# The psychophysics of compositionality: Relational scene perception occurs in a canonical order

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**Abstract**

We see not only objects and their features (e.g., glass vases or wooden tables) but also relations between them (e.g., a vase on a table). An emerging view accounts for such relational representations by positing that visual perception is compositional: Much like language, where words combine to form phrases and sentences, many visual representations contain discrete constituents that combine in systematic ways. This perspective raises a fundamental question: What principles guide the compositional process for relational representations, and how are these representations built over time? Here, we tested the hypothesis that the mind constructs relational representations in a canonical order. Inspired by a distinction from the cognitive linguistics tradition, we predicted that 'reference' objects (large, stable, or physically controlling objects; e.g., tables) take precedence over 'figure' objects (e.g., vases) during scene composition. In Experiment 1, participants who were instructed to arrange items to match linguistic descriptions (e.g., "The vase is on the table", "The table is supporting the vase") consistently placed reference objects first (e.g., table, then vase). Experiments 2–5 extended these findings to visual recognition itself: Participants were faster to verify a description when the reference object appeared before the figure object in the scene, rather than vice versa. This Reference-first advantage emerged rapidly (within 100 ms), persisted in a purely visual task, and could not be explained by differences in object size or shape. Together, our findings reveal psychophysical principles underlying compositionality for object relations in visual processing: the mind builds relational representations sequentially, respecting each element's role.

***Keywords:*** *relations; scene perception; intuitive physics; anchor objects; language of thought*

## 1 INTRODUCTION

Look at the image in Figure 1A. What do you see? Certainly you see colors, textures, edges, and countless other visual features—the deep green of a plant, the glossiness of a vase, the grain of a wooden table, and the wicker of a square basket. However, beyond these properties, you may also appreciate something about how the objects *relate* to one another: The plant is sitting *on* the table and the basket is resting *below* it (Fig. 1B). Relational representations are a core topic of study in many domains of higher-level cognition, such as analogical reasoning (Gattis, 2004; Goldwater & Gentner, 2015; Jamrozik & Gentner, 2015; Webb, Fu, Bihl, Holyoak, & Lu, 2023), linguistic reference (Johannes, Wilson, & Landau, 2016; Landau & Jackendoff, 1993; Levinson, 2003; Talmy, 1983; Webb, Holyoak, & Lu, 2023), and causal ascription (Gerstenberg, Peterson, Goodman, Lagnado, & Tenenbaum, 2017; Kominsky et al., 2017; Wolff & Song, 2003).

However, a growing body of empirical evidence suggests that more basic processes of visual perception also encode sophisticated relations such as those depicted in Figure 1B (Hafri, Bonner, Landau, & Firestone, 2024; Hafri & Firestone, 2021; Hafri, Trueswell, &

Strickland, 2018; Lovett & Franconeri, 2017). Moreover, this evidence suggests that these relations are not merely detected by visual processing but also represented by the visual system in ways that are structured and systematic, as though such representations have parts that combine into wholes; in other words, they are represented *compositionally* (Hafri, Green, & Firestone, 2023). On this scheme, for example, when seeing a plant on a table, the mind represents the scene not as an undifferentiated collection of pixels or textures, but rather in terms of the discrete constituents *plant*, *table*, and ON.

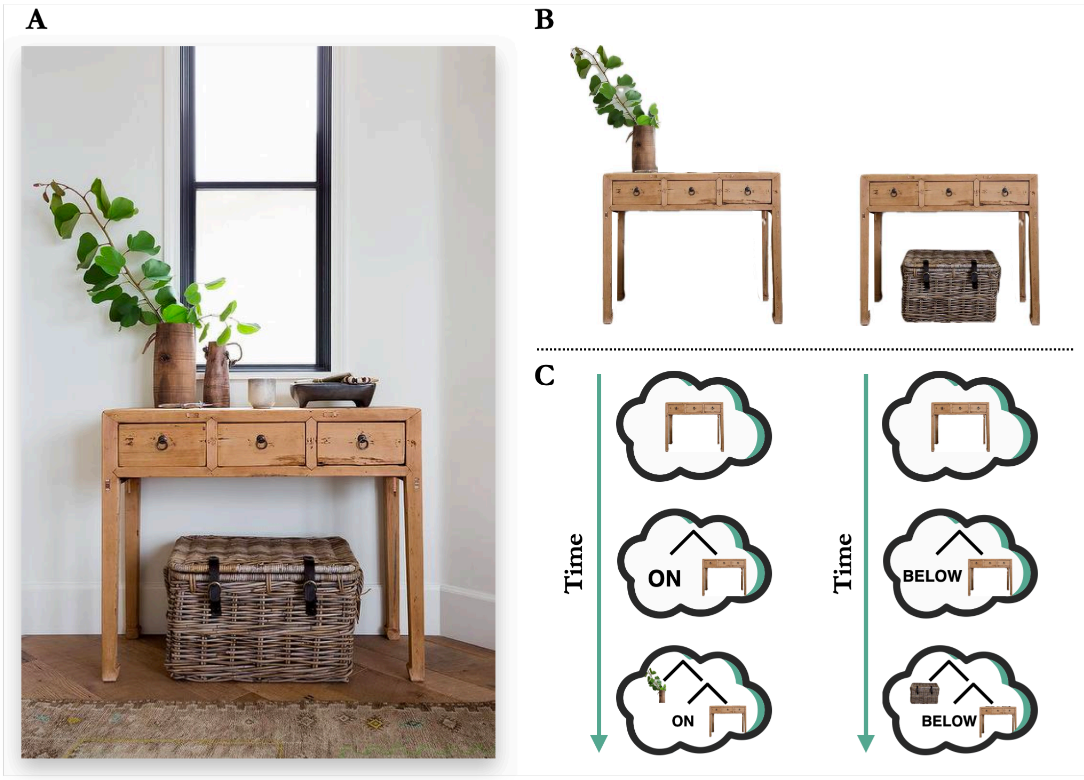


**Figure 1:** The world contains not only objects and features, but also relations holding between them. (A) We see the plant and its greenness, the table and its size, and so on. But we also appreciate that the plant is sitting *on* the table, and the basket is resting *below* it. (B) A growing literature suggests that visual perception rapidly and spontaneously forms representations of such relations. How does it do so? (C) Despite the fact that the objects are presented to the eyes simultaneously, here we explore the possibility that the mind adopts a sequential order to combine discrete elements into relational representations, with reference objects (e.g., the table) serving as the primary element or 'scaffold.'

This perspective raises a question: How does the mind join these parts together in forming sophisticated relational representations? Here, we explore the nature of this visual compositional process, using as a case study the sort of relational representations depicted in Figure 1A.

## 1.1 Compositionality in visual perception

Compositionality refers to a form of representation in which complex representations are systematically constructed by combining their constituent parts (Fodor & Pylyshyn, 1988).

In this sense, it is not particularly controversial to suggest that compositionality can be observed in some forms of basic visual representation. For example, recent theoretical work has examined how principles of compositionality apply to visual representations of the bounding contours of objects, suggesting that perceiving contours depends on different modes of composition, such as combining features to fragments and fragments to contours (Lande, 2023). Compositionality is also a fundamental principle in influential theories of object recognition. For example, the Recognition-by-Components theory proposes that objects are represented by freely combining a set of basic components ('geons') (Biederman, 1987) into more sophisticated structures; and more recent accounts describe shapes via their parts' intrinsic axes and connections (their 'skeletons'), often in a hierarchical tree format (Feldman & Singh, 2006). Ample empirical evidence supports the psychological reality of such compositional representations (Ayzenberg & Lourenco, 2022; Bonnen, Wagner, & Yamins, 2023; Firestone & Scholl, 2014; Lewis & Frank, 2016; Lowet, Firestone, & Scholl, 2018; Sun & Firestone, 2021; Van Tonder, Lyons, & Ejima, 2002; Wilder, Feldman, & Singh, 2011).

While at first this focus on composition might seem to apply only *within* objects, more recent theoretical work has made the case that this form of representation extends beyond single objects and their contours, to representations that hold *between* objects. Cavanagh (2021) recently proposed a 'language of vision,' whereby visual processing separates images into language-like components, including components such as 'visual nouns' (objects), 'visual verbs' (actions), and 'visual prepositions' (spatial relations), and structurally combines them into 'sentences' (descriptions). In this framework, such 'visual sentences' embody the principle of compositionality in vision, since they capture the relations that combines discrete components into a holistic representation. However, while we can extract information about such entities *based* on visual observation, it is an open question how the mind does so. Are such representations constructed via deliberative reasoning processes (after more basic elements are extracted), or automatically extracted and represented in visual processing itself?

Recent work lends support the latter possibility. First, there is evidence that relations are represented abstractly and categorically in visual perception. Observers performing rapid target-recognition tasks 'confuse' scenes depicting the same relation with one another, even when the participating objects share few visual features in common, e.g., a phone in a basket being mistaken for a knife in a cup (Hafri et al., 2024; Vettori, Hochmann, & Papeo, 2024). Confusion errors of this sort occur because representing the relation abstracted away from its constituent objects makes distinct scenes appear similar. Furthermore, even spatial relations that appear to vary from instance to instance are represented in an 'all-or-none,' categorical fashion. When a small ring approaches from above and passes a big ring, the spatial relation between the two is perceived in terms of discrete categories such as *above*, *touching*, *overlapping*, and *containing*. The visual system is especially sensitive to metric changes that cross category boundaries (e.g., from overlapping to containing) than those that do not (e.g., from less overlapping to more overlapping) (Lovett &

Franconeri, 2017).

Second, there is also evidence that visual processing binds representations of arbitrary entities to distinct roles in a relational *structure*. For example, in a relational scene where a girl is pushing a boy, the girl fills the role of *Agent* (i.e., the initiator of the action) and the boy the role of *Patient* (the recipient of the action). Recent work has shown that this binding happens rapidly and spontaneously: When observers repeatedly reported the location of a target individual (e.g., boy) in a stream of action photographs (e.g., girl-kicking-boy, boy-pushing-girl), they were slower when the target individual's role (Agent/Patient) switched (e.g., pusher on trial $n + 1$ but kickee on trial $n$) (Hafri et al., 2018). Thus, visual processing is sensitive to this structure, such that changes to this structure produce response costs even when observers are engaged in orthogonal tasks (Hafri, Papafragou, & Trueswell, 2013; Hafri et al., 2018; Vettori, Odin, Hochmann, & Papeo, 2023).

