cases — they are each the 'same' — the second case is surely more difficult than the first. This is because the two red objects are separated by a greater angular distance than the two blue objects are (120° apart for red *versus* 30° apart for blue), and it takes longer to mentally align the objects when they must cover more ground to get there. First reported by Shepard and Metzler[1] over half a century ago, this foundational discovery suggested that 'mental rotation' of objects mirrors their physical rotation in the real world, as if the mind steps through each intermediate pose until the two objects match. The form of spatial thinking implied by this result — an internal mental process distinct from verbal or propositional thought[2] — launched several still-active research programs, and the findings remain a mainstay of both introductory courses and sophisticated theorizing.

However, a paper published recently in *Current Biology* by Stewart *et al.*[3] shows how a core assumption about this process has missed something important about the perceiver's point-of-view.

To appreciate the context for the new work of Stewart *et al.*[3], it is worth noting just how many productive research questions have arisen from this seemingly straightforward correspondence between physical space and mental space. Does this discovery imply that we generate 'pictures' of the world in our heads[4,5]? Do individuals who perform well at mental rotation excel at other forms of spatial reasoning[6]? Is mental rotation a trainable skill, in ways that might form effective educational interventions[7]? How do people with *aphantasia*, who report weak or nonexistent mental imagery, complete this task[8]? Which non-human animals have this capacity[9]? All of these questions and more remain the focus of ongoing investigation and debate.

However, one aspect of these results that has been less controversial concerns the coordinate system of the mental space itself, which has traditionally been assumed to be *distal* or *allocentric* — one in which pose-to-pose transformations are performed with reference to "the standard axes of our visual world"[6] without consideration of any particular visual perspective. For example, under this assumption, a 30° difference between objects is just that — 30° of angular distance to cover, no matter which 30° it happens to be. It is this assumption that is the focus of the Stewart *et al.*[3] study.

Stewart *et al.*[3] note some puzzling findings in the literature, including cases in which pairs of objects that are separated by the same objective angular distance nevertheless vary in how similar they look and how easily they are compared. Examples of such pairs studied by the authors appear in Figure 1B. The two green objects and the two yellow objects are both 30° apart from one another, yet most observers find that the two green objects seem 'closer' to one another in viewpoint than the two yellow objects do. But why should this be? If each pair is separated by the same physical distance, then they should also be separated by the same mental distance, at least according to the standard account.

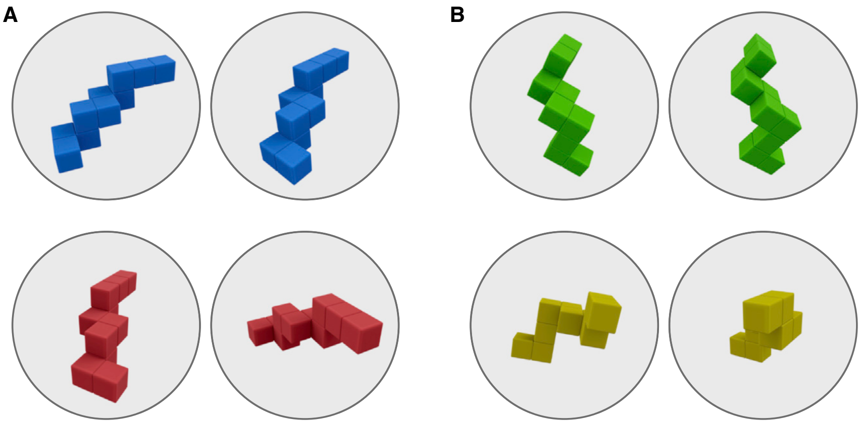

Figure 1. Stimuli used in studies of mental rotation.
(A) The two blue objects are the same 3D shape presented at different orientations; the same is true of the two red objects. But appreciating this similarity is easier for the blue pair than the red pair, because the blue pair is separated by only 30°, whereas the red pair is separated by 120°. Foundational work in visual cognition accounts for this result by proposing a 1-to-1 correspondence between the physical space an object inhabits and the mental space in which it is manipulated.[1] (B) New work by Stewart *et al.*[3] adds nuance to this assumption, first by noting striking non-linearities in mentally comparing objects. For example, the green pair of objects and the yellow pair of objects are both separated by 30°; but most observers find that the yellow objects somehow seem more distant from one another in viewpoint. Stewart *et al.* account for this pattern by modeling the retinal motion that would be produced by the objects' rotation, which is greater for the yellow pair than the green pair even though they would traverse the same angular distance. This work reveals a previously unknown influence of the observer's perspective, revising assumptions about the relationship between physical space and mental space.

