COMPARATIVE BEHAVIOR

Matching sounds to shapes: Evidence of the bouba-kiki effect in naïve baby chicks

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Humans across multiple languages spontaneously associate the nonwords "kiki" and "bouba" with spiky and round shapes, respectively, a phenomenon named the bouba-kiki effect. To explore the origin of this association, and whether it is unique to humans, we tested the bouba-kiki effect in baby domestic chickens (*Gallus gallus*). As a precocial species, chicks can be tested shortly after hatching, allowing us to control their pretest experiences. Similar to humans, both 3-day-old [Experiment 1 (Exp. 1)] and 1-day-old (Exp. 2) chicks spontaneously choose a spiky shape when hearing the "kiki" sound and a round shape when hearing the "bouba" sound. Results from naïve young animals suggest a predisposed mechanism for matching the dimensions of shape and sound, which may be widespread across species.

In his pioneering work in 1947, Wolfgang Kölher described the spontaneous tendency of adult humans to associate a round shape with the nonword "Maluma" and a spiky shape with the nonword "Takete" (*1*). This was interpreted as a form of sound-symbolism, suggesting that the relationship between sound and meaning is not purely arbitrary. Several studies replicated this effect, which since the 2001 study by Ramachandran and Hubbard has been renamed the bouba-kiki effect (*2*), i.e., the nonwords "bouba" and "kiki" were matched to the round and the spiky shape, respectively.

However, it is yet to be known how the spontaneous tendency to match shapes and sounds originates. These associations could emerge due to early exposure to multisensory information and word sounds (*3*) or to orthography (*3*–*5*): People might consider the sounds [b] and [o] rounder than the sounds [k] and [i] due to the shape of the letters (*4*). Alternatively, it may be an experience-independent and spontaneous ability (*2*, *6*) in which form-to-meaning correspondences constitute a predisposed perceptual mechanism at the basis of language acquisition, facilitating vocabulary construction and communication in infancy (*7*, *8*). The strongest evidence in favor of this view comes from crosslinguistic and language evolution studies, as well as research in preverbal infants. The first attested the bouba-kiki effect in cultures with different linguistic systems and orthographic appearance of letters (*9*–*11*). The latter showed that, before language production, infants (4 months old) already exhibit the bouba-kiki effect (*12*), possibly due to a biologically endowed ability to map and integrate multimodal input (*13*). However, studies on infants could not completely rule out an experience-driven origin of the effect resulting from infants' fast learning rate (*13*–*15*), their high sensitivity to environmental statistical regularities (*16*, *17*) and the large number of symbolic associations of sounds to which they are exposed when interacting with adults (*18*).

Comparative research has provided evidence of other instances of crossmodal correspondences, in which animals spontaneously associate auditory information with another sensory dimension. These include a pitch-luminance association, observed in chimpanzees (*19*) and tortoises (*20*), in which high and low pitches are linked to brighter and darker stimuli, respectively; and a pitch-size association, reported in chimpanzees (*21*), dogs (*22*, *23*), and tortoises (*24*), in which high and low pitches correspond to smaller and larger shapes, respectively. These crossmodal correspondences may be part of a broader set of predisposed associations that reflect natural co-occurrences. Such predispositions would help animals form coherent and meaningful representations of objects and events, facilitating or hindering evolutionary relevant associations (*25*, *26*). For instance, the bouba-kiki effect may stem from the physical properties of objects, in which round objects, when hitting or rolling on a surface, typically produce lower-frequency and more continuous sounds compared with spiky objects of the same size (*27*). However, previous attempts to demonstrate the bouba-kiki effect in adult apes have been unsuccessful. Both chimpanzees and gorillas (*28*), as well as one bonobo (*29*) failed to show a spontaneous bouba-kiki association when tested. This raises the question of whether sound-shape correspondences, such as the bouba-kiki effect, are in fact part of a widespread set of predispositions that aids interaction with the environment, or whether it is a uniquely human system of associations shaped by language-related experiences.

