COGNITIVE SCIENCE
A Multidisciplinary Journal

Cognitive Science 47 (2023) e13244

ISSN: 1551-6709 online
DOI: 10.1111/cogs.13244

This article is part of the "Progress & Puzzles of Cognitive Science" letter series.

The Binding Problem 2.0: Beyond Perceptual Features

Xinchi Yu,[a,b] Ellen Lau[a,b]

[a]*Program of Neuroscience and Cognitive Science, University of Maryland*
[b]*Department of Linguistics, University of Maryland*

Received 28 October 2022; received in revised form 22 December 2022; accepted 4 January 2023

Abstract

The "binding problem" has been a central question in vision science for some 30 years: When encoding multiple objects or maintaining them in working memory, how are we able to represent the correspondence between a specific feature and its corresponding object correctly? In this letter we argue that the boundaries of this research program in fact extend far beyond vision, and we call for coordinated pursuit across the broader cognitive science community of this central question for cognition, which we dub "Binding Problem 2.0".

Keywords: Binding; Object indexicals; Language comprehension; Vision; Conceptual/semantic representation; Multimodality

For some 30 years, rich insights into the architecture of visual perception have followed from a body of vision research centered on the "binding problem:" When encoding multiple objects or maintaining them in working memory, how are we able to represent the correspondence between a specific feature and its corresponding object correctly (Treisman, 1996, 1998; von der Malsburg, 1995; Zhang, Zhang, & Fang, 2020)? For example, when faced with a red circle and a blue square, how does our visual system not confuse its representation with that of a red square and a blue circle? The binding problem is unlikely to be fully resolved by conjunctive coding (i.e., the same cohort of neurons representing multiple visual features, Di Lollo, 2010, 2012), as we are able to bind novel feature configurations together and we can also represent two largely identical objects as two separate objects but not one. Furthermore,

Correspondence should be sent to Xinchi Yu and Ellen Lau, Department of Linguistics, University of Maryland, Marie Mount Hall, College Park, MD 20742, USA. E-mail: xcyu@umd.edu; ellenlau@umd.edu