Stewart *et al.*[3] propose and test a solution to this puzzle, in ways that add nuance to the allocentricity assumption and its accordant one-to-one mapping between physical and mental space. Rather than propose that objects are manipulated in a perspectiveless coordinate system, the authors suggest that the mind simulates the patterns of optic flow that would reach the observer's eyes during the object's rotation, as if subjects mentally 'render' the retinal motion of the rotating objects. The extent of these anticipated two-dimensional retinal-image changes then guides similarity judgments; the more retinal motion would be produced by aligning two objects, the farther apart in orientation the objects are judged to be.

To test their model, Stewart *et al.*[3] generated a library of oriented-block stimuli and presented them to viewers at a range of viewpoints and degrees of rotation. On each trial of the task, observers were shown two 'standard' objects spaced at a given angular distance, and then they were asked to adjust a new pair of 'test' objects to be as far apart from one another as the standard. As predicted, not all angular displacements of the same objective magnitude were treated as equally far apart. To account for these patterns, the authors built a model that simulates the two-dimensional displacement vectors for all of the objects' visible surfaces as they rotate to become aligned with one another; the model then averages the magnitude of these displacement vectors at each timestep. This value, which might be thought of as a summary statistic of all the retinal-image changes that would be produced by the object as it rotates, predicted human similarity judgments better than did the actual angular displacement between the objects in three dimensions. In other words, subjects seem to rely more on two-dimensional information capturing their subjective perspective than on allocentric three-dimensional objective angular rotation.

Importantly, this account captures the non-uniformities that are observed elsewhere in the literature and which are illustrated in Figure 1B. Whereas the objective angular distance in three-dimensional space is equal across the green pair and yellow pair (as noted above), the yellow objects would produce greater retinal motion were they to rotate into alignment — which is why the green objects seem closer in view than the yellow objects do. "When we compare objects," Stewart *et al.*[3] conclude, "we do not do so in a distal three-dimensional representation as previously assumed, but by measuring how much the proximal stimulus would change if we watched the object rotate."

The experiments invite some natural follow-up questions. For example, would the same results hold not only for images on a screen — which are, after all, presented in two dimensions — but also for real objects in the real world? Stewart *et al.*[3] suggest that they would (and provide further modeling evidence for this hypothesis), but this is ultimately an empirical question that remains open to further investigation. If even real, physical, three-dimensional objects are still compared in terms of their two-dimensional image properties, that would be especially compelling evidence for this new account. Future work could further validate their model by moving beyond viewpoint similarity judgments to the sorts of same-different tasks used in the original Shepard and Metzler[1] report relating angular distance to response time.

As Stewart *et al.*[3] note, their account joins other recent studies that have emphasized the "perspectival" character of visual perception. For example, Gayet *et al.*[10], reporting in *Current Biology*, showed that observers who expect to fixate a far-away object (*versus* a nearby object) anticipate its smaller two-dimensional retinal size from the perceiver's point-of-view, even when the objects have the same distal size. Similarly, Morales *et al.*[11] showed that observers who must locate a distally elliptical object in a search array get distracted by non-elliptical objects that have two-dimensional elliptical projections from the observer's perspective. Each of these findings suggests a more prominent role for proximal visual information than is traditionally assumed in perception research (and as such remain the subject of debate[12–16]). They also connect up with foundational issues in vision science[17] and even the philosophy of perception, which has long puzzled over the relationship between objectivity and subjectivity in visuospatial experience[18–20].

Beyond its implications within and across disciplines, this new work also testifies to the importance of a well-motivated research question and elegant experimental design. The methods supporting the Stewart *et al.*[3] study have been available for decades — no high-resolution neuroimaging, special subject populations, expensive equipment, or advanced machine-learning techniques were required — and the phenomenon in question has been lying in plain sight since the 1970s. Yet their novel and perspective-shifting approach sheds light on unobservable spaces existing only in our minds.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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Chronobiology: Is daylight saving time a deer-saving time?

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Earlier human activity relative to sunrise and sunset, the very essence of daylight saving time, is linked with health and safety detriments in humans. A new study predicts that deer, at least, may benefit from earlier human activity through reduced deer–vehicle collisions.

Daylight saving time (DST) regulations are under debate again in many countries around the world. The US and the EU are considering abolishing the bi-annual switches into and out of DST but have yet to decide if they will settle for permanent standard time or permanent DST. The public and political debates are rife with personal anecdotes, wrong assumptions and strong convictions, so empirical evidence on the advantages of either timing system is all the more important to encourage evidence-based policy — and highlight unintended side effects that may require tailored mitigation measures. In this issue of *Current Biology*, Cunningham *et al.*[1] investigated one of these potential side effects by analyzing the likelihood of deer–vehicle collisions in the US under different timing regimes, finding that the timing of humans on the road to and from work significantly adds to the risks of wildlife encounters and collisions.