Our study tackles sound-shape correspondences from an alternative phylogenetic and ontogenetic perspective, testing the bouba-kiki effect in naïve newborn chicks. The domestic chicken (*Gallus gallus*) represents an optimal model for this aim, as chicks are precocial and can therefore be tested at the earliest stages of life (*30*, *31*) and are known to share analogous predisposed cognitive and perceptual mechanisms with human infants (*31*–*39*). Chicks (3 days old) tested for space-luminance spontaneous crossmodal associations (*40*) performed similarly to adult humans (*41*) (although a lack of evidence was found for pitch-luminance) (*42*). Recently, spontaneous crossmodal associations have been observed in chicks even shortly after hatching, further indicating that the brain may be naturally organized to support such associations (*43*). Specifically, newly hatched chicks first explored a smooth or a bumpy object in complete darkness (tactile-only) and were later able to recognize the familiar object solely by its visual appearance. This implies that the brain might be biologically predisposed to link certain kinds of sensory information, even in the absence of direct experience, through common neural coding mechanisms (*19*, *24*, *25*). These organizational principles can be understood as a species-level prior that structures and orients subsequent learning.

We investigated whether baby domestic chickens are sensitive to the bouba-kiki effect by conducting two experiments that differed regarding age of chicks at testing and the procedures employed. In Experiment 1 (Exp. 1), we employed a validated training-based paradigm already used in crossmodal studies with chicks (*40*, *44*). We trained 42 naïve 3-day-old chicks (17 females) to circumnavigate a panel depicting a shape with both round and spiky edges (Fig. 1A and movie S1). During the test, chicks underwent 24 trials in which they were presented with two panels, one depicting a spiky shape and one depicting a round shape, while either the sound "bouba" or "kiki" (pseudo-randomly alternated between trials) was played (Fig. 1B, movie S1, and audio S1 and S2). We hypothesized that, if chicks rely on human-like sound-shape associations, they will choose the panel with the spiky shape when hearing the "kiki" sound and that with the round shape when hearing the "bouba" sound. In Exp. 2 (40 individuals, 20 females) we tightened control over three critical factors: maturation (the test took place within the first 24 hours after hatching rather than on the third day of life), social experience (individual housing rather than social groups), and trained associations (chicks were tested without any prior training or reward) (see supplementary text for a detailed description of the rearing environment). Each chick underwent a 30-min habituation phase with the ambiguous shape (same as Exp. 1) displayed on a monitor (Fig. 2A and movie S1), followed by 30-min break in an empty, lit cage. The chick was then

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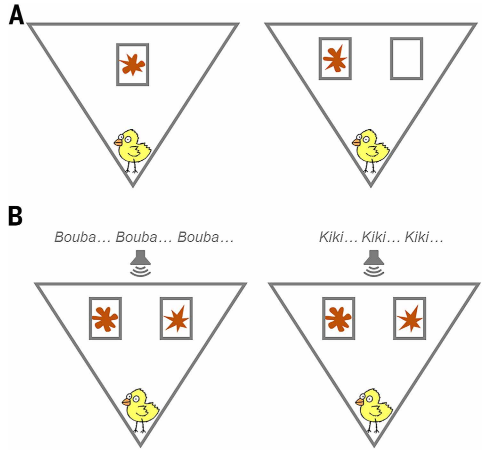

Fig. 1. Exp. 1 experimental paradigm. (**A**) Training. (Left) The chick learned to circumnavigate a central panel depicting an ambiguous shape featuring both spiky and round edges to retrieve a palatable food reward. (Right) Thereafter the chick was presented with two panels (one blank) and learned to circumnavigate the one depicting the ambiguous shape to obtain the food reward. The position (left/right) of the baited panel was counterbalanced between training trials. To pass the training phase, the chick had to detour the correct panel (i.e., the one depicting the ambiguous shape) in six of eight consecutive trials. (**B**) An example of a "bouba" testing trial (left) and of a "kiki" testing trial (right). The chick could see both a round and a spiky shape simultaneously presented each on one of the two panels, while a hidden speaker repeated the nonword "bouba" or "kiki." Each chick underwent 24 test trials with the background sound and position (left/right) of the shapes pseudo-randomly alternated between trials. At test, no reward was present.