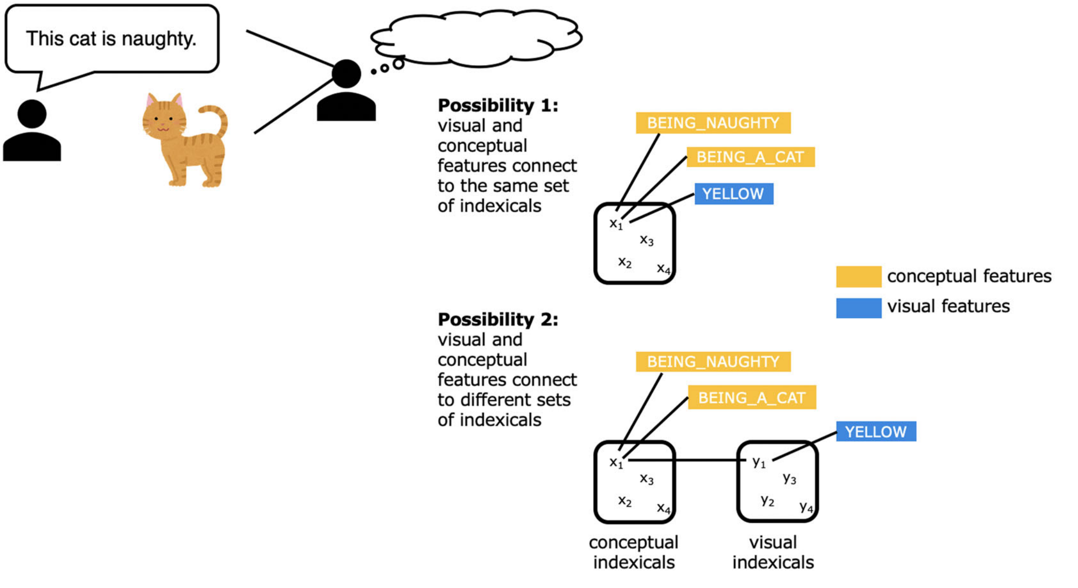

Fig. 1. Do visual indexicals also bind to non-perceptual (e.g., semantic/conceptual) features? One possibility is that the same indexical can connect to both visual (i.e., perceptual) features like YELLOW and conceptual features like BEING_NAUGHTY and BEING_A_CAT ("Possibility 1" in the figure). Another possibility is that visual and conceptual features are bound to different sets of indexicals respectively ("Possibility 2" in the figure). Note that here we do not make a distinction between the representation of the conceptual feature CAT (which is the concept CAT) and the conceptual feature BEING_A_CAT.

brain-lesioned patients suffering from simultanagnosia display selective problems with accurate binding of features to objects (Coslett & Saffran, 1991; Friedman-Hill, Robertson, & Treisman, 1995; Rafal, 2001). This suggests another mechanism beyond simply representing features. Many vision scientists have proposed the existence of a set of indexicals (or files, pointers, etc.) binding visual features together with the support of psychological and neural evidence (Cavanagh, Hunt, Afraz, & Rolfs, 2010; Green & Quilty-Dunn, 2021; Kahneman, Treisman, & Gibbs, 1992; Kibbe & Leslie, 2011; Leslie, Xu, Tremoulet, & Scholl, 1998; Naughtin, Mattingley, & Dux, 2016; Pylyshyn, 1989, 2001; Quilty-Dunn, Porot, & Mandelbaum, 2022; Scholl & Leslie, 1999; Thyer et al., 2022; Wilson, Adamo, Barense, & Ferber, 2012; Xu & Chun, 2006, 2007; Zhu, Zhang, & von der Heydt, 2020). These indexicals are content-independent: They temporarily "point" to the features bound to an object rather than representing content themselves (Marcus, 2001).

In this letter, we propose as a new research program for cognitive science the "Binding Problem 2.0," extending these questions beyond visual perception. Do object indexicals really belong to the theory of *visual* working memory, or do they serve a *broader, non-perceptual* role in cognitive computation? Imagine the case in which you see a yellow cat and are told by a companion "this cat is naughty" (Fig. 1). Since object indexicals seem to stand in for entities in the world, do they not serve a similar role as the mental indexicals required for discourse comprehension (Brodbeck, Gwilliams, & Pylkkänen, 2016; Brody, 2020; Heim, 1982;

Hurford, 2003; Kamp, 1981), and might they not bind semantic/conceptual features of these entities as well as their perceptual features? Surprisingly, this question has received relatively little attention in the broader cognitive science and neuroscience community over the years despite its deep importance, although recent years have seen several thoughtful discussions among philosophers and developmental scientists (Murez, Smortchkova, & Strickland, 2020; Recanati, 2013; Revencu & Csibra, 2022; for review, see Brody, 2020). Careful empirical investigation coordinated across domains and research groups is now needed. Here, we propose a set of specific questions whose collective pursuit could lead to rapid advances in our understanding of this central cognitive mechanism.

Do the same set of indexicals bind visual/perceptual and semantic/conceptual features? As noted above, when we are receiving information about a scene or situation, we need the ability to track the set of features defined for particular entities across time whether the input is visual (a running cat and a jumping dog in your line of vision) or linguistic input (e.g., "The cat is running and the dog is jumping"). Visual attention is guided by conceptual content as well as perceptual features (e.g., Hayes & Henderson, 2019), and object tracking does not seem to depend on continuous visual stimulation (as evidenced by spatiotemporal working memory and the perception of object permanence across occlusion). Are these facts evidence that so-called "visual" object indexicals also bind non-perceptual conceptual properties, and that the same set of indexicals supports the tracking of referents in discourse comprehension? Or does the real-time spatial coordinate information provided by vision motivate a specific indexical system for visual perception that is rooted in space and perceptual features only, such that a different set of indexicals is needed for binding representations derived from language and thought (Fig. 1)? Evidence could come from more research investigating the relationship between deficits in binding perceptual features and deficits in binding conceptual features.