The above work suggests that visual processing represents relations in ways that preserve the identities of both the entities themselves and the relations in which they participate. This representational scheme is often called *role-filler independence* (Quilty-Dunn, Porot, & Mandelbaum, 2023), and it makes such representations compositional: Just as individual words compose together to form phrases and sentences in language, relational representations contain discrete constituents that combine in systematic ways (Hafri, Green, & Firestone, 2023). The existence of visual relational representations with this property suggests that some aspects of perception may exhibit core properties of a 'Language of Thought (LoT)' (Fodor, 1975; Quilty-Dunn et al., 2023), a format of representation that can readily accommodate compositionality in ways that other formats that are more traditionally associated with visual perception may not (i.e., iconic or 'picture-like' formats; Block, 2023; Burge, 2022; Carey, 2009; Kosslyn, Thompson, & Ganis, 2006).

### 1.2 Our question: What constraints govern the process of visual composition?

While compositionality is traditionally discussed in terms of representational *format*, the existence of LoT-like representations in visual perception raises an intriguing question about the compositional *process* itself: How are such representations composed by the mind from their constituent parts? In other domains such as speech processing, structured representations are constructed incrementally, as the speech signal is dynamic and temporally extended, unfolding over time (Christiansen & Chater, 2016). By contrast, in visual processing, relational content (objects and their visual features) is in principle immediately available from an image. Despite this, might visual relational representations also be 'built' sequentially by the mind (Figure 1C)?

Classic research in visual cognition offers clues about the dynamic nature of relational processing in vision. Ullman (1987) proposed the concept of *visual routines*—sequences of spatial operations executed to extract simple relations, such as whether one object is INSIDE, ON, or COLLINEAR with another. One well-known example of such visual routines is *curve-tracing*, in which the visual system systematically follows a curve's contour in order to judge whether two points lie on the same or different curve (Jolicoeur, Ullman,

& Mackay, 1986, 1991). These routines occur dynamically in both space and time, and are generally considered to require effort and intentional initiation (though see Wong & Scholl, 2024). However, this work primarily examines simple geometric features such as points, lines, and curves. It remains unclear how—or whether—such routines extend to more sophisticated relations between real-world objects (e.g., those shown in Figure 1A). These relations are fundamentally different: rather than being defined purely by spatial properties like continuity or particular distances, they often involve abstract roles or physical forces (e.g., Support, Containment). As such, they cannot be traced or followed in any literal sense. Instead, visual processing for such relations may rely on a different kind of routine—one that sequentially combines objects into a structured mental representation. If so, what principles govern this compositional process?

Insights from event cognition suggest that the *roles* of participants such as Agent and Patient are crucial for determining how relational scenes are processed in time. A range of 'Agent advantages' have been reported in the literature: relative to Patients, Agents are prioritized in visual search, recognition, and attention (Segalowitz, 1982); allow for better predictions about upcoming events (Cohn & Paczynski, 2013); facilitate the processing of actions (Cohn & Paczynski, 2013); and elicit stronger neural responses (Cohn, Paczynski, & Kutas, 2017). The primary function of Agent is even more evident in psycholinguistic research: When the Agent comes before the Patient in an English sentence (i.e., Agent as grammatical subject), readers find it easier to grasp the sentence's meaning. For example, a sentence like *the dog bit the man* is processed more readily than its passive counterpart, *the man was bitten by the dog* (Ferreira, 2003). On one hand, this Agent advantage seems intuitive: as the initiator of an action, the Agent often carries more information and ranks early as the subject in the sentence. Thus, it is possible that such advantages would only apply to Agent-Patient relationships and not extend beyond them, to spatial or physical relations involving inanimate entities. On the other hand, the ease of processing Agent-first order in event relations might reflect a more general mechanism in relational processing that applies to relations of all types. How, then, are other types of visual relations represented?

Here, we extend research on Agent-Patient events into more fundamental forms of relational processing, by testing the hypothesis that the mind builds spatial and physical relations sequentially, according to the roles of the participating objects. The objects in a relational scene can assume different roles (often called 'thematic roles' in linguistics). In spatial or physical relations such as ON or BELOW, these roles are known as 'Reference' (sometimes called 'Ground') and 'Figure'. Reference objects are generally those that are large, stable, and/or physically 'control' other objects, while figure objects are those that are small and/or mobile (Gleitman, Gleitman, Miller, & Ostrin, 1996; Landau & Jackendoff, 1993; Talmy, 1975).

Of note, there is a systematic relationship between the non-linguistic construal of such entities and the structural positions in which they are encoded in linguistic utterances, with the reference object placed farther down in the syntactic structure of the utterance than the figure (Landau & Gleitman, 2015). For example, in the sentence 'The bike is to the left of the garage', the grammatical subject (bike) is figure, and the grammatical object (garage) is reference. Interestingly, despite the fact that figure objects are often the subject of a sentence and thus (in English) appear first in sequence, the cognitive representation of such relations appears to be such that the reference object is primary. According to a tradition known as cognitive linguistics Miller and Johnson-Laird (1976); Talmy (1975), the reference object defines the spatial or physical reference frame relative to which the figure object is located (see also Gleitman et al., 1996; Landau & Jackendoff, 1993). Indeed, this fundamental asymmetry is precisely why the term 'Reference' is used in the first place. The asymmetric placement of entities in a linguistic utterance can even influence reference and figure assignment. Consider an utterance such as "The garage is next to the bike"; here, the garage and bike are in syntactic roles usually associated with figure and reference objects, respectively. This shift in structure either makes the sentence sound unnatural (or even imbues these entities with the properties corresponding to the roles associated with these syntactic positions; as if, e.g., there a small garage on wheels moving around a giant, stationary bike statue; Gleitman et al., 1996). This suggests that syntactic structure not only reflects, but can actively shape, relational interpretation in language. (As we show later, this linguistic influence may play a role in scene composition when visual properties alone do not provide sufficient cues.)

Vision research also hints at the primary role of reference objects in constructing relational scenes. For example, studies on complex scene perception suggest that visual processing takes advantage of the unique role of 'anchor' objects to guide search and recognition (Võ, Boettcher, & Draschkow, 2019). In cluttered scenes (e.g., a classroom), observers were slower to find the target object (eraser) if the anchor object (chalkboard) was swapped with an irrelevant object (map) (Boettcher, Draschkow, Dienhart, & Võ, 2018). Studies with simpler geometric stimuli also suggest that figure and reference objects play different roles in the temporal construction of relations. Indeed, prior work has found that the perception of certain spatial relations requires serial processing (Holcombe, Linares, & Vaziri-Pashkam, 2011). Evidence from attentional cuing also indicates that previewing the location of one object in a spatial relation can influence processing speed. Roth and Franconeri (2012) showed that observers responded faster to questions such as "Is the red disc above the blue disc?" when they previewed the linguistic subject (red disc) before seeing the full relation between two objects (Roth & Franconeri, 2012).

Developmental research also supports a structured composition process in representing certain spatial and physical relations. When children acted out a relational scene with real-world objects according to a statement (e.g., "The green block is on the top of the pink block."), they made fewer errors when they placed the figure object (green block) relative to a fixed reference object (pink block) than vice versa (Huttenlocher & Straus, 1968a). In similar work using both active and passive statements (e.g., "The red truck is pushing the blue truck"; "The blue truck is pulled by the red truck", etc.), children reconstructed relational scenes with real-world objects more quickly when placing the Agent (the red truck) with respect to the Patient, regardless of which entity served as the grammatical subject

(Huttenlocher, Eisenberg, & Strauss, 1968b). Although the above work is suggestive, the hypothesis that relational perception follows a canonical order has not yet been tested in psychophysical experiments. It remains unclear whether the visual system builds relations in an order that respects the objects' roles.

### 1.3 The present experiments: How to build a scene

Our work takes inspiration from the cognitive linguistics literature in hypothesizing that reference objects (e.g., tables, shelves, etc.) rather than figure objects (e.g., vases, laptops, etc.) serve as the scaffold for relational representations in visual perception (Gleitman et al., 1996; Landau & Jackendoff, 1993; Talmy, 1975). To test this hypothesis, we asked whether participants would construct relational scenes following a 'Reference-first' order, and whether participants' visual processing of relational scenes would be facilitated when they have visual access to the reference object before the figure object (as opposed to vice versa). We created relational scenes from various household objects (e.g., laptop, desk, lamp, nightstand), encompassing physical relations (e.g., desk supporting laptop) and spatial relations (e.g., laptop below desk). In Experiment 1, participants read linguistic descriptions and manually arranged objects on-screen to match the described relation, allowing us to replicate previous findings of a Reference-first advantage in manual construction tasks (Huttenlocher et al., 1968b; Huttenlocher & Straus, 1968a). Experiments 2–5 used a recognition paradigm in which participants matched visual scenes to linguistic or pictorial probes viewed just beforehand. This paradigm builds on the classic sentence–picture verification task, which has traditionally been used to study how people determine whether a linguistic statement accurately describes a picture (Clark & Chase, 1972, 1974). In the standard version of the task, participants read a sentence and view a scene, and then verify whether the sentence correctly describes the image. We introduced a crucial change: instead of presenting the full relational scene at once, we presented the objects asynchronously, either with the reference or figure object appearing first.

To foreshadow the key results, we found a Reference-object advantage across all five experiments: Participants employed a reference-first order in composing relational scenes, and they were faster to recognize a visual scene when the reference object appeared before the figure object rather than vice-versa. We further found that when visual and physical differences between objects were eliminated, the linguistic structure of the probe sentence influenced the order of composition. Taken together, these results suggest that even though visual scene information is in principle available to the observer all at once, the mind composes relational representations sequentially, in ways that respect the role of each element in the relation.

## 2 EXPERIMENT 1 – Manual Construction of Relational Scenes

How do people construct relational representations? Experiment 1 took a literal approach to this question by asking whether participants have a preference for the order in which they place constituent objects to compose relational scenes. Our approach was inspired by early studies of sentence comprehension conducted by Huttenlocher and colleagues, in which children placed one object with respect to a fixed object according to a statement (Huttenlocher et al., 1968b; Huttenlocher & Straus, 1968a). Children had an easier time doing so when the reference object was fixed in place first. The current study aimed to extend these previous findings by employing a similar paradigm, but with key differences: While previous studies fixed an object for children and asked them to place another object relative to it, our task allowed adult participants to place objects in whatever order they wanted. On each trial, participants were asked to compose a scene to match a pre-specified linguistic description by dragging objects into a framed workspace. While they could do so in whatever order they liked, we predicted that they would move the reference object first, even without external pressure to do so.

## 2.1 Method

### 2.1.1 Open Science Practices

An archive of the data, code, stimuli, experiment preregistrations, and other relevant materials is available at:
https://osf.io/vzxdg/?view_only=5b194f89f42542429f6c69b64b2e3630.