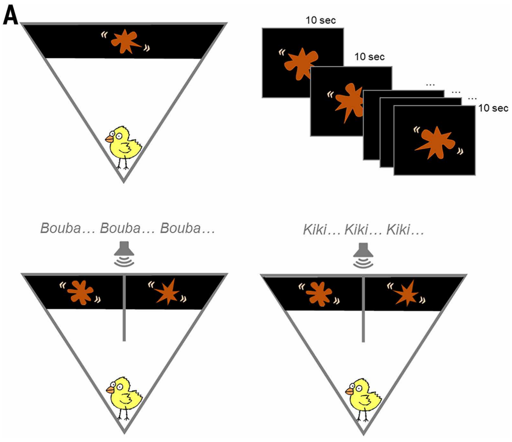

Fig. 2. Exp. 2 experimental paradigm. (**A**) Habituation (Left). The chick was left free to explore a triangular arena while a series of ambiguous shapes (having both spiky and round edges) were sequentially presented at the center of a computer screen. (Right) Each shape remained visible on the screen for 10 s and was immediately substituted by a new one. Each shape performed a small tilting movement to enhance its saliency for the animals. (**B**) At test, two stimuli were projected simultaneously in the right and left halves of the screen: one round shape and one spiky shape (same as those used for Exp. 1). Each stimulus pair remained visible for 10 s before being immediately replaced by the next, and performed the same tilting movement used as an attentional cue during habituation. The test lasted a total of 6 min, during which the chick was free to explore either shape. The sound played ("bouba" or "kiki") and the position of the shapes (left or right) remained stable during individual tests and were counterbalanced between subjects.

reintroduced into the arena, where the monitor displayed the round and spiky shapes side by side while either the sound "bouba" or "kiki" was played for the first time. Chicks were let free to move around for 6 min while we recorded the first shape approached and the total time spent exploring each shape (Fig. 2B and movie S1). We hypothesized that, if chicks possess an early-emerging predisposition for sound-shape associations, those hearing "kiki" will preferentially approach and spend longer exploring the spiky shape (and the round shape for those hearing "bouba"). Results were similar in the two experiments and in line with our hypotheses, supporting an early-emerging, experience-independent sensitivity to crossmodal associations in chicks, akin to humans.

Studying a precocial animal with tight control on its experience prior to testing (*30*, *34*) allowed us to pinpoint the developmental origin of the bouba-kiki effect and of sound-shape correspondences and to address the role of experience on its emergence. Additionally, evidence from a bird species can provide relevant insights on the evolution of this phenomenon, considering the wide phylogenetic distance between mammals and birds (with the last common ancestors dated between 300 and 320 million years ago) (*45*, *46*).

Results

Exp. 1

Chicks preferred the round shape when hearing "bouba" [P(round) = 0.66, SE = 0.02, $P < 0.001$], and the spiky shape when hearing "kiki" [P(round) = 0.44, SE = 0.02, $P < 0.01$] (Fig. 3). To control for any a priori preference for either the spiky or round stimulus, we ran a control condition on a separate group of 29 subjects. Instead of using the "bouba" and "kiki" sounds, we alternated between silence (i.e., no sound played) and classical music excerpts (see audio S1 and S2). Silent trials aimed at assessing chicks' spontaneous preferences in the absence of auditory stimulation whereas music trials were employed to assess their responses under auditory conditions that were not expected to influence shape preference. We found no effect of the condition (silence or music). Overall, chicks preferred the round over the spiky stimulus [P(round) = 0.58, SE = 0.02, z.ratio = 3.64, $P < 0.01$]. Notably, this preference remained different from the one observed in the experimental group [Welch's two-sample t test: ("bouba" versus control trials: $t = 2.48$, $P = 0.02$; "kiki versus control trials: $t = -5.3$, $P < 0.001$) (Fig. 3).