What is the capacity of these indexical representations? What limits this capacity? Working memory studies using visual shapes as stimuli have classically suggested a capacity of four indexicals (Awh, Barton, & Vogel, 2007; Cowan, 2001; Luck & Vogel, 1997, 2013; Xu & Chun, 2009). However, the exact numerical limit of this capacity and the nature of this capacity remain debated. For example, many researchers argue that working memory is not characterized by a fixed limit in terms of the number of slots/indexicals but rather that capacity is constrained by a resource pool that is also sensitive to the number of features to be encoded on each item (Bays et al., 2022; Ma, Husain, & Bays, 2014). Less is known, however, about whether indexicals binding varying numbers of conceptual properties display the same capacity dynamics as those observed for perceptual features. Investigation of this question may also reveal insights into whether/how indexicals are internally structured and whether perceptual properties are more "automatically" bound than conceptual ones.

How are indexicals implemented neurally? The notion of indexicals can be seen as a proposal at the computational and algorithmic levels (Marr, 1982). How are indexicals implemented neurally? One possibility is that an indexical is just one neuron or a cohort of neurons pointing to neurons representing different features (cf. von der Heydt, 2015) through, for example, enhanced excitatory synaptic connectivity. Another possibility is that an indexical is implemented by the temporal synchrony among the features bound to this object ("temporal binding," cf. Singer, 1999; von der Malsburg, 1995), without explicit indexical neuron(s).

EEG (electroencephalography; Thyer et al., 2022; Wilson et al., 2012) and fMRI (functional magnetic resonance imaging; Naughtin et al., 2016; Xu & Chun, 2006) studies identifying the neural markers of the indexical system have left open both possibilities, as both high temporal and spatial resolution are required to tell apart the two possibilities. A broad, field-wide effort is needed to develop and refine neural markers for indexicals with spatially and temporally sensitive measures like MEG (magnetoencephalography) or ECoG (electrocorticography). The development of neural signatures for the indexical system would provide the precision needed to investigate richer combinatorial representations in which indexicals participate, such as groupings (Peterson, Gözenman, Arciniega, & Berryhill, 2015; Thyer et al., 2022) and multiple-participant events (e.g., the cat chased the dog; see also O'Reilly, Ranganath, & Russin, 2022).

What role do indexicals play in solving the "type-token" problem? A fundamental and long-standing problem for cognitive science is how to model the relationship represented between general "types" or "kinds" and the individual instances or "tokens" that instantiate them (Prasada, 2021; Prasada, Salajegheh, Bowles, & Poeppel, 2008; Scholl & Leslie, 1999). For example, in seeing a particular animal, we may identify it as being of the type represented by the CAT concept, but the properties we attribute to it (e.g., YELLOW) are attributed to the individual animal and not the CAT type (in other words, encoding that the individual cat in front of you is yellow does not entail encoding that all cats are yellow). This distinction has sometimes been neglected in discussions of the binding problem; for example, in some versions of role-filler binding models, "the cat chased the mouse" is described as binding the "role" CHASER and the "filler" CAT (Hummel & Holyoak, 1997, 2003; Lalisse & Smolensky, 2021; Plate, 1994). In fact, indexicals are needed to encode the intuitive interpretation that it is a *particular* cat that was involved in a particular chasing event, not the CAT type. New work could investigate how the temporary feature bindings provided by indexicals are used to represent type-token relationships in scenes and discourses, and whether the structure of these representations is different from the representation of instances of kinds in longer-term memory.