For each experiment, we preregistered the sample size, experimental design, and analyses (including exclusion criteria and some secondary analyses). Demos of the experiments can be viewed at https://palresearch.org/buildingrelations, so readers can experience them as participants did.

### 2.1.2 Participants

We recruited 40 participants for this experiment from the online platform Prolific (https://www.prolific.co/). (For a discussion of this participant pool's reliability, see Peer, Brandimarte, Samat, & Acquisti, 2017.) This sample size was determined based on a smaller pilot study. Participants were prescreened for a minimum approval rate of 85%, at least 50 prior submissions, normal or corrected-to-normal vision, native English proficiency, and U.S. nationality. Sample sizes were preregistered for this and all other experiments. All studies were approved by the Johns Hopkins University Institutional Review Board.

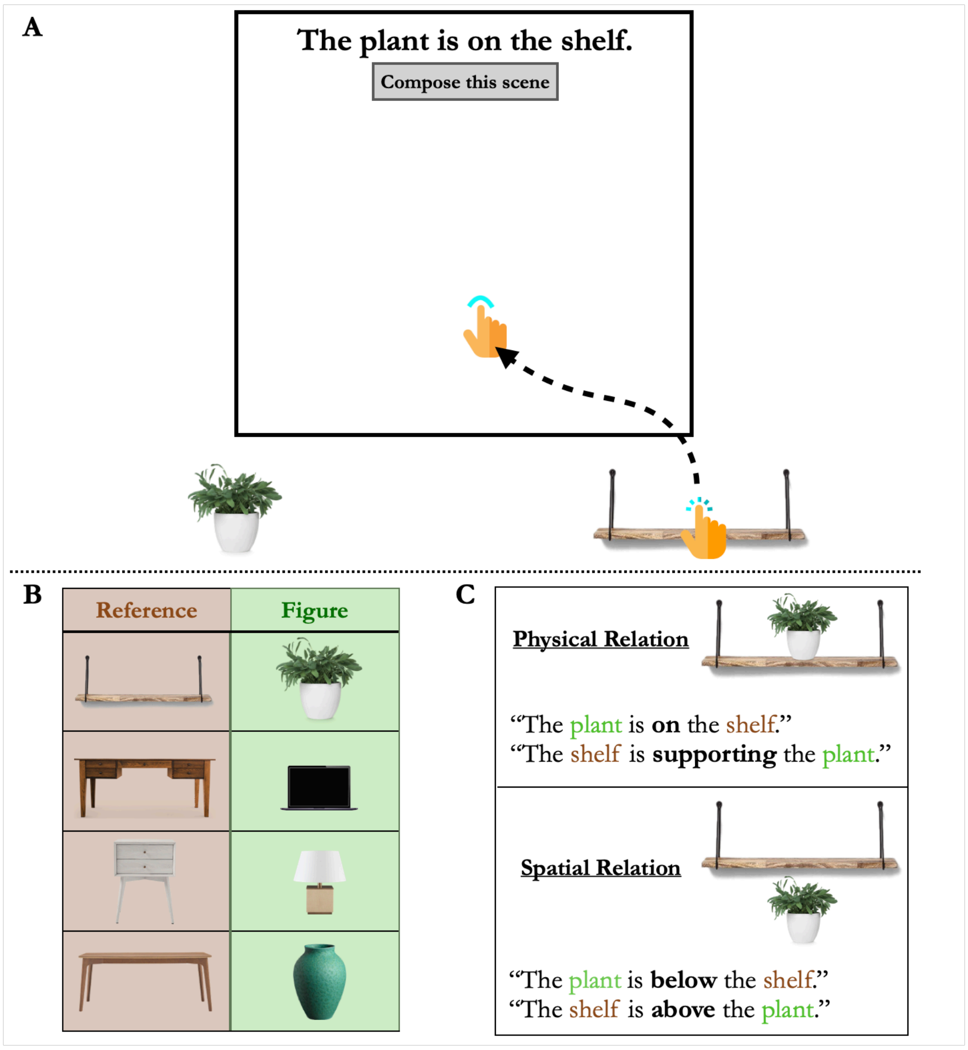


**Figure 2:** Illustration of the manual-composition task used in Experiment 1. (A) On each trial, participants were asked to compose a scene by moving two objects into the workspace, according to a sentence that described a relational scene. (B) The objects used to compose the scenes were four pairs of objects, with one reference object and one figure object in each pair. (C) The relational scenes were divided into two categories: physical relations and spatial relations. Each scene was described in two ways: either the figure object or the reference object was the grammatical subject of the descriptive sentence, and thus was the first mentioned entity in the sentence.

### 2.1.3 Stimuli

Eight colored images were used in the experiment, grouped into four pairs: vase/table, laptop/desk, lamp/nightstand, and plant/shelf (Figure 2B). Each pair consisted of a reference object that was relatively large and stable (e.g., table, desk, nightstand, and shelf) and a figure object that was relatively small and mobile (e.g., vase, laptop, lamp, and plant).

Participants were provided with sentences that described a relation between the two objects in each pair. These sentences varied along two dimensions: (1) whether the depicted relation was physical or (merely) spatial (e.g., "the plant is on the shelf" describes a physical relation, and "the plant is below the shelf" describes a spatial relation); and (2) whether the reference object or the figure object was the grammatical subject of the sentence or not (e.g., in “the plant is on the shelf,” the figure object, ‘plant,’ is the subject, while in “the shelf is supporting the plant,” the reference object, ‘shelf,’ is the subject). See Figure 2C for a complete list of sentences for one of the object pairs.

Images ranged in size from 120 × 68 pixels to 417 × 186 pixels and were presented in the participant’s Web browser. The workspace was presented at 600 × 600 pixels, with a white background. Because of the nature of online studies, we could not know the exact viewing distance, screen size, and luminance (etc.) of these stimuli as they appeared to participants. However, any distortions introduced by a given participant’s viewing distance or monitor settings would have been equated across all stimuli and conditions.

#### 2.1.4 Procedure

The experimental task is depicted in Figure 2A. On each trial, participants first read a statement describing a relation between two objects, and then they clicked a button to indicate they were ready to compose the scene. Immediately after the click, the two mentioned objects appeared beneath the workspace (one on the right and the other on the left). Participants dragged each object into the workspace in whatever way they chose to compose a scene that correctly reflected the statement. Once both objects were inside the workspace, participants were able to click on a button to proceed to the next trial.

Overall, the experiment consisted of 32 trials. The four object pairs were combined with the four types of sentences, which made 16 unique trials. Each combination of object pair and sentence appeared twice: once with the figure object on the left side (below the workspace), once with the figure object on the right side. Trial order was randomized across participants.

#### 2.1.5 Exclusions

As specified in the preregistration, we planned to exclude trials where the composed visual scenes did not accurately match the linguistic descriptions. To do so, we preregistered scene-specific boundaries within which each object should be placed in the particular scene in order to be considered accurate (with these boundaries detailed in the preregistration). We also planned to exclude any participant who had low overall accuracy ($<$ 90%), lacked at least one trial in each combination of the key factors (Relation Type, Sentence Structure, and Object Side), or failed to provide a complete dataset.

### 2.2 Results

One participant was excluded for failing to submit a complete dataset. As expected, subjects had little difficulty completing the task, with a mean accuracy of 98.7% in composing the visual scenes to match the linguistic descriptions given.

Crucially, participants overwhelmingly placed the reference object first (e.g., shelf before plant), doing so on 96.7% of trials across participants, $t(38) = 48.13$, $p < 2.2 \times 10^{-16}$. This pattern held regardless of sentence order (i.e., whether the reference object was the grammatical subject or object of the sentence), object identity (all four pairs of images), and relation type (physical or spatial). Moreover, this Reference-first preference emerged at the very beginning of the task: Even in the very first trial of the experiment, a majority of participants (34 out of 39) moved the reference object before moving the figure object (binomial test, $p = 2.43 \times 10^{-16}$). These effects held even when including all trials (including those coded as incorrect, $t(38) = 48.66$, $p < 2.2 \times 10^{-16}$), and they generalized across the different object pairs ($t$-test across object-pair means, $ts(38) \geq 35.90$, $ps < 2.2 \times 10^{-16}$). We also conducted a repeated-measures ANOVA across subject means of Reference-first proportion, with the factors of interest as Relation, Sentence Structure, and Object Side, and found that these factors did not significantly modulate the Reference-first effect ($Fs(1, 38) \leq 3.65$, $ps \geq 0.064$)).

These results provide initial evidence that the mind applies a canonical routine in constructing relational scenes. They also raise the possibility that the mind adopts this Reference-first routine in representing visual relations more broadly, including in visual recognition. We explore this possibility in the remaining experiments of this paper.

# 3 EXPERIMENT 2 – Visual Recognition of Relational Scenes

Experiment 1 revealed a predominant order in relational scene 'production': participants preferred to move the reference object into the scene first and position the figure object relative to it. Does this pattern extend beyond mere preferences and drive visual processing itself? Experiment 2 asked whether relational representations are built according to a similar compositional routine in visual *recognition*.

To do so, we used a variant of the 'sentence-picture verification task' initially developed by Clark and Chase (1972, 1974) to investigate how people decide whether or not a linguistic statement accurately describes a picture. In such a task, participants read a sentence (e.g., "The star is above the plus sign") and are asked to verify whether it is a correct description of an image that appears soon after. We made one crucial change to the standard paradigm: Instead of showing the image all at once, sometimes the reference object (e.g., the table) appeared a half-second before the figure object (e.g., the laptop), or vice versa.

Manipulating this display order allowed us to ask whether there is a privileged order for visual recognition. We reasoned that if the visual system builds relational representations sequentially, following the Reference-first order pattern observed in Experiment 1, then participants would be faster to verify the target sentence when they saw the reference object right before the figure object, because this presentation order would 'match' the order in which the mind constructs such representations.

## 3.1 Method

### 3.1.1 Participants

As per our preregistration, 40 participants were recruited through Prolific. This sample size was determined by a power analysis on a small pilot study that produced similar results and indicated a 99% probability of detecting the effect of interest. Participants in this and subsequent experiments had to pass the same pre-screening criteria as in Experiment 1, and they could participate only if they had not previously completed a related experiment in this series.