Exp. 2

Chicks in the "bouba" condition explored the round shape for longer (mean exploration time = 199.56 sec, SE = 25.12 sec) than the spiky one (mean exploration time = 57.53 sec, SE = 21.44 sec), with a significant difference between the two times (contrast round-spiky = 142 sec, SE = 31, $t = 4.58$, $P < 0.001$). Vice-versa, chicks in the "kiki" condition explored the spiky shape for longer (mean exploration time = 144.07 sec, SE = 23.13 sec) than the round one (mean exploration time = 44.1 sec, SE = 17.37 sec), with a significant difference between the two times (contrast round-spiky = –100 sec, SE = 31 sec, $t = -3.22$, $P = 0.003$) (Fig. 3C).

The sound-shape association holds also when considering the first shape approached. Chicks in the "bouba" condition first approached the round shape 80% of the times (odd ratio round/spiky = 16, SE = 12.65, z = 3.51, $P < 0.001$), whereas chicks in the "kiki" condition first approached the round shape 25% of the time (odd ratio round/spiky 0.08, SE = 0.06, z = –3.7, $P = 0.001$).

Discussion

We observed a spontaneous tendency in 3- and 1-day-old chicks to associate a round shape with the "bouba" sound and a spiky shape with the "kiki" sound. Our results, together with previous evidence in domestic chicks (*40*, *43*), points toward a predisposed mechanism for crossmodal associations. This may likely serve the scope of coordinating information from different sensory modalities to build unified representations of entities.

Data from other nonhuman species, including primates (*19*, *21*, *47*), dogs (*22*, *23*), and tortoises (*20*, *24*) suggest that such a mechanism

