suggested that, when dendritic filopodia become stabilized, they typically remain part of the mature arbor[14]. By contrast, starburst bridges become stable parts of the arbor during its 'spider's web' phase, which lasts several days, but all such bridges are ultimately eliminated. It remains unclear whether other neurons use similar transient structures to pattern their dendrites, or whether bridges are specifically needed by starburst cells to support unique aspects of their morphology, such as their radial patterning or their confinement to a 2D plane.

For over 20 years, we have known about the fascinating molecular systems underlying self-avoidance, and the neurobiologically significant dendritic patterning phenotypes that arise when these systems are manipulated. Ing-Esteves and Lefebvre[9] shine new light on these old problems, providing a breakthrough in understanding how cPcdh molecules influence cellular behaviors to pattern dendrites. In doing so, they highlight the power of careful observation — watching the biological events that we care about — in helping us understand how such behaviors work. Their important results will make possible future studies defining how other cell types implement self-avoidance, in both vertebrates and invertebrates and across a variety of different cell types and circuits.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Snider, J., Pillai, A., and Stevens, C.F. (2010). A universal property of axonal and dendritic arbors. Neuron *66*, 45–56.
2. Chklovskii, D.B. (2004). Synaptic connectivity and neuronal morphology: two sides of the same coin. Neuron *43*, 609–617.
3. Kramer, A.P., and Kuwada, J.Y. (1983). Formation of the receptive fields of leech mechanosensory neurons during embryonic development. J. Neurosci. *3*, 2474–2486.
4. Schmucker, D., Clemens, J.C., Shu, H., Worby, C.A., Xiao, J., Muda, M., Dixon, J.E., and Zipursky, S.L. (2000). Drosophila Dscam is an axon guidance receptor exhibiting extraordinary molecular diversity. Cell *101*, 671–684.
5. Wojtowicz, W.M., Wu, W., Andre, I., Qian, B., Baker, D., and Zipursky, S.L. (2007). A vast repertoire of Dscam binding specificities arises from modular interactions of variable Ig domains. Cell *130*, 1134–1145.
6. Soba, P., Zhu, S., Emoto, K., Younger, S., Yang, S.J., Yu, H.H., Lee, T., Jan, L.Y., and Jan, Y.-N. (2007). Drosophila sensory neurons require Dscam for dendritic self-avoidance and proper dendritic field organization. Neuron *54*, 403–416.
7. Zipursky, S.L., and Sanes, J.R. (2010). Chemoaffinity revisited: dscams, protocadherins, and neural circuit assembly. Cell *143*, 343–353.
8. Lefebvre, J.L., Kostadinov, D., Chen, W.V., Maniatis, T., and Sanes, J.R. (2012). Protocadherins mediate dendritic self-avoidance in the mammalian nervous system. Nature *488*, 517–521.
9. Ing-Esteves, S., and Lefebvre, J.L. (2024). Gamma-protocadherins regulate dendrite self-recognition and dynamics to drive self-avoidance. Curr. Biol. *34*, 4224–4239.
10. Rubinstein, R., Thu, C.A., Goodman, K.M., Wolcott, H.N., Bahna, F., Mannepalli, S., Ahlsen, G., Chevee, M., Halim, A., Clausen, H., *et al*. (2015). Molecular logic of neuronal self-recognition through protocadherin domain interactions. Cell *163*, 629–642.
11. Thu, C.A., Chen, W.V., Rubinstein, R., Chevee, M., Wolcott, H.N., Felsovalyi, K.O., Tapia, J.C., Shapiro, L., Honig, B., and Maniatis, T. (2014). Single-cell identity generated by combinatorial homophilic interactions between alpha, beta, and gamma protocadherins. Cell *158*, 1045–1059.
12. Matthews, B.J., Kim, M.E., Flanagan, J.J., Hattori, D., Clemens, J.C., Zipursky, S.L., and Grueber, W.B. (2007). Dendrite self-avoidance is controlled by Dscam. Cell *129*, 593–604.
13. Vaney, D.I., Sivyer, B., and Taylor, W.R. (2012). Direction selectivity in the retina: symmetry and asymmetry in structure and function. Nat. Rev. Neurosci. *13*, 194–208.
14. Cline, H., and Haas, K. (2008). The regulation of dendritic arbor development and plasticity by glutamatergic synaptic input: a review of the synaptotrophic hypothesis. J. Physiol. *586*, 1509–1517.
15. Lefebvre, J.L., Sanes, J.R., and Kay, J.N. (2015). Development of dendritic form and function. Annu. Rev. Cell Dev. Biol. *31*, 741–777.