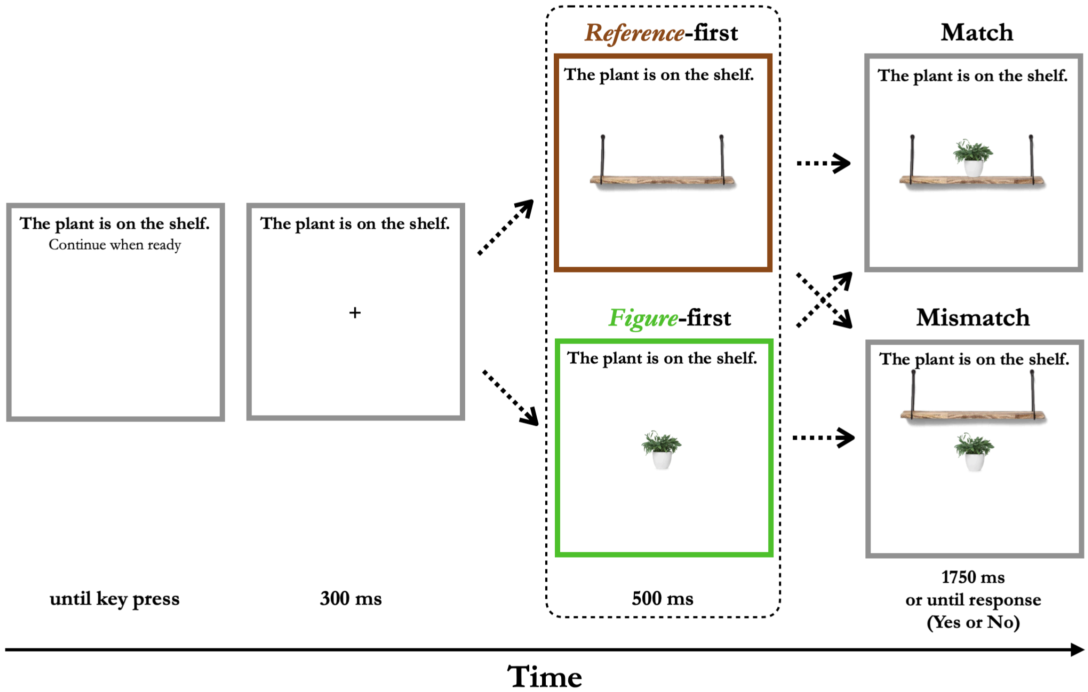


**Figure 3:** Illustration of the visual recognition task. At the beginning of each trial, participants were given a sentence describing a relational scene. Once they pressed a key to proceed, a fixation cross appeared in the center of the frame for 300 ms, and then either the reference or figure object appeared at the center. After 500 ms, this was followed by the other object, which completed the scene. (On some trials, the objects appeared simultaneously.) Participants indicated whether the resultant scene matched or mismatched the sentence description as rapidly and accurately as possible, before the trial timed out. (For simplicity, the 500-ms blank display before fixation is omitted in this figure.)

### 3.1.2 Design and Procedure

Participants were instructed that on each trial, they would read a sentence and then have to verify whether a subsequently presented visual scene matched the sentence. Figure 3 illustrates the trial sequence. All sentences and scenes were presented on a white background within a 600 × 600 pixel frame. At the beginning of each trial, participants read a sentence that described a relational scene (e.g., "The laptop is on the table"), presented at the top of the frame. After reading, they pressed the space bar to indicate that they were ready to continue (but had to remain on the sentence screen for at least 500 ms). Once participants pressed the key, a blank screen appeared for 500 ms, followed by a fixation cross at the center of the scene for 300 ms. Then the to-be-verified scene was presented. The sentence remained at the top of the image frame throughout the trial.

Each visual scene was presented in one of three object-order conditions: (1) Reference-first, in which the reference object was presented first and then the figure object appeared 500 ms later; (2) Figure-first, in which the figure object was presented first, followed by the reference object 500 ms later; and (3) Simultaneous, in which both reference and figure objects appeared at the same time, right after the fixation cross disappeared. After the full scene was displayed, participants judged whether the complete scene matched the pre-specified sentential description as fast as possible without sacrificing accuracy, by pressing either Y for a match or N for a mismatch. Trials timed out if no response was given within 1750 ms. Of note, in the two 500-ms delay conditions (Reference-first and Figure-first), the first presented object always appeared at central fixation, so its location was not predictive of the correct response. (In the Simultaneous condition, the center object could be either Figure or Reference, as described below.)

All four pairs of objects and 16 sentences used in Experiment 1 (Figure 2) were also used in this experiment. Several factors were fully crossed within participants: (a) Relation Type (spatial or physical), (b) Second Image Delay (0 ms or 500 ms), (c) Sentence Structure (Figure-as-subject or Reference-as-subject), (d) Trial Type (match or mismatch), and (e) Center Object Type (either the reference or figure object), yielding 128 test trials ($2 \times 2 \times 2 \times 2 \times 2 \times 4$ object pairs). Object images were the same size as in Experiment 1.

The key factor of interest was the presentation order of objects, determined by the combination of the factors Second Image Delay and Center Object. In particular, at the 0-ms second image delay (i.e., the Simultaneous condition), the object presented centrally in the visual scene was either Reference or Figure; while at the 500-ms delay, the object presented first (Reference or Figure) would always appear at the center. Six practice trials preceded the test trials and contained objects not used in the main study (a book and bookshelf), all in the Simultaneous object-order condition. This resulted in 134 trials in total. Test trial order was randomized for each participant.

### 3.1.3 Analysis

As stated in our preregistration, the dependent variable was the participant's response time (RT) on each trial, measured from the onset of the second image. (For the Simultaneous condition, the onset of the second image was also the onset of the full scene.) Only Match trials in which the visual scene matched the sentence description were analyzed. We also excluded trials that timed out before a response was given, error trials, and trials in which RTs were extraordinarily fast ($<$ 200 ms). Additionally, we excluded participants who met any of the following criteria: (a) Low overall accuracy ($<$ 90%), (b) too many time-outs ($>$ 5% of trials), (c) too many extraordinarily fast RTs on test trials ($>$ 5% of RTs $<$ 200 ms), (d) after trial exclusion, not having at least one trial in a cell for each combination of the factors of interest (i.e., Relation Type, Object Order, and Sentence Structure), or (e) failing to contribute a complete dataset. However, note that none of the results reported here or in subsequent experiments were dependent on the particular exclusion criteria used for RT or accuracy; in other words, the effects were significant in the same direction regardless of whether the exclusion criteria were applied or not.

We conducted a repeated-measures analysis of variance (ANOVA) on participant means of inverse-transformed response times (-1000/RT, correctly answered Match trials only) to examine the main effects of Object Order, Relation Type, and Sentence Structure, as well as their interactions. Our primary question in this study concerned Object Order: In particular, we expected to observe shorter RTs when the reference object was presented right before the figure object in the scene, as compared to vice versa. We expected this to hold regardless of relation type (spatial or physical). Crucially, we predicted that this would also hold regardless of sentence structure (i.e., whether the figure or reference object appeared as the grammatical subject of the sentence), which would indicate that any object-order advantage observed was not simply driven by the order in which objects were mentioned in the sentence.

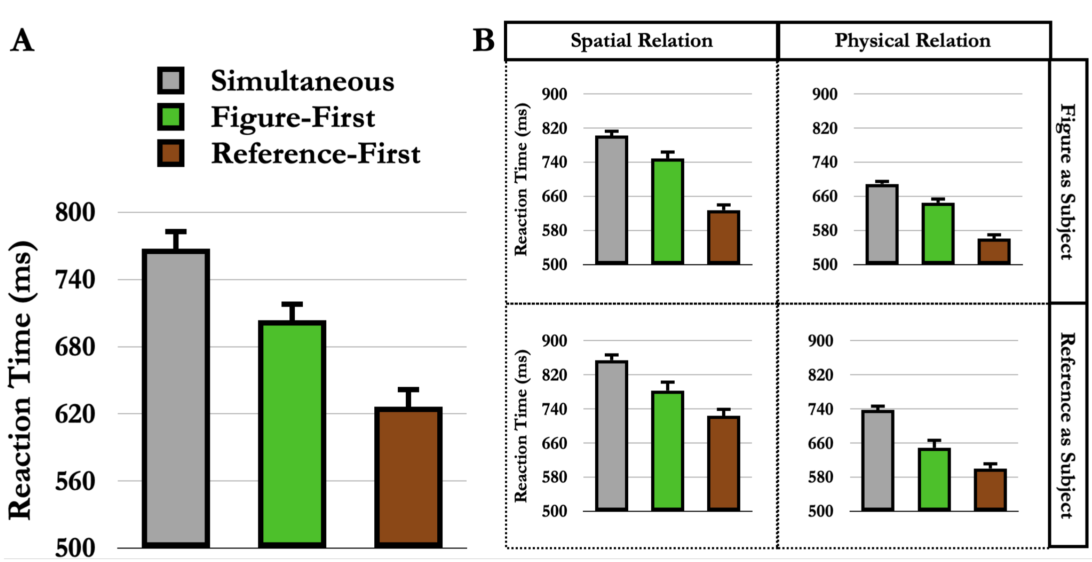


**Figure 4:** Results of Experiment 2. (A) Participants were faster verifying the relational scene when the reference object appeared first and the figure object second, compared to when the order was reversed or when both objects appeared simultaneously. (B) This Reference-first advantage in relational recognition emerged for both spatial ("above"/"below") and physical relations ("on"/"support"), regardless of which object was mentioned first in the sentence. Bars reflect mean response times across participants (computed from correct trials only), and error bars reflect within-participant 95% confidence intervals.

## 3.2 Results

Three participants were excluded based on preregistered criteria, leaving 37 participants for further analysis. As expected, participants had little difficulty completing the task, with a mean accuracy of 97% and a mean response time (across all conditions) of 741 ms.

The ANOVA revealed a significant main effect of Object Order, $F(2, 72) = 77.98, p = 2 \times 10^{-16}, \eta^2 = 0.68$. As shown in Figure 4A, the mean RT for the Reference-first condition was shorter than Figure-first and Simultaneous conditions, indicating that participants were faster to recognize the visual scene and verify that it matched the sentence when the reference object appeared before the figure object. Subsequent Holm-Bonferroni-corrected paired-samples *t*-tests revealed significant pairwise differences between the three Object-Order conditions (Reference-first vs. Figure-first, Reference-first vs. Simultaneous, and Figure-first vs. Simultaneous, all $ts(36) \geq 5.44$, $ps \leq 0.0001$, $ds \geq 0.25$). We note that the Simultaneous condition was slower than both the other two conditions. While we did not have strong predictions with respect to this condition, one possible explanation is that sequential presentation, even in the Figure-first condition, helps pre-segment the objects, whereas in the Simultaneous condition, participants can only begin to perform this segmentation once all objects have appeared on the display.