These initial questions are just the beginning. *What is the developmental trajectory of the indexical system(s)?* Prior work has demonstrated that infants make use of visual indexicals (Feigenson, Carey, & Hauser, 2002; Kibbe & Leslie, 2011; Xu & Carey, 1996), opening a wide range of research questions about whether and how this capacity changes across the first several years of life. For example, does the ability to bind different types of perceptual and conceptual features emerge at different points in development? *What is the evolutionary trajectory of the indexical system(s)? What differences exist in the indexical system(s) across species, and why?* Although it has been shown that some non-human animals can track visual objects across time (Cheries, Newman, Santos, & Scholl, 2006; Rugani, Fontanari, Simoni, Regolin, & Vallortigara, 2009; Uller, Hauser, & Carey, 2001; Zhu et al., 2020), whether or not they are tracking visual objects through *indexicals* is unclear (Nieder, 2005). Furthermore, it is unknown whether some animals are able to bind *conceptual* features to indexicals, although many do seem to have concepts (i.e., conceptual features; Fitch, 2020; Lin, Chen, Kuang, Wang, & Tsien, 2007). In the course of evolution, did the binding of conceptual features to indexicals emerge together with the concepts themselves? How might the language system have impacted the indexical system(s) across the course of evolution, and what is the nature of their interface in modern humans (Knowlton & Gomes, 2022)? Many more such questions, demanding the collective forces of subfields across the cognitive sciences, remain to be asked and solved within Binding Problem 2.0.

Acknowledgments

We would like to thank the editor and two anonymous reviewers for their comments and suggestions to an earlier version of this article. This research was supported by a grant awarded to EL from the National Science Foundation (BCS-1749407).

References

Awh, E., Barton, B., & Vogel, E. K. (2007). Visual working memory represents a fixed number of items regardless of complexity. *Psychological Science*, *18*(7), 622–628.

Bays, P., Schneegans, S., Ma, W. J., & Brady, T. (2022). Representation and computation in working memory. PsyArXiv.

Brodbeck, C., Gwilliams, L., & Pylkkänen, L. (2016). Language in context: MEG evidence for modality-general and-specific responses to reference resolution. *eNeuro*, 3(6), ENEURO.0145-16.2016.

Brody, G. (2020). *Indexing objects in vision and communication*. Central European University.

Cavanagh, P., Hunt, A. R., Afraz, A., & Rolfs, M. (2010). Visual stability based on remapping of attention pointers. *Trends in Cognitive Sciences*, *14*(4), 147–153.

Cheries, E. W., Newman, G. E., Santos, L. R., & Scholl, B. J. (2006). Units of visual individuation in rhesus macaques: objects or unbound features? *Perception*, *35*(8), 1057–1071.

Coslett, H. B., & Saffran, E. (1991). Simultanagnosia: To see but not two see. *Brain*, *114*(4), 1523–1545.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*(1), 87–114.

Di Lollo, V. (2010). Iterative reentrant processing: A conceptual framework for perception and cognition (the blinding problem? No worries, mate). In V. Coltheart (Ed.), *Tutorials in visual cognition* (pp. 9–42). New York, NY: Psychology Press.

Di Lollo, V. (2012). The feature-binding problem is an ill-posed problem. *Trends in Cognitive Sciences*, *16*(6), 317–321.

Feigenson, L., Carey, S., & Hauser, M. (2002). The representations underlying infants' choice of more: Object files versus analog magnitudes. *Psychological Science*, *13*(2), 150–156.

Fitch, W. T. (2020). Animal cognition and the evolution of human language: why we cannot focus solely on communication. *Philosophical Transactions of the Royal Society B*, *375*(1789), 20190046.

Friedman-Hill, S. R., Robertson, L. C., & Treisman, A. (1995). Parietal contributions to visual feature binding: evidence from a patient with bilateral lesions. *Science*, *269*(5225), 853–855.

Green, E. J., & Quilty-Dunn, J. (2021). What is an object file?. *The British Journal for the Philosophy of Science*, 72(3). https://doi.org/10.1093/bjps/axx055.

Hayes, T. R., & Henderson, J. M. (2019). Scene semantics involuntarily guide attention during visual search. *Psychonomic Bulletin & Review*, *26*(5), 1683–1689.