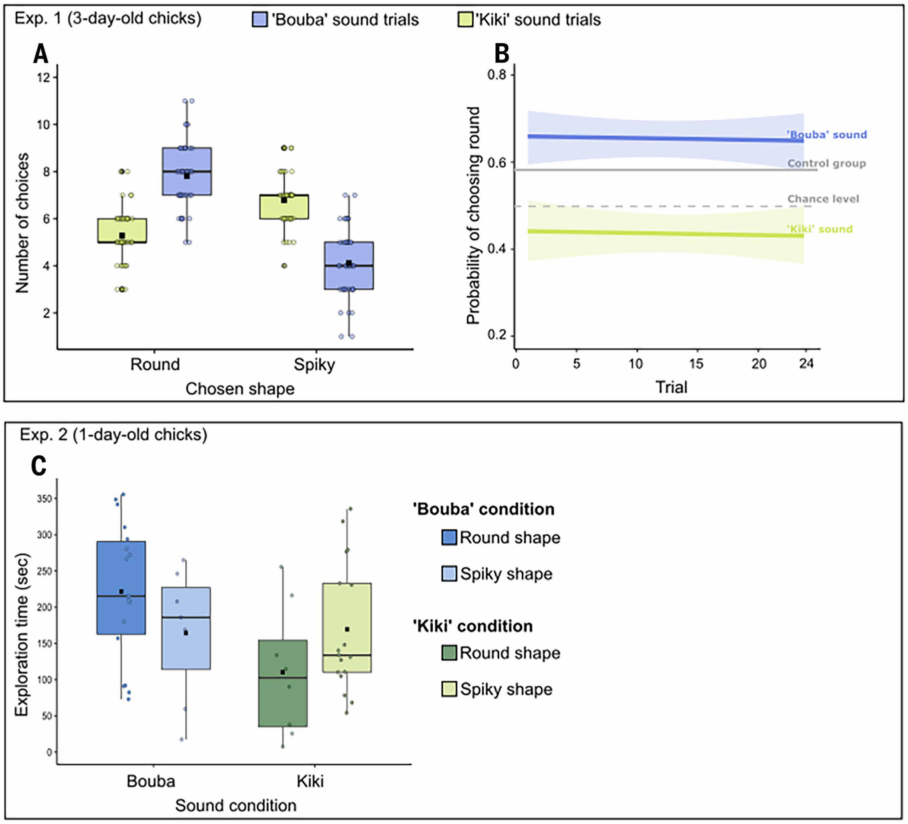

Fig. 3. Results. (**A**) Results from Exp. 1. On the *y*-axis, the number of choices (out of 12 trials) in which the chicks circumnavigated the round (left) or spiky (right) panel while being presented with the "kiki" (green) or "bouba" (blue) sound. The boxplot shows the 25th percentile and the 75th percentile; the horizontal bar in the boxplot represents the median and the black square represents the mean. Each dot represents the performance of a single subject. Overall, chicks consistently chose the panel with the spiky shape significantly more often when hearing "kiki" and that with the round shape when hearing "bouba." (**B**) Results from Exp. 1 plotted by trials. The *x*-axis represents the testing trials (from 1 to 24). The *y*-axis depicts the probability of approaching the round shape when hearing the "bouba" (light blue) or "kiki" (green) sound. The shaded areas indicate 95% confidence intervals. The dashed gray line represents chance level ($P = 0.5$). The solid light-gray line represents chicks' average preference for the round shape in the conditions with no sounds/classical music ($P = 0.58$). Overall, chicks consistently chose the panel with the spiky shape when hearing "kiki" significantly more often and that with the round shape when hearing "bouba." Their choice is significantly different from both chance level and from the preference baseline established with the control group. (**C**) Results from Exp. 2. The *y*-axis represents the time (in seconds) chicks spent exploring each stimulus when hearing the "bouba" (left) or the "kiki" (right) sound. Preference for the round shape is shown in dark blue ("bouba" condition) and dark green ("kiki" condition); preference for the spiky shape is shown in light blue ("bouba" condition) and light green ("kiki" condition). The boxplots display the 25th percentile and the 75th percentile; the horizontal bar indicates the median and the black square indicates the mean. Each dot corresponds to an individual subject. Overall, chicks tested in the "bouba" condition explored the round shape longer whereas chicks tested in the "kiki" condition explored the spiky shape longer.

may be shared across different taxa and possibly reflects an old evolutionary organizing principle of the brain (*19*, *24*). Notably, in humans there is evidence of noncognitive processing of bouba and kiki sounds, which may evoke different levels of emotional arousal (*48*). Further studies reinforce this view, showing that the effect is mainly related to perceptual, rather than speech-related factors, such as the possibility of perceiving the sounds as linguistic (*49*) or mechanical-articulatory constraints and pronounceability (*50*).

Altogether, these findings suggest that the bouba-kiki effect represents another case of unlearned crossmodal correspondences. Rooted in a shared system of crossmodal associations, species-specific sensory, perceptual, and cognitive capacities may yield different developmental outcomes and adaptations to their ecological contexts. In humans for instance, sound-shape associations may contribute to early lexical development by helping infants structure and attend to referents in a complex environment, building a vocabulary (*7*, *8*, *14*), and potentially reducing cognitive load (*8*, *14*). From this perspective, one potential utility of crossmodal correspondences could lie in their contribution to communication. Indeed, several nonhuman species display communicative systems that map specific acoustic signals to external referents, such as alarm calls for different predators in vervet monkeys (*51*, *52*) and Japanese tits (*53*, *54*), or food-specific grunts in chimpanzees (*54*). Similarly, domestic chickens exhibit a surprisingly rich vocal repertoire, with around 30 distinct vocalizations identified in both adults and juveniles (*55*, *56*) and including referential and socially modulated calls that vary in acoustic structure depending on the context and threat type. Although these communicative behaviors are not necessarily sound-symbolic they may still build upon early developing predispositions for associating structured auditory signals with external stimuli. Even though newly hatched chicks produce only rudimentary vocalizations, primarily distress calls and pleasure notes (*55*–*57*), they may already possess the neural foundations for processing such multisensory correspondences, similar to how human infants are sensitive to linguistic structure well before they begin to speak (*12*).