Cognitive development: The origins of structured thought in the mind

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Linguistic syntax lets us communicate complex, structured thoughts, like whether a dog chased a man or vice versa. New work shows that seven-month-olds can entertain such structured thoughts even before acquiring their native language, revealing the origins of this sophisticated ability.

Consider the three sentences shown in Figure 1A. Although sentences (1) and (2) both involve a dog, a man, and an act of pursuit, they differ in one crucial aspect: their *structure*, or who did what to whom. In (1) the dog is the *agent* (the 'who') and the man is the *patient* (the 'whom'), while in (2) these roles are reversed. By contrast, assignment of these thematic

A

(1) The dog is chasing the man.

(2) The man is chasing the dog.

(3) The dog is licking the man.

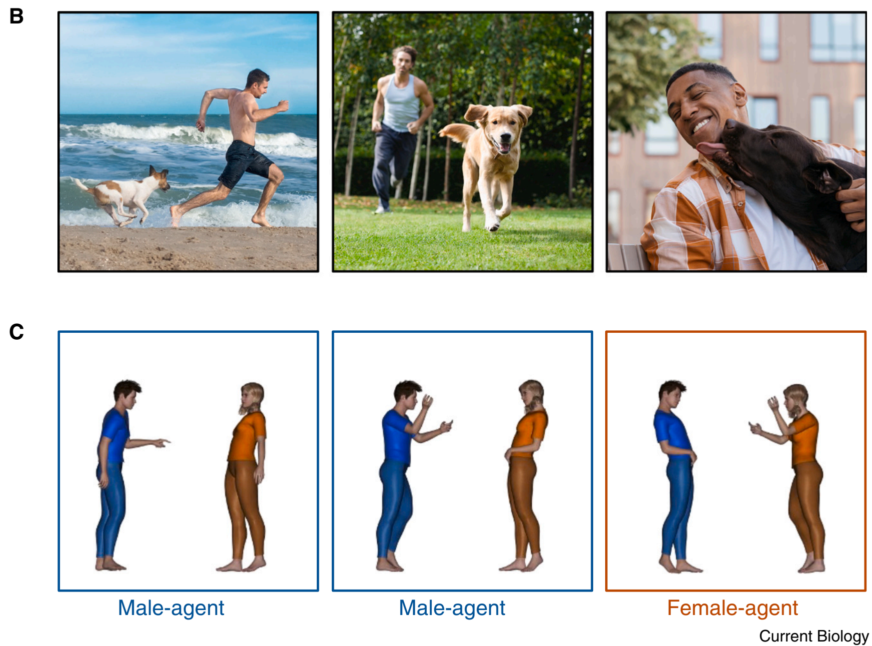

Figure 1. Matching events across language and vision requires the capacity to represent event structure non-linguistically.
(A) Sentences (1) and (2) involve the same participants (a dog and a man) and action (chasing), but the *event structure*, or assignment of the thematic roles agent and patient, is different. In contrast, the event structure in sentences (1) and (3) is the same, despite that they involve different actions (chasing versus licking). (B) At first glance, these images and the sentences in panel (A) have little in common: the images have colors, contours, and shapes, while the sentences have letters, words, and phrases. Yet we spontaneously appreciate that the images involve a dog and a man involved in different actions — and we can easily match each image to its corresponding sentence in panel (A). This demonstrates that we represent event structure both linguistically and non-linguistically. (C) Papeo *et al.*[2] showed that prelinguistic infants are sensitive to non-linguistic event structure. Infants were repeatedly shown images with one particular event structure (e.g., male-agent/female-patient; left and middle scenes). After infants habituated, they were shown a scene with the reversed structure (e.g., female-agent/male-patient; right panel). Infants looked longer at scenes with reversed structure relative to scenes with the same structure. These effects were replicated with a complementary measure (pupil dilation) and did not occur when the individuals in the scenes were back-to-back with no interaction. (Photo credits for panel (B): ESBuka, Shutterstock; Tom Merton, iStock; Oleksii Didok, iStock.)

roles is the same in sentences (1) and (3). Our ability to make such distinctions draws upon *syntax*, the set of abstract linguistic rules for combining elements such as nouns and verbs to form sentences[1].