Heim, I. R. (1982). *The semantics of definite and indefinite noun phrases*. University of Massachusetts Amherst.

Hummel, J. E., & Holyoak, K. J. (1997). Distributed representations of structure: A theory of analogical access and mapping. *Psychological Review*, *104*(3), 427.

Hummel, J. E., & Holyoak, K. J. (2003). A symbolic-connectionist theory of relational inference and generalization. *Psychological Review*, *110*(2), 220.

Hurford, J. R. (2003). The neural basis of predicate-argument structure. *Behavioral and Brain Sciences*, *26*(3), 261–283.

Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive Psychology*, *24*(2), 175–219.

Kamp, H. (1981). A theory of truth and semantic representation, In J.A.G. Groenendijk, T.M.V. Janssen, & M.B.J. Stokhof (Eds.), *Formal methods in the study of language* (pp. 277–322). Amsterdam: Mathematisch Centrum.

Kibbe, M. M., & Leslie, A. M. (2011). What do infants remember when they forget? Location and identity in 6-month-olds' memory for objects. *Psychological Science*, *22*(12), 1500–1505.

Knowlton, T., & Gomes, V. (2022). Linguistic and non-linguistic cues to acquiring the strong distributivity of each. *Proceedings of the Linguistic Society of America*, *7*(1), 5236.

Lalisse, M., & Smolensky, P. (2021). Distributed neural encoding of binding to thematic roles. *arXiv*.

Leslie, A. M., Xu, F., Tremoulet, P. D., & Scholl, B. J. (1998). Indexing and the object concept: developing 'what' and 'where' systems. *Trends in Cognitive Sciences*, *2*(1), 10–18.

Lin, L., Chen, G., Kuang, H., Wang, D., & Tsien, J. Z. (2007). Neural encoding of the concept of nest in the mouse brain. *Proceedings of the National Academy of Sciences*, *104*(14), 6066–6071.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*(6657), 279–281.

Luck, S. J., & Vogel, E. K. (2013). Visual working memory capacity: from psychophysics and neurobiology to individual differences. *Trends in Cognitive Sciences*, *17*(8), 391–400.

Ma, W. J., Husain, M., & Bays, P. M. (2014). Changing concepts of working memory. *Nature Neuroscience*, *17*(3), 347–356.

Marcus, G. F. (2001). *The algebraic mind: Integrating connectionism and cognitive science*. MIT press.

Marr, D. (1982). *Vision: A Computational Approach*. San Francisco, CA: Freeman and Co.

Murez, M., Smortchkova, J., & Strickland, B. (2020). The Mental Files Theory of Singular Thought. In R. Goodman, J. Genone, & N. Kroll (Eds.),*Singular thought and mental files* (pp.107-142). Oxford, England: Oxford University Press.

Naughtin, C. K., Mattingley, J. B., & Dux, P. E. (2016). Distributed and overlapping neural substrates for object individuation and identification in visual short-term memory. *Cerebral Cortex*, *26*(2), 566–575.

Nieder, A. (2005). Counting on neurons: the neurobiology of numerical competence. *Nature Reviews Neuroscience*, *6*(3), 177–190.

O'Reilly, R. C., Ranganath, C., & Russin, J. L. (2022). The Structure of Systematicity in the Brain. *Current Directions in Psychological Science*, *31*(2), 124–130.

Peterson, D. J., Gözenman, F., Arciniega, H., & Berryhill, M. E. (2015). Contralateral delay activity tracks the influence of Gestalt grouping principles on active visual working memory representations. *Attention, Perception, & Psychophysics*, *77*(7), 2270–2283.

Plate, T. A. (1994). *Distributed representations and nested compositional structure*. University of Toronto, Department of Computer Science.

Prasada, S. (2021). The physical basis of conceptual representation. *Cognition*, *214*, 104751.

Prasada, S., Salajegheh, A., Bowles, A., & Poeppel, D. (2008). Characterising kinds and instances of kinds: ERP reflections. *Language and Cognitive Processes*, *23*(2), 226–240.