Figure 4B illustrates the effect of Object Order, split by Relation Type and Sentence Structure. As predicted, the 'Reference-object advantage' arose for both physical and spatial relational scenes, and it held no matter the order of elements mentioned in the sentence descriptions. Indeed, while there was a significant interaction of Object Order and Sentence Structure ($F(2, 72) = 7.0, p = 0.0017, \eta^2 = 0.16$), Holm-Bonferroni-corrected paired-samples *t*-tests confirmed significant pairwise differences between the three Object-Order conditions at each level of Sentence Structure (all $ts(36) \geq 3.22$, $ps \leq 0.005$, $ds \geq 0.54$). In addition, Relation Type and Sentence Structure both emerged as significant main effects (Relation Type: $F(1, 36) = 129.80, p = 1.7 \times 10^{-13}, \eta^2 = 0.78$; Sentence Structure: $F(1, 36) = 11.89, p = 0.0015, \eta^2 = 0.25$). However, there was no significant three-way interaction among the three factors ($F(2, 72) = 1.40, p = 0.25, \eta^2 = 0.037$).[1]

We also conducted secondary preregistered analyses to test whether the effect of Object Order generalized across the different object pairs. A repeated-measures ANOVA for mean RTs across object pairs showed a significant main effect of Object Order, $F(2, 6) = 55.8, p = 1.33 \times 10^{-14}, \eta^2 = 0.95$. Subsequent Holm-Bonferroni-corrected paired-samples *t*-tests revealed significant pairwise differences of the three Object-Order conditions, all $ts(3) \geq 3.85$, $ps \leq 0.033$, $ds \geq 1.92$.

# 4 EXPERIMENT 3 – Timing of the Compositional Process

Experiment 2 revealed a Reference-first advantage in the recognition of relational visual scenes: Participants were faster to match the scene to the pre-specified linguistic description when the reference object appeared just a half-second before the figure object, rather than vice versa. This result raises a natural question: How quickly does this effect emerge? Here we probed the timing of the compositional process in detail. We ran the same study as before, but with one change: We systematically varied the onset of the second object in

[1] It is worth noting that one prompt version differs slightly from the others: the Reference-first physical-relation sentence probe used constructions such as "The table is supporting the vase," which employs a verb ("support") rather than a preposition (as in "on," "above," or "below"). However, no appreciable slowdown was observed in this condition compared to the others (see Figure 4B). Moreover, the absence of a significant three-way interaction suggests that the object-order effect for this condition was largely consistent in both direction and magnitude with the other conditions.

the scene, from very early (100 ms) to late (1000 ms). This manipulation also allowed us to distinguish between different possible underlying mental processes driving the Reference-first advantage. One possibility is that the effect arises from deliberate, cognitive expectations: Participants may form predictions about what will appear next based on the first object's identity. In that case, the effect might take time to emerge and possibly strengthen as more time is available for reasoning between presentation of the two objects. Alternatively, visual processing itself might enforce a Reference-first order when constructing relational representations. In this case, we would expect the effect to emerge rapidly, even with minimal delays between the first and second object. By systematically varying the presentation timing, we aimed to distinguish between these possibilities.

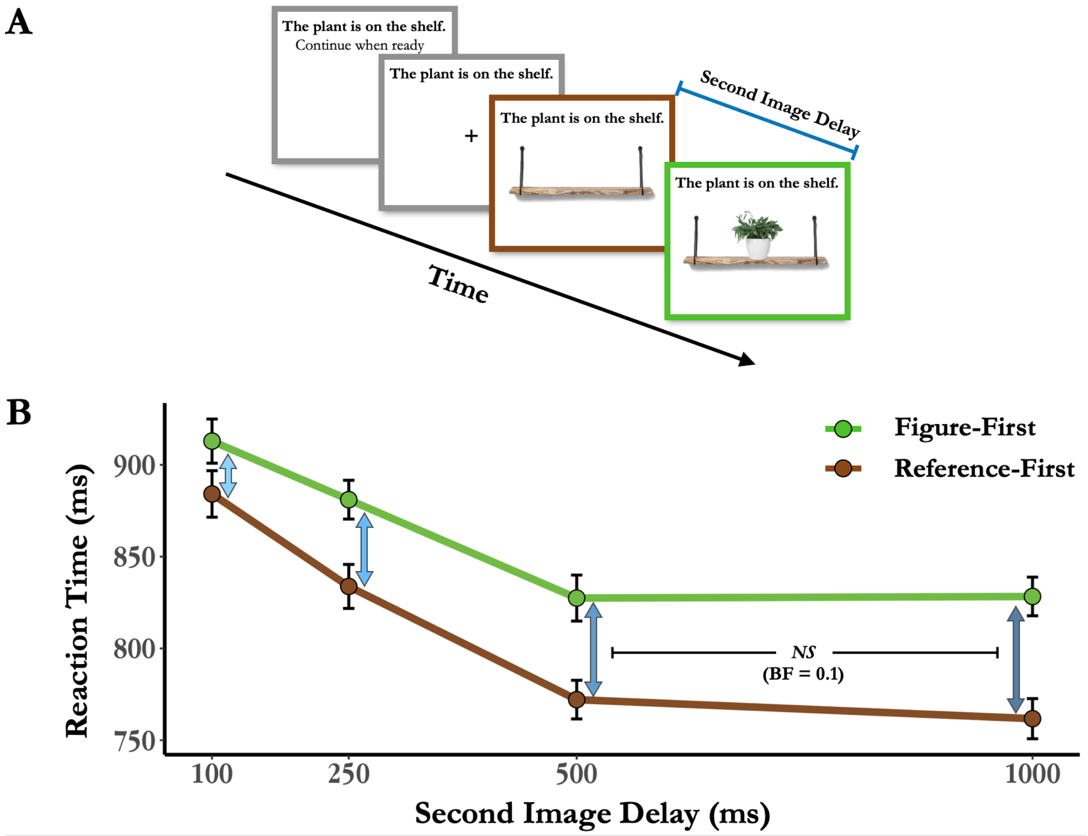


**Figure 5:** Trial structure and results of Experiment 3. (A) The delay between figure object and reference object presentation was systematically varied from 100 ms to 1000 ms. (For simplicity, blank displays during the trial are omitted from this figure.) (B) The Reference-first advantage (i.e., faster RTs when the reference object appeared first) emerged as early as 100 ms, increased to a peak at 500 ms, and then plateaued. Filled circles reflect mean response times across participants (computed from correct trials only), and error bars reflect within-participant 95% confidence intervals.

## 4.1 Method

### 4.1.1 Participants

One-hundred fifty participants were recruited through Prolific. This sample size was chosen based on a power analysis of a small pilot study and was preregistered.

### 4.1.2 Procedure

Stimuli, procedures, and exclusion criteria were identical to those in Experiment 2, except that the onset delay of the second object varied across trials: 100 ms, 250 ms, 500 ms, and 1000 ms (Figure 5A). There was no Simultaneous (i.e., 0 ms) condition in this experiment. Otherwise, the factors in the experiment were the same as in Experiment 2: 4 (Second Image Delay) $\times$ 2 (Object Order: Reference-first or Figure-first) $\times$ 2 (Relation Type: Physical or Spatial) $\times$ 2 (Trial Type: Match or Mismatch) $\times$ 2 (Sentence Structure: Figure-as-subject or Reference-as-subject), yielding 64 trials. The four pairs of objects were fully distributed among three primary factors—Second Image Delay, Object Order, and Relation Type—and randomly assigned among other factors (Trial Type [Match or Mismatch] and Sentence Structure [Reference-as-subject or Figure-as-subject]). Participants were given six practice trials at the beginning of the experiment to become familiar with the task (all with 0-ms delay between the first and second object).

## 4.2 Results

Twenty-four participants were excluded based on preregistered criteria, leaving 126 participants for further analysis. The remaining participants had little difficulty completing the study, with a mean accuracy of 97% and a mean response time (across all conditions) of 865 ms.

We first conducted a repeated-measures ANOVA on participant means of inverse-transformed response times (-1000/RT, correctly answered Match trials only) to examine the main effects of interest in this experiment—Second Image Delay, Object Order, Relation Type—as well as their interactions. Consistent with Experiment 2, the ANOVA revealed a significant main effect of Object Order, $F(1, 125) = 85.89, p = 7.02 \times 10^{-16}, \eta^2 = 0.41$, confirming an overall Reference-first RT advantage.

The ANOVA also revealed a significant interaction between Object Order and Second Image Delay, $F(3, 375) = 4.35, p < 0.01, \eta^2 = 0.033$, suggesting that the magnitude of Reference-first advantage differed depending on the onset delay of the second object. To examine this further, we first computed the mean Reference-first RT advantage at each level of delay (collapsing over Relation Type) by subtracting Reference-first from Figure-first inverse RTs. One-sample *t*-tests showed a significant Reference-first advantage at all delay conditions (100 ms: $t(125) = 2.5$, $p = 0.013$, $d = 0.22$; 250 ms: $t(125) = 4.7$, $p = 1.29 \times 10^{-5}$, $d = 0.22$; 500 ms: $t(125) = 5.8$, $p = 1.31 \times 10^{-7}$, $d = 0.22$; 1000 ms: $t(125) = 6.4$, $p = 9.60 \times 10^{-9}$, $d = 0.22$). That is, participants were faster to verify relational scenes when the reference object appeared right before the figure object, even with a minimal 100-ms delay (Figure 5B).

To further explore how this effect unfolded over time, we conducted a series of paired-sample *t*-tests to compare the Reference-first advantage between each pair of delay conditions. The Reference-first advantage significantly increased from the 100-ms delay to the 500-ms delay ($t(125) = 3.14$, $p < 0.01$, $d = 0.28$), but then showed no further increase in magnitude from 500 ms to 1000 ms, $t(125) = 0.25$, $p = 0.80$). An exploratory Bayesian paired-sample $t$-test provided further evidence in favor of no difference between the 500-ms and 1000-ms conditions ($BF_{01} = 0.1$, using the default Cauchy prior with scale $\sqrt{2}/2$). In other words, the Reference-first RT advantage peaked at the 500-ms delay and then plateaued (See Figure 5B).

Overall, the Reference-first advantage emerged even when the figure object appeared just a brief moment after the reference object (just 100 ms). This effect quickly increased and then plateaued after a half-second delay. These results suggest that the compositional process for building relational representations from visual scenes is rapid and does not rely on slow, deliberate reasoning processes, such as predicting what should happen next after seeing a given object.