Now look at the images in Figure 1B. Which image matches which sentence? You may find this task easy, but notice that it requires complex cognitive machinery of its own: since the images all involve dogs, men, and some kind of action, you must mentally arrange these elements in the right way. In other words, just as you represent event structure in language, you must also represent such structure *non-linguistically*. This raises a key question: When and how does this capacity develop? A study reported in this issue of *Current Biology* by Papeo *et al.*[2] shows that the capacity for structured thought is present by seven months of age, well before infants acquire their native language's syntax. This finding sheds light on the origins of this capacity, informs debates about the relationship between language and thought, and may also have implications for implementing cognitive functions in artificial-intelligence systems.

Papeo *et al.*'s work appears amidst a resurgence of interest in the *language-of-thought* hypothesis (LoTH)[3–5]. LoTH suggests that thought itself has a language-like format, with discrete, abstract elements that combine systematically. Indeed, assigning roles like agent and patient exemplifies a core property of LoT known as *role-filler independence*[5,6].

The relationship between natural language and thought is complex, with some researchers arguing that language facilitates certain types of combinatorial thought, e.g., inferences across spatial and featural domains[7]. However, serendipitous cases from language development also suggest the opposite causal direction: linguistically isolated deaf children spontaneously create combinatorial homesign systems to communicate their pre-existing structured thoughts, with some of these systems evolving into fully fledged natural languages like Nicaraguan Sign Language[8]. Although fascinating, this work leaves crucial questions unanswered: does the capacity for structured thought emerge only gradually in development, in the service of communication? Or is it rooted in early non-linguistic capacities? Papeo *et al.*'s study suggests the latter, pointing to a deep-seated cognitive capacity that precedes and may support language acquisition.

Papeo *et al.*[2] tested prelinguistic infants to see whether they could distinguish events based on their role assignments: a male agent acting on a female patient or vice versa. Using a habituation paradigm, the researchers repeatedly showed infants scenes of two individuals (male and female) whose postures varied from scene to scene, as if engaged in different interactions (Figure 1C). Importantly, the habituation scenes always had the same event structure (e.g., male-agent/female-patient). After infants lost interest, they were shown an event with the reversed structure (e.g., female-agent/male-patient). Dishabituation after the switch would indicate sensitivity to event structure. The results were clear: infants looked longer at scenes with switched roles relative to scenes where the roles remained the same, indicating sensitivity to event structure. In two additional experiments, the researchers used a complementary measure, pupil dilation, which is an indicator of surprise. Infants were shown 'standard' scenes of a male-agent/female-patient interspersed with rare 'deviant' scenes with the reversed structure. Infants' pupils dilated in response to the deviant scenes, again confirming their sensitivity to changes in event structure. Crucially, these effects could not be explained solely by low-level differences like posture alone: they did not occur when both habituation and test scenes (or standard and deviant scenes) showed the two individuals back-to-back with no interaction. Moreover, the roles that infants represented were relatively abstract: the effects generalized across scenes with roles defined by different perceptual cues, such as posture (agents often have more active postures than patients) and facing direction (agents face patients, while patients may be turned away). Thus, the experiments showed that infants represent abstract event structure itself.

Papeo *et al.*'s findings provide decisive evidence that acquiring a natural language is not necessary for developing abstract and structured thoughts about the world. In fact, these findings may help explain how children acquire certain aspects of natural language — in particular, how they determine the mapping of non-linguistic event participants to grammatical roles, such as assigning the agent-like participant to subject and patient-like participant to object. Without this ability, children would have to learn piecemeal how the roles for chasing, licking, eating, and the like map to different grammatical positions. Infants' early sensitivity to event structure may even influence how languages evolve: since agent and patient roles are available early on, then languages would presumably be easier to learn if they align with these prelinguistic distinctions[9].

Papeo *et al.*'s work prompts natural questions. For example, how far down the phylogenetic tree does the capacity to assign thematic roles go[10]? Empirical work suggests that non-human primates represent information related to event structure, such as identifying the presence of social interactions between conspecifics[11] and distinguishing helpers from hinderers[12]. This raises the intriguing possibility that non-human primates might also assign abstract roles like agent and patient. If true, it would imply that the capacity for structured thought is not uniquely human; instead, perhaps human-specific language adaptations involve those that enable externalization of language (e.g., by 'linearizing' hierarchical structure, with one word following the next in sequence). Moreover, while Papeo *et al.* show that infants can assign abstract roles, whether they have an LoT with the same properties and compositional rules as adults do is an empirical question[4] (e.g., with abstract relational concepts like *same*[13]).