Pylyshyn, Z. (1989). The role of location indexes in spatial perception: A sketch of the FINST spatial-index model. *Cognition*, *32*(1), 65–97.

Pylyshyn, Z. W. (2001). Visual indexes, preconceptual objects, and situated vision. *Cognition*, *80*(1-2), 127–158.

Quilty-Dunn, J., Porot, N., & Mandelbaum, E. (2022). The best game in town: The re-emergence of the language of thought hypothesis across the cognitive sciences. *Behavioral and Brain Sciences*. https://doi.org/10.1017/S0140525X22002849

Rafal, R. (2001). Balint's syndrome. In *Handbook of neuropsychology* (pp. 121–141).

Recanati, F. (2013). Mental Files: Replies to my Critics. *Disputatio*, *5*(36), 207–242.

Revencu, B., & Csibra, G. (2022). For 19-month-olds, what happens on-screen stays on-screen. *Open Mind*, *5*, 71–90.

Rugani, R., Fontanari, L., Simoni, E., Regolin, L., & Vallortigara, G. (2009). Arithmetic in newborn chicks. *Proceedings of the Royal Society B: Biological Sciences*, *276*(1666), 2451–2460.

Scholl, B. J., & A. M. Leslie. (1999). Explaining the infant's object concept: beyond the perception/cognition dichotomy. In E. Lepore, Z. Pylyshyn (Eds.), *What is cognitive science* (pp. 26–73). Malden, MA: Blackwell.

Singer, W. (1999). Neuronal synchrony: a versatile code for the definition of relations? *Neuron*, *24*(1), 49–65.

Thyer, W., Adam, K. C. S., Diaz, G. K., Velázquez Sánchez, I. N., Vogel, E. K., & Awh, E. (2022). Storage in visual working memory recruits a content-independent indexical system. *Psychological Science*, *33*(10), 1680-1694. https://doi.org/10.1177/095679762210909

Treisman, A. (1996). The binding problem. *Current Opinion in Neurobiology*, *6*(2), 171–178.

Treisman, A. (1998). Feature binding, attention and object perception. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *353*(1373), 1295–1306.

Uller, C., Hauser, M., & Carey, S. (2001). Spontaneous representation of number in cotton-top tamarins (*Saguinus oedipus*). *Journal of Comparative Psychology*, *115*(3), 248.

von der Heydt, R. (2015). Figure–ground organization and the emergence of proto-objects in the visual cortex. *Frontiers in Psychology*, *6*, 1695.

von der Malsburg, C. (1995). Binding in models of perception and brain function. *Current Opinion in Neurobiology*, *5*(4), 520–526.

Wilson, K. E., Adamo, M., Barense, M. D., & Ferber, S. (2012). To bind or not to bind: Addressing the question of object representation in visual short-term memory. *Journal of Vision*, *12*(8), 14–14.

Xu, F., & Carey, S. (1996). Infants' metaphysics: The case of numerical identity. *Cognitive Psychology*, *30*(2), 111–153.

Xu, Y., & Chun, M. M. (2006). Dissociable neural mechanisms supporting visual short-term memory for objects. *Nature*, *440*(7080), 91–95.

Xu, Y., & Chun, M. M. (2007). Visual grouping in human parietal cortex. *Proceedings of the National Academy of Sciences*, *104*(47), 18766–18771.

Xu, Y., & Chun, M. M. (2009). Selecting and perceiving multiple visual objects. *Trends in Cognitive Sciences*, *13*(4), 167–174.

Zhang, Y., Zhang, Y. Y., & Fang, F. (2020). Neural mechanisms of feature binding. *Science China Life Sciences*, *63*, 926–928.

Zhu, S. D., Zhang, L. A., & von der Heydt, R. (2020). Searching for object indexicals in the visual cortex. *Journal of Neurophysiology*, *123*(5), 1979–1994.