# 5 EXPERIMENT 4 - Image-Only Composition

The previous experiments found that relational scenes were matched more quickly to their corresponding linguistic descriptions when the reference object appeared before the figure object, illuminating the compositional process for between-object relations in visual recognition. However, the task involved both visual and linguistic components: participants compared a visual representation to a linguistic one (i.e., the previously presented sentence). Considering the compositional nature of natural language, it is conceivable that the linguistic probe could have influenced how the recognition process unfolded, without any corresponding compositional process within recognition itself.

The present experiment minimized that potential influence by running the original recognition study with one crucial change: we replaced the linguistic probe with a visual one. This allowed us to test whether evidence of compositional visual processing emerges independent of the format of the probe stimulus.

## 5.1 Method

### 5.1.1 Participants

Forty participants were recruited for this experiment. This sample size was the same as Experiments 1 and 2.

### 5.1.2 Procedure

The same stimulus set from Experiments 2 and 3 was used in this recognition task. The paradigm was similar to that used in Experiments 2 and 3, with one key difference: instead of using linguistic descriptions as probes, each trial began with a pictorial probe showing a target relational scene. As shown in Figure 6A, the probe image was presented for 350 ms, followed by a mask image for 350 ms. The mask was a box-scrambled version of all object images (chosen randomly with replacement from 16 masks, made up of $22 \times 22$ blocks), and was included to interrupt the formation of afterimages and iconic memory for the probe. After the mask, a blank screen of 100 ms and a fixation cross of 300 ms were displayed. Then, either the figure object or the reference object was displayed, followed by the second object 500 ms later. At this point, participants responded whether the scene matched the probe image or did not. The experiment followed a 2 (Relation Type: Physical vs. Spatial) $\times$ 2 (Object Order: Figure-first or Reference-first) $\times$ 2 (Trial Type: Match or Mismatch) $\times$ 4 (Object Pairs) design resulted in 32 unique trials. Each unique trial repeated twice, and there were also 6 practice trials at the beginning of the session, resulting in a total of 70 trials. Practice trials always featured a 500-ms delay between objects. The probe was presented centered on a frame with a gray background and dashed border, scaled to 75% of the size of the target scene in order to avoid overlap in image features between probe and target.

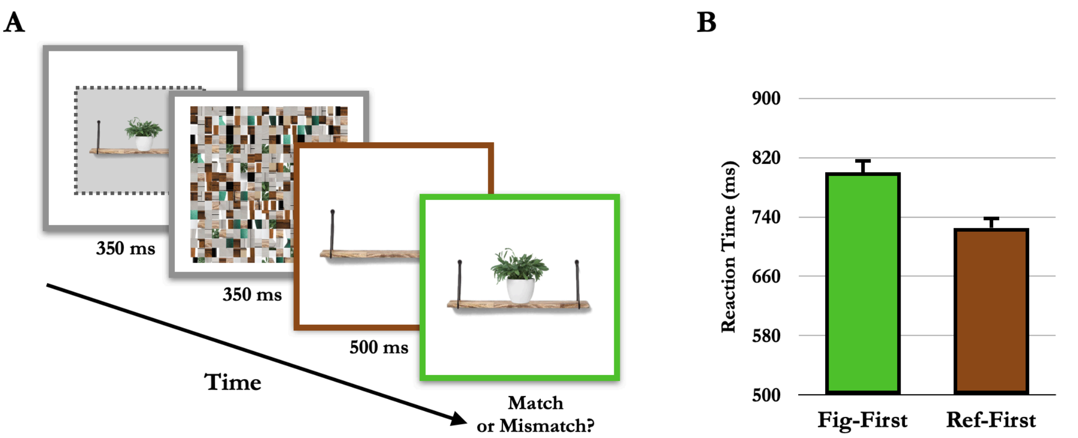


**Figure 6:** Trial structure and results of Experiment 4. (A) Participants viewed a relational scene; after being replaced by a mask, its constituent objects reappeared either in a Reference-first or Figure-first sequence (e.g., the shelf appearing before the plant). Participants then judged whether the second scene matched the first. (For simplicity, the blank display and fixation cross during the trial are omitted from this figure.) (B) Responses were faster when the reference object was displayed first. Bars reflect mean response times across participants (computed from correct trials only), and error bars reflect within-participant 95%confidence intervals.

## 5.2 Results

Six participants were excluded based on our preregistered exclusion criteria, leaving 34 participants for further analysis. The remaining participants had little difficulty completing the study, with a mean accuracy of 96% and a mean response time (across all conditions) of 773 ms.

As shown in Figure 6B, a Reference-first RT advantage was again observed: Participants were faster to match the visual scene with the pictorial probe when the reference object appeared right before the figure object in the scene, rather than vice versa (725 ms vs. 800 ms). A 2 $\times$ 2 repeated-measures ANOVA on participant means of inverse-transformed response times (-1000/RT, correctly answered Match trials only) that included Object Order and Relation Type as factors confirmed a significant main effect of Object Order ($F(1, 33) = 44.61, p = 1.33 \times 10^{-7}, \eta^2 = 0.57$). There was also a significant effect of Relation Type ($F(1, 33) = 112.4, p = 3.67 \times 10^{-12}, \eta^2 = 0.77$), with responses to physical relations being faster than those to spatial relations (690 ms vs. 836 ms). There was no significant interaction between Object Order and Relation Type ($F(1, 33) = 0.51, p = 0.48, \eta^2 = 0.015$).

These findings demonstrate a Reference-first advantage independent of the format of the probe stimulus. This suggests that the compositional process for building relational representations can arise in visual processing alone, rather than arising only from a cognitive comparison between representations formed from linguistic and visual modalities.

# 6 EXPERIMENT 5 - Identical-Object Composition

Our previous experiments consistently revealed a canonical order for visual recognition of relational scenes, suggesting that reference objects, rather than figure objects, take precedence in forming relational representations. However, in those experiments, the roles of the objects were confounded with certain visual properties. As shown in Figure 2B, the reference objects used (i.e., table, desk, nightstand, and shelf) were typically large, rectilinear, and stable, while the figure objects (i.e., vase, laptop, lamp and plant) were smaller, more mobile, and contained more rounded features. While an object's role in a relational scene is often predictable from properties such as size, shape, or other mid-level visual features, these properties are not essential for determining role. Instead, what often defines Reference-hood, particularly for relations such as support-from-below ("on"), is whether one object physically *controls* another (Landau & Gleitman, 2015; Talmy, 1975). These 'hidden' forces underlie many sophisticated relations between objects, transcending the lower-level visual properties of individual objects, which are typically extracted efficiently in the course of visual processing (Long, Konkle, Cohen, & Alvarez, 2016; Long, Yu, & Konkle, 2018). Thus, it remains unclear whether the Reference-first effect is driven solely by low- or mid-level visual differences between objects or also by the more abstract relationships between them: relations like ON, SUPPORT, ABOVE, or BELOW. The previous experiments could not distinguish between these two possibilities.

To do so, we ran a final recognition experiment using a completely new set of object stimuli. Instead of the previous objects, which differed in their visual properties (i.e., the table, laptop, etc.), we used identical objects differing only in color: a red book and a blue book. Consider the support relation depicted in Figure 7A. Here, the red book *supports* the blue book by exerting a stabilizing force (against gravity). This 'hidden' force establishes the red book as the reference object, while the blue book, being physically controlled, is the figure object.

The situation differs for spatial relations without physical control, such as ABOVE. Imagine a blue book above a red book; what determines role assignment here? Talmy and others (Gleitman et al., 1996; Landau & Jackendoff, 1993; Talmy, 1975) noted that Figure and Reference roles parallel grammatical roles in language, with figure objects (e.g., a cat) often mapped to Subject position and reference objects (e.g., a mat) to Complement position—the deeper position in syntactic structure (see Figure 7B). Crucially, this mapping is bidirectional: syntactic structure can shape how objects are interpreted as Figure or Reference. For instance, the sentences *The bike is next to the garage* and *The garage is next to the bike* differ in their implied interpretations. While the second sentence is unusual, it becomes plausible in a context where the garage is mobile and the bike is stationary—precisely the properties that figure and reference objects, respectively, often possess. This suggests that syntax can guide relational interpretation in the absence of visual cues and even 'imbue' participating objects with the typical properties of their assigned roles.

To test this, we reintroduced the sentence-picture verification task here. For physical relations such as SUPPORT, we hypothesized that sentence structure would again not influence the Reference-first advantage, as Reference roles are determined by physical control (Figure 7A). However, for spatial relations like ABOVE, we predicted that sentence structure would play a key role. For instance, in Figure 7B, where the sentence is *The blue book is above the red book*, the blue book occupies Subject position and the red book Complement position. Based on prior theoretical work (Gleitman et al., 1996; Landau & Jackendoff, 1993; Talmy, 1975), we hypothesized that the Complement object—in this case, the red book—would gain a response-time advantage, consistent with the Reference-first effect. Notably, this does not correspond to a simple mapping between sentence order and image order. For example, in Figure 7C, the Complement object (red book) is the *second* item mentioned in the sentence but is expected to afford a processing advantage when viewed *first* in the scene due to its role as Reference (determined by syntactic position in the sentence probe).[2]

By designing the experiment in this way, with new controlled object stimuli and a sentence-verification task, we aimed to investigate the interplay between linguistic and visual influences on the compositional process.

## 6.1 Method

### 6.1.1 Participants

In line with our preregistration, 100 participants were recruited through Prolific. This sample size was chosen based on a power analysis of a small pilot study.

### 6.1.2 Stimuli and Procedure

The relational scenes in this experiment consisted of two identical objects differing only in color: a red book and blue book. As in previous experiments, we tested two types of relations: physical and spatial. For physical relations, Reference and Figure roles were determined by physical control, with the supporting object designated as the Reference

[2] We also piloted an image-only version of the task using the book stimuli, where participants viewed spatial relations (e.g., red book above blue book) without linguistic prompts. Preliminary data appeared to show a *bottom-first* RT advantage: Participants responded faster when the object positioned at the bottom of the scene (e.g., the blue book) appeared first. While we initially expected no preference for spatial relations, this result suggests that, in the absence of linguistic or physical-control cues (i.e., support-from-below), a bottom-first strategy may emerge as a default visual bias (see Langley & McBeath, 2023 for evidence that lower regions of scenes are perceptually salient). However, as will be shown, Experiment 5 revealed that the bottom-first bias for visual relations is flexible: Linguistic structure effectively overrides it for spatial relations like ABOVE, while physical control dominates role assignment for ON relations regardless of order in the linguistic probe.