Finally, an open question is which *parts* of the mind are involved in this capacity. An intriguing possibility is that the ability to distinguish event structures exists not only in the non-linguistic cognitive processes of infants but also in their perceptual systems. This ability would enable them to quickly and effortlessly differentiate between scenes involving, e.g., a man chasing a dog and a dog chasing a man, while spontaneously appreciating the similarity between scenes such as a dog chasing a man and a dog licking a man (Figure 1B). This idea aligns with recent evidence that adult visual processing automatically extracts such structure[14–16]. Although it is unlikely that infants' visual systems come with perceptual templates for abstract entities like agents and patients, it seems plausible that they would be primed to quickly learn what perceptual inputs reliably indicate the presence of certain event categories and roles. To test whether infants extract event structure in this way, developmental researchers must demonstrate key signatures of perceptual processing, including rapid and automatic operation[17]. If shown, this would suggest remarkable continuity in human perceptual processing across development and might call for a reevaluation of perception's role in enabling infants to infer high-level information about the world.

Beyond the intriguing questions this work raises about human cognition, it may also serve as a rejoinder to recent big-data approaches in artificial intelligence (AI), which often assume that the ability to make structured inferences arises from extensive exposure to language and even the visual contexts in which it is embedded[18]. Papeo *et al.*'s findings suggest that alternative approaches to modeling this capacity deserve reconsideration[19] — especially in light of the significant ethical and environmental costs associated with big-data approaches in AI[20].

To summarize, Papeo *et al.*'s findings make clear that infants possess a remarkable capacity for understanding the abstract structure of situations and events in the world around them — a kind of 'syntax without language' — potentially forming a basis for eventually mastering their native language's syntax and enabling them to communicate their sophisticated thoughts and to understand the thoughts of others.

DECLARATION OF INTERESTS

The author declares no competing interests.

REFERENCES

1. Chomsky, N. (1957). Syntactic Structures (The Hague: Mouton).
2. Papeo, L., Vettori, S., Serraille, E., Odin, C., Rostami, F., and Hochmann, J.-R. (2024). Abstract thematic roles in infants' representation of social events. Curr. Biol. *34*, 4294–4300.
3. Fodor, J.A. (1975). The Language of Thought (Cambridge, MA: Crowell).
4. Mandelbaum, E., Dunham, Y., Feiman, R., Firestone, C., Green, E.J., Harris, D., Kibbe, M.M., Kurdi, B., Mylopoulos, M., Shepherd, J., *et al*. (2022). Problems and mysteries of the many languages of thought. Cogn. Sci. *46*, e13225.
5. Quilty-Dunn, J., Porot, N., and Mandelbaum, E. (2023). The best game in town: The reemergence of the language-of-thought hypothesis across the cognitive sciences. Behav. Brain Sci. *46*, e261.
6. Hafri, A., Bonner, M.F., Landau, B., and Firestone, C. (2024). A phone in a basket looks like a knife in a cup: Role-filler independence in visual processing. Open Mind *8*, 766–794.
7. Spelke, E.S. (2003). What makes us smart? Core knowledge and natural language. In Language in Mind: Advances in the Study of Language and Thought (Cambridge, MA: The MIT Press), pp. 277–311.
8. Kocab, A., Pyers, J., and Senghas, A. (2015). Referential shift in Nicaraguan Sign Language: a transition from lexical to spatial devices. Front. Psychol. *5*, 1540.
9. Strickland, B. (2017). Language reflects "core" cognition: a new theory about the origin of cross-linguistic regularities. Cogn. Sci. *41*, 70–101.
10. Wilson, V.A.D., Zuberbühler, K., and Bickel, B. (2022). The evolutionary origins of syntax: Event cognition in nonhuman primates. Sci. Adv. *8*, eabn8464.

11. Goupil, N., Rayson, H., Serraille, É., Massera, A., Ferrari, P.F., Hochmann, J.-R., and Papeo, L. (2024). Visual preference for socially relevant spatial relations in humans and monkeys. Psychol. Sci. *35*, 681–693.