In Exp. 1, chicks in the silent and classical music conditions showed an initial preference for the round shape, consistent with previous evidence in this species (*58*–*60*) and human infants (*61*, *62*). This preference was then strengthened when hearing "bouba" or overridden when hearing "kiki." Similarly, a stronger response to "bouba" is also reported in humans (*11*). We also observed that the bouba-kiki effect remained stable throughout testing, which contrasts with previous studies on other spontaneous crossmodal associations (*24*, *40*). By including refresh trials (rewarded) prior to each test block (unrewarded), and a time break between each block, we may have reinstated chicks' attention and motivation toward the testing stimuli (*63*), thus preserving the initial association. Alternatively, sound-shape associations may be deeply rooted and thus less subject to habituation or extinction. In Exp. 2, we replicated the sound-shape association effect under more stringent conditions. By testing chicks on the day of hatching, we minimized the possibility of prior experience, directly tackling the question of whether the effect arises from postnatal learning or maturation, or rather reflects an early-emerging predisposition. Notably, the convergence of results employing two different experimental paradigms supports the robustness of the finding and further points to the precocial or predisposed origin of sound-shape associations. In both experiments, our analysis focuses on population-level effects rather than individual preferences as we consider sound-shape correspondences to be a general predisposition, representing a readiness to form associations (individual performance for both experiments is available in data S1 and the supplementary text). As such, it not expected to appear in all participants to the same extent due to both intrinsic (and functional) phenotypical variations or environmental conditions (*64*–*66*). Research in chicks as well as other animal models (*24*, *40*, *42*, *44*) and humans (*67–69*) supports this idea, showing that although predispositions are broadly present, they exhibit high interindividual variability rather than strict universality.

Previous studies on nonhuman primates (chimpanzees, gorillas, and one bonobo) failed to observe the bouba-kiki association (*28*, *29*). It seems unlikely that a predisposition for sound-shape association could have evolved separately in birds and humans while being absent in our closest relatives, the other great apes. We argue that this inconsistency likely stems from methodological differences as well as from key features such as age, level of prior expertise, and training of the subjects. For instance, at the time of testing, the bonobo Kanzi was already capable of associating sounds and shapes to the point that he could match up to 500 visual-auditory pairs (*29*, *70*, *71*). Thus, it is possible that the properties of his limited "lexical repertoire" could have influenced or biased his responses. Another relevant factor could have been the use of random reward schedules that may have reduced animals' motivation in trying to respond correctly. Thus although it remains possible that apes may not be sensitive to sound-shape associations, it is crucial to re-evaluate their responses in light of the task they are facing and their ecological needs (*72*).

In conclusion, in our study we showed that baby domestic chickens (*Gallus gallus*) respond to sound-shape associations, similar to humans, preferentially matching the sounds "bouba" and "kiki" to a round and a spiky shape, respectively. In particular, our data place the origin of sound-shape crossmodal matching at the earliest stages of life, possibly hinting at a predisposed experience-independent mechanism. Direct evidence in an animal model suggests that, rather than being a culturally learned phenomenon unique to humans, the bouba-kiki effect and sound-shape correspondences may belong to a set of predisposed associations shared across species.