(Figure 7A). For spatial relations, however, Reference and Figure roles were determined by the grammatical structure of the sentence probe (Figure 7B). For example, when the sentence "The red book is below the blue book" served as the linguistic probe, the grammatical complement (i.e., blue book) functioned as Reference, and the grammatical subject (i.e., red book) functioned as Figure.

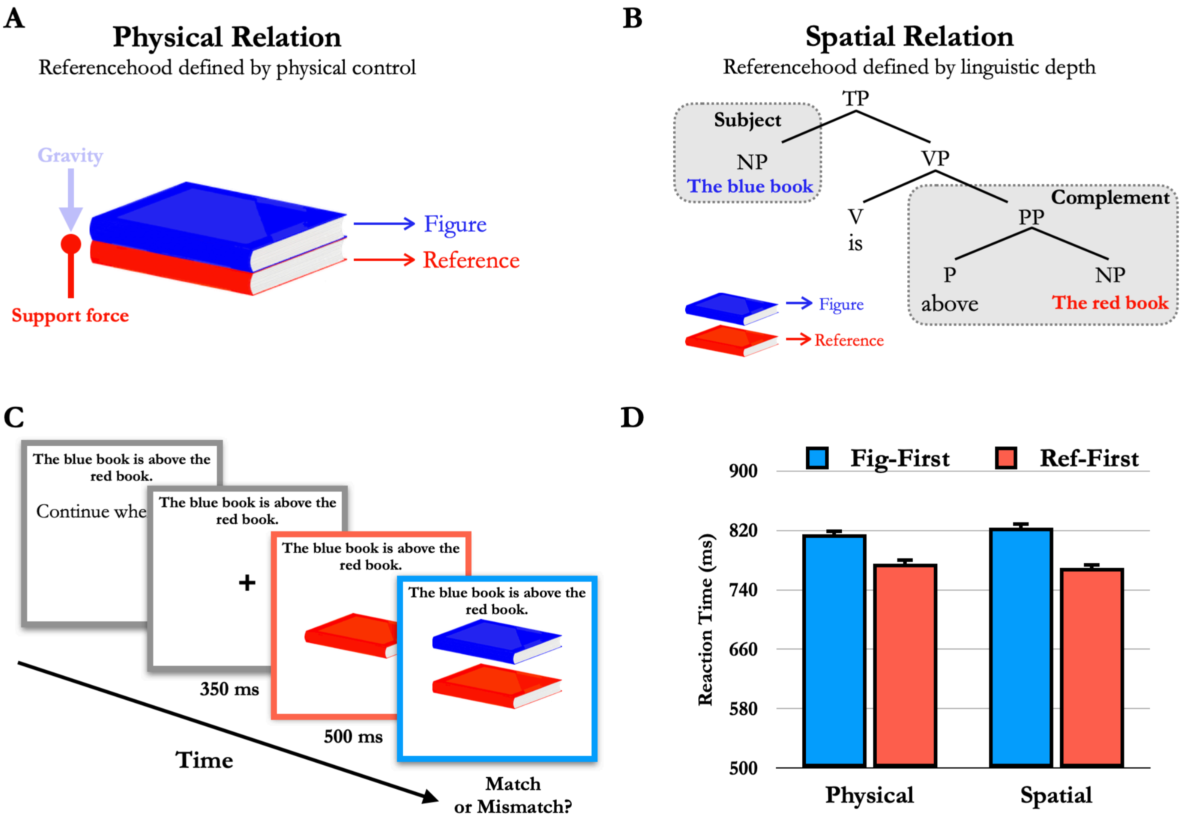


**Figure 7:** Illustration of the identical-object task in Experiment 5. Since the two objects differed only in color, their roles were determined by either physical control or linguistic structure. In the experiment, the colors of figure and reference object were counterbalanced. (A) For physical relations, the reference object provided support against the force of gravity for the figure object. (B) For spatial relations, the reference object was the entity embedded deeper in the linguistic structure than the figure object. (C) In the task, participants read a sentence description at the beginning of each trial and then verified whether the subsequent scene matched the description. (The 500-ms blank between sentence and fixation is omitted from the figure for simplicity.) (D) Results showed that participants were faster in verifying scenes when the reference object appeared before the figure object, for both physical and spatial relations. Bars reflect mean response times across participants (computed from correct trials only), and error bars reflect within-participant 95% confidence intervals.

As in previous experiments, there were several factors fully crossed within participant: (a) Relation Type (Physical or Spatial); (b) Book Order (Red or Blue book appearing first in the visual scene); (c) Sentence Structure (Red or Blue book as grammatical subject of the linguistic probe); and (d) Role Assignment (Red or Blue book serving as Reference in the visual relation). This resulted in 16 unique trials ($2 \times 2 \times 2 \times 2$), with each repeated 4 times, yielding 64 Match trials. In addition, there were 64 Mismatch trials, consisting of 3 types: (i) Role Mismatch (16 trials): The Reference and Figure roles were swapped (e.g., if the sentence stated, "The red book is on the blue book", the visual scene depicted a *blue* book on a *red* book); (ii) Relation Mismatch (16 trials): The relational category was changed (e.g., if the sentence stated, "The red book is on the blue book", the visual scene depicted a blue book *above* a red book); and (iii) Full Mismatch (32 trials): Both role assignment and relational category were inconsistent with the sentence. The full experiment consisted of 136 trials (8 practice trials, 64 Match trials, and 64 Mismatch trials). The 128 test trials were presented in a fully randomized order for each participant.

For analyses, we created a new Object Order factor (with Reference-First and Figure-First conditions), where Reference and Figure were defined differently based on the Relation Type. For physical relations, the supporting object was Reference and the supported object was Figure. By contrast, for spatial relations, these were based on grammatical position in the sentence probe: the grammatical object served as Reference and the grammatical subject as Figure.

## 6.2 Results

In accordance with our preregistered exclusion criteria, 16 participants were excluded, leaving 84 participants for further analysis. The remaining participants had little difficulty completing the study, with a mean accuracy of 97% and a mean response time (across all conditions) of 846 ms.

As shown in Figure 7D, even though the figure and reference objects were identical in size and shape, participants were still faster verifying the relational scene when the reference object appeared before the figure object than vice versa (772 ms vs. 820 ms). This Reference-first RT advantage was confirmed by a 2 × 2 repeated-measures ANOVA, which revealed a main effect of Object Order ($F(1, 83) = 57.40, p = 4.51 \times 10^{-11}, \eta^2 = 0.41$). There was also a marginally significant interaction between Relation Type and Object Order ($F(1, 83) = 3.77, p = 0.056, \eta^2 = 0.043$), but no significant main effect of Relation Type ($F(1, 83) = 0.12, p = 0.74, \eta^2 = 0.0014$).

To further examine the effect of Object Order within each Relation Type, we conducted Holm-Bonferroni-corrected paired-samples *t*-tests separately for physical relations and spatial relations. Both analyses confirmed the advantage for the Reference-first order (Physical: ($t(83) = 7.70, p_{corrected} = 5.20 \times 10^{-11}, d = 0.84$; Spatial: $t(83) = 4.03, p_{corrected} = 1.24 \times 10^{-4}, d = 0.44$). Finally, to determine whether the Object-Order effect was stronger for certain relational words over others, we conducted two separate paired *t*-tests on the Reference-first RT advantage (computed as in Experiment 3): one for physical relations ("on" vs."supporting") and one for spatial relations ("below" vs."above"). Neither test was significant ($ts(83) < 1.37$, corrected $ps > 0.34$).

This experiment disentangled objects' relational roles from relevant visual properties (e.g., size, shape), allowing us to draw several conclusions. First, the persistence of the Reference-first RT advantage suggests that the Reference-first advantage may be driven by objects' abstract roles as Reference and Figure, rather than solely from their visual features. Second, when the asymmetry between objects is not given by their visual differences intrinsic to the objects (e.g., size, shape) nor by their physical relationship (e.g., via physical control), the syntactic structure of a linguistic description can guide Figure and Reference assignments, shaping the order in which relational representations are mentally constructed.[3]

# 7 General Discussion

The present work investigated how everyday visual relations (such as one object supporting another) are represented in the mind, revealing key principles governing how they are composed in time. In a manual construction task (Experiment 1), participants assembled relational scenes by placing reference objects (e.g., tables, desks) first, followed by figure objects (e.g., vases, laptops). Similarly, in a series of visual recognition tasks (Experiments 2–5), participants demonstrated a Reference-first advantage, responding faster when the reference object appeared before the figure object. This Reference-first advantage emerged rapidly—within just 100 ms—and plateaued by 500 ms (Experiment 3), suggesting that it does not rely on deliberative expectations about object order. Notably, this effect persisted even without linguistic prompts, suggesting that the visual system independently employs a Reference-first compositional routine (Experiment 4). Finally, we found that relational roles (Reference or Figure) are assigned based on different sources of information. While visual properties or physical control appear to be primary drivers of Figure and Reference role assignments, linguistic descriptions can guide role assignments in the absence of large asymmetries in these cues, and thus dictate the order in which to build relational representations (Experiment 5). Taken together, our findings suggest that the mind automatically employs a sequential routine for composing relational representations, respecting each object's role in the relation: Reference first, Figure second.

## 7.1 Understanding perception as a compositional process

Our work aligns with a growing body of research exploring compositional representations in visual perception. Classic theories of object representation propose that objects are not processed as undifferentiated wholes, but rather as hierarchically decomposed structures consisting of parts and subparts (Biederman, 1987; Feldman & Singh, 2006; Marr & Nishihara, 1978). Such hierarchical structures not only define the relations among constituent parts but also establish a principle of primacy, whereby certain components carry greater weight than others in the representation. For example, the main skeletal axis of a shape is

[3] To further test whether the linguistic effects in Experiment 5 were driven by syntactic structure rather than surface word order, we piloted a version of the task using *it*-cleft sentences (e.g., *It is the red book that is below the blue book* vs. *It is the red book that the blue book is below*). These sentences reverse the order in which the objects are mentioned while preserving the deeper syntactic structure (i.e., which entity serves as subject vs. complement). Preliminary results trended in the predicted direction—consistent with syntactic structure driving the effect—but the task proved challenging for participants due to the processing complexity of *it*-cleft sentences, leading to longer and more variable response times. For this reason, we did not pursue a full version of this study, though the pilot findings support the conclusion that syntactic structure, rather than linear word order, determines relational composition in such cases.

given greater representational priority than the 'ribs' that define the peripheral parts of a shape, reflecting an intrinsic ordering principle in object perception (El-Gaaly, Froyen, Elgammal, Feldman, & Singh, 2015; Feldman & Singh, 2006). This hierarchical precedence is even reflected in how object representations are 'grown' or generated in the mind: Mounting empirical evidence suggests that such representations are composed in a systematic order, where main axes emerge before subordinate branches, reinforcing the psychological reality of these processes (Ayzenberg & Lourenco, 2022; Destler, Singh, & Feldman, 2023; Sun & Firestone, 2022).