12. Krupenye, C., and Hare, B. (2018). Bonobos prefer individuals that hinder others over those that help. Curr. Biol. *28*, 280–286.e5.

13. Hochmann, J.-R. (2023). Incomplete language-of-thought in infancy. Behav. Brain Sci. *46*, e278.

14. Hafri, A., Papafragou, A., and Trueswell, J.C. (2013). Getting the gist of events: Recognition of two-participant actions from brief displays. J. Exp. Psychol. Gen. *142*, 880–905.

15. Hafri, A., Trueswell, J.C., and Strickland, B. (2018). Encoding of event roles from visual scenes is rapid, spontaneous, and interacts with higher-level visual processing. Cognition *175*, 36–52.

16. Vettori, S., Odin, C., Hochmann, J.-R., and Papeo, L. (2023). A perceptual cue-based mechanism for automatic assignment of thematic agent and patient roles. Preprint at PsyArXiv, https://doi.org/10.31234/osf.io/ydgca.

17. Hafri, A., and Firestone, C. (2021). The perception of relations. Trends Cogn. Sci. *25*, 475–492.

18. Vong, W.K., Wang, W., Orhan, A.E., and Lake, B.M. (2024). Grounded language acquisition through the eyes and ears of a single child. Science *383*, 504–511.

19. Fodor, J.A., and Pylyshyn, Z.W. (1988). Connectionism and cognitive architecture: a critical analysis. Cognition *28*, 3–71.

20. Gomes, V. (2024). Whither developmental psycholinguistics? Preprint at PsyArXiv, https://doi.org/10.31234/osf.io/zm57t.

Neuroscience: A big step forward for motor control in *Drosophila*

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Connectomics approaches are fundamentally changing the way scientists investigate the brain. Recently published connectomes have enabled dissection of the intricate motor circuits in the fly's version of the spinal cord on a synaptic level. This has allowed reconstruction of complete sensorimotor pathways in *Drosophila*.

In the supermarket, you've likely never consciously controlled the precise placement of your feet as you approached the fruit section, or pondered the muscle forces needed to pick up a mango. And yet, you have accomplished such demanding motor control tasks all your life. This is possible because your spinal cord does this job for you, while your brain is busy strategizing and asking higher-level questions, like: do I really want mango? Motor control is achieved through the exquisite interplay of descending input from the brain, rhythmically active premotor networks in the spinal cord, and local feedback from sensory organs in and on the limbs[1] — all tailored to coordinating movements required to complete the task at hand. The nervous system of fruit flies, which, as the name suggests, spend a considerable amount of their lives hunting for fruit, needs to solve similar motor control tasks (Figure 1A). In fact, the fly's nervous system is able to orchestrate delicate movements of the body during flight — controlled by four power and 13 steering muscles per wing — and walking — driven by 108 muscles controlling 30 joints across six legs. While the field has made great progress at identifying core motor circuits for specific behaviors[2], it remains difficult to understand how these circuits interact and coordinate with each other.

Two recent papers[3,4] from the Tuthill and Lee labs constitute a major step towards understanding how motor circuits in the fly's version of the spinal cord, the ventral nerve cord (VNC), control leg and wing movements to turn thoughts into action. The first, by Azevedo *et al.*[3], presents the synaptic wiring diagram — a 'connectome' — of a female adult nerve cord (FANC). The second, by Lesser, Azevedo *et al.*[4], uses the FANC connectome to investigate principles of motor circuit organization in the leg and wing control systems. Together with previously published connectomes of the *Drosophila* brain[5–7] and parallel efforts in a male VNC[8], these groundbreaking papers make it possible to trace sensorimotor pathways throughout the entire nervous system.

Azevedo *et al.*[3] applied machine learning tools to analyse over 20 million electron microcopy (EM) images[9], each depicting a thin slice of the VNC: they were able to segment 15,000 neurons, and predict 45 million synaptic connections between them to generate the FANC dataset. Ultimately, however, behavioral output is based on muscle contractions. To understand how motor circuits control movement, it is necessary to map each motor neuron to the muscle it innervates, and each muscle to a specific joint and movement direction — for example, leg extension or flexion. For this purpose, Azevedo *et al.*[3] combined the FANC connectome with an X-ray dataset of a fly leg[10] and high-resolution fluorescence images of motor neurons. The overall result is a comprehensive atlas of the wing