Our findings extend this principle beyond individual objects to between-object relations: Just as certain object parts take precedence in forming object representations, certain relational constituents (here, reference objects) take precedence in forming relational representations. In doing so, our work contributes to growing scientific attention on visual relations as a fundamental unit of perception and cognition (for reviews and discussion, see Cavanagh, 2021; Hafri & Firestone, 2021; Hafri, Green, & Firestone, 2023; Hafri & Papeo, in press; Hochmann & Papeo, 2021; Hummel & Holyoak, 2003; Kaiser, Quek, Cichy, & Peelen, 2019; Miller & Johnson-Laird, 1976; Papeo, 2020; Peelen, Berlot, & de Lange, 2024; Quilty-Dunn et al., 2023; Võ et al., 2019).

The fact that compositional representations exist both within and between objects may suggest a fundamental and general kind of compositional process that extends across diverse relational domains. One key example comes from social cognition, where event representations are sensitive to certain compositional orders for relational roles like Agent and Patient. In particular, Agents are prioritized in perception, recognition, and prediction of events, substantiating their primary role in relational encoding (Brocard, Wilson, Berton, Zuberbühler, & Bickel, 2024; Cohn & Paczynski, 2013; Cohn et al., 2017; Hafri et al., 2018; Sauppe & Flecken, 2021; Ünal, Wilson, Trueswell, & Papafragou, 2024; Wilson, Zuberbühler, & Bickel, 2022). Recent work shows that these event-based relational representations exist even in the minds of preverbal infants, indicating that such compositional processes do not rely on natural language but are rooted in early-emerging non-linguistic cognitive capacities (Hafri, 2024; Papeo et al., 2024). Our findings extend these insights from social relations to physical and spatial ones, demonstrating that compositional principles govern not only event structure but also the perception of objects in space. This is consistent with the idea that relational structure, rather than individual objects, form the backbone of visual scene perception writ large.

In this way, the present work also dovetails with a renewed interest in the 'Language-of-Thought' (LoT) hypothesis (Fodor, 1975), which has re-emerged in debates over the format of mental representation (see Quilty-Dunn et al., 2023, and commentaries therein). The LoT framework proposes that certain types of mental representations are composed of discrete, combinable elements—a principle originally formulated to explain systematicity and productivity in language and high-level reasoning. Recent extensions of this framework suggest that LoT-like representations may exist across many cognitive systems, including in visual perception (Mandelbaum et al., 2022). In a recent article (Hafri, Green, &

Firestone, 2023), we built on this idea, arguing that visual perception exhibits core LoT-like properties, where discrete perceptual units (e.g., object parts or whole objects) combine systematically.

The current work extends this proposal not only by reinforcing the notion that visual perception involves compositional representations, but also by revealing the *processes* by which they are constructed—in other words, the 'psychophysics' of relational composition, or the timing and ordering of how relational structures are built from their parts. Our results provide evidence for a sequential combinatorial process that operates over abstract relational roles and generalizes beyond event structure to spatial and physical relations, advancing beyond previous work in this area (Boettcher et al., 2018; Franconeri, Scimeca, Roth, Helseth, & Kahn, 2012; Holcombe et al., 2011). Our findings suggest that visual composition is not an instantaneous process, but one that unfolds in a structured, role-sensitive manner, akin to how linguistic syntax forms a structural basis for interpreting utterances.

### 7.2 The interface between vision and language

Our findings highlight a novel aspect of how visual and linguistic systems might interact during scene perception. On the one hand, the exact word order of the linguistic prompts we employed did not generally alter the order by which relational representations were constructed (indexed by RT differences between Reference- and Figure-first orders). On the other hand, Experiment 5 demonstrated that linguistic structure can guide the assignment of Figure and Reference roles when strong visual cues to asymmetry are absent (e.g., in visually symmetric relations such as *above* or *below*; Gleitman et al., 1996; Talmy, 1975).

More broadly, our findings suggest that while the visual and linguistic systems may operate largely independently, they converge under conditions of perceptual ambiguity: Linguistic descriptions typically exert little influence on scene processing (at least of the kind studied here), but when perceptual cues are ambiguous, language can 'imbue' objects with relational roles, influencing the compositional process. However, we suspect that this influence of language does not directly alter visual representations themselves (e.g., by changing the objects' appearance in the scene; Firestone & Scholl, 2016). Instead, it may function as a kind of 'cognitive instruction,' guiding how observers attend to and encode an upcoming image (Knowlton et al., 2021)—albeit in a manner that may not reach explicit awareness. Crucially, whatever the precise mechanism by which language influences scene processing here, its effect is not determined merely by the probe's surface word order (where the reference object appears second) but by its syntactic structure—that is, by what occupies the deeper, hierarchically primary position.

This pattern joins classic and more recent literature detailing the interactions between linguistic and visual systems (Cavanagh, 2021; Jackendoff, 1987; Miller & Johnson-Laird, 1976; Strickland, 2017). For example, in recent work, we found that the mind is sensitive to correspondences between linguistic and visual notions of symmetry (Hafri, Gleitman, Landau, & Trueswell, 2023). Despite the striking differences between a butterfly's appearance and a sentence like *Mary and Bill marry*, both share an abstract symmetry—an invariance to transformation. In images, this is evident in the bilateral symmetry of a butterfly; in language, it is reflected in flexible argument order for certain predicates like *marry* (e.g., *Mary marries Bill* vs. *Bill marries Mary*). In cross-modal matching tasks, we observed surprising correspondences across such stimuli, providing evidence for these intuitive psychological connections between symmetry in vision and language. These and other findings (e.g., De Freitas & Alvarez, 2018) suggest that the mind employs common formats and principles across cognitive systems—allowing perceptual representations of relations to be readily accessed by higher-level processes (Hafri, Green, & Firestone, 2023; Quilty-Dunn, 2020) and, in some cases, enabling linguistic representations to guide attentional patterns in scene perception.

### 7.3 Open questions and future directions

These connections across cognitive systems raise a broader question: Why do syntactic roles in language appear to align so strongly with perceptual compositional order? In syntactic structures, complements—where reference objects often reside—occupy deeper positions in the hierarchy than subjects (where figure objects often end up). In many syntactic frameworks, linguistic structures are assumed to be derived bottom-up (Chomsky, 1995). Likewise, psycholinguistic evidence shows that planning and parsing unfold incrementally—often anticipating material that is syntactically deeper, even if it appears earlier in the linear sequence (Momma & Phillips, 2018). This pattern mirrors our findings and may reflect a general cognitive principle in which structure is built incrementally from the most foundational elements (e.g., reference objects) upward. While speculative, this suggests a striking parallel between visual composition and linguistic derivation that warrants further investigation.

Our findings also highlight an intriguing dissociation between event and non-event relational representations in the alignment of compositional order and grammatical order. In event representations, Agents—typically dynamic entities that move or initiate change—are psychologically primary and usually mapped to grammatical subject position. In contrast, for physical and spatial relations like those studied here, reference objects are primary yet are generally mapped to grammatical *complement* positions, occupying deeper levels in hierarchical syntactic structure. While speculative, we suggest that this difference in mapping may reflect underlying differences in the functional properties of Agents and reference objects. Dowty's (1991) proto-role theory aims to formalize how prototypically Agent-like properties (such as movement or initiating change) determine the mappings between event participants (arguments of verbs like *kick* or *fear*) and grammatical roles (subject and object); however, this framework does not straightforwardly extend to non-event relations. Reference objects illustrate this tension clearly: although capable of initiating change (an "Agent-like" property—e.g., a table moving can cause a vase atop it to move as well), they typically function as stable, stationary anchors (a more "Patient-like" property). Thus, a complementary theoretical framework may be needed to capture generalizations across non-event relations like those studied here.

Our work also opens important avenues for future research. One critical question concerns how the mind learns to identify reference objects as such, as well as their capacity to control other objects in physical or spatial relations. Experiments 1–4 showed that visual properties such as size, stability, and rectilinearity often determine Reference role assignment, consistent with findings on "anchor" objects in scene perception (Boettcher et al., 2018; Võ et al., 2019). However, the results of Experiment 5 reveal that Reference role assignment can also emerge from more abstract principles, such as intuitive physics (see also Firestone & Scholl, 2017; Little & Firestone, 2021) or even linguistic structure. Developmental research suggests that pre-linguistic infants are sensitive to relational concepts like support and containment (Baillargeon et al., 2012; Hespos & Spelke, 2004), raising the possibility that early interactions with physical forces inform the mind's sensitivity to Reference-hood. How these early experiences integrate with visual properties and higher-level conceptual principles remains an open question.

Finally, another important open question is what additional visual routines underlie relational composition beyond those documented for simple geometric relations (Jolicoeur et al., 1986, 1991; Ullman, 1987; Wong & Scholl, 2024). While our work uncovered a Reference-first order for spatial and physical relations, other routines may contribute to the construction of everyday relational scenes. Moreover, questions remain about how more complex relations are represented compositionally, beyond the simpler dyadic cases studied here. For instance, transfer events (e.g., *giving*) or caused motion (e.g., hitting a ball with a racket into the net) involve at least three roles (Tatone & Csibra, 2024; Ünal et al., 2024). Likewise, relational structures may be embedded. Consider a cat on a mat that is in a box. Is this situation represented as two independent relations (cat-on-mat and mat-in-box) or as a single embedded relation (cat-on-mat in box)? Our approach, using a sentence–picture verification task with delayed presentations, may prove fruitful in addressing these questions.

### 7.4 Conclusions

In sum, this work reveals a fundamental principle of relational composition: the mind constructs relational representations sequentially, respecting the roles of elements in the relation. By uncovering a Reference-first compositional routine, we show that visual perception employs a structured process akin to compositional principles observed in language and event cognition. More broadly, these findings provide new insights into the nature of visual representation, the underlying construction algorithms, and the deep connections between perception, language, and intuitive physics.

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# CRediT authorship contribution statement

**Zekun Sun**: Conceptualization, Methodology, Software, Investigation, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Visualization. **Chaz Firestone**: Conceptualization, Methodology, Writing - Review & Editing, Supervision, Funding acquisition. **Alon Hafri**: Conceptualization, Methodology, Software, Investigation, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision.

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