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SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.adq7188
Methods; Supplementary Text S1; References (*47*, *48*); Data S1 and S2; Movie S1;
Audio S1 to S4

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COMMENTARY

PERSPECTIVES

PSYCHOLOGY

In search of meaning

The origins of language are not found in the bouba-kiki effect

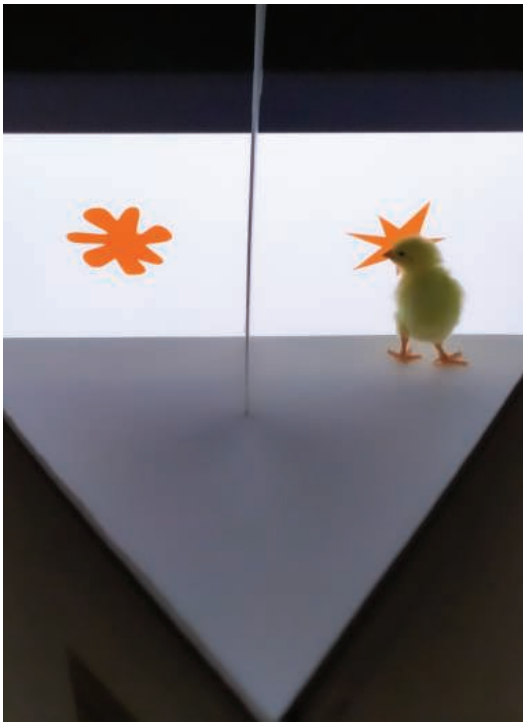
Marcus Perlman and **Bodo Winter**

The bouba-kiki effect—the association of spoken pseudowords such as “bouba” with rounded figures and “kiki” with pointed figures—has been touted as evidence that people can attribute meaning to new words based on a perceived correspondence between sound and shape. The effect, particularly with “bouba,” is evident early in human development (*1*) and is robust across diverse cultures and linguistic backgrounds (*2*). On page 836 of this issue, Loconsole *et al.* (*3*) report that the bouba-kiki effect is also exhibited by newly hatched chickens. The authors propose that such sound-shape correspondences may belong to a set of innate cross-modal associations that are shared across species, rather than being a speech-related phenomenon that is distinctive to humans.

Loconsole *et al.* placed 3-day-old chicks in a small enclosure in which they faced two panels—one displaying a rounded figure and the other a pointed figure—while a recorded voice repeated either the word “bouba” or “kiki.” Permitted to freely explore the panels, the chicks showed the same bias as humans, moving more frequently toward the panel displaying the rounded shape when they heard “bouba” and to the panel with the pointed shape when they heard “kiki” (see the photo). One-day-old chicks showed a similar bias, moving toward the panel corresponding to the word that was played and spending more time exploring that panel. These results reveal that the bouba-kiki effect is rooted deep in vertebrate phylogeny, suggesting that birds and mammals—and by inference, their reptilian common ancestor—are born with a predisposition to map certain kinds of sounds with certain kinds of visual stimuli. This inborn bias could help animals coordinate sensory information between the two modalities to build unified representations of physical entities.

Given such a broad phylogenetic basis, what is the relevance of the bouba-kiki effect for understanding the origins of human language? The phenomenon has received much research attention because the sound-shape correspondence might provide a solution to the so-called “symbol grounding problem.” Before the establishment of a conventional spoken language in human evolution (or the acquisition of one during child development), commonly shared associations between sounds and shapes could have provided a preliminary connection between spoken forms and meanings (*4*, *5*). Other cross-modal associations, such as between pitch and luminance (high or low pitch with bright or dark, respectively) and between pitch and size (high or low pitch with small or large, respectively), could also have facilitated the establishment of new vocal symbols in the early emergence of speech.

However, growing evidence from linguistics and cognitive science suggests that these innate associations represent just a small fraction of humans’ far wider capacity for iconicity—people’s general ability to exploit resemblance between form and meaning for communication. In recent decades, this research has contributed to a marked shift in the understanding of language (*6*–*8*). No longer equated with spoken symbols that bear no resemblance to their meaning, language is now seen as multimodal, expressed through visual signs (*9*) and speech-associated gestures (*10*), as well as speech. Within this framework, languages express meaning both through conventional connections between word forms and meanings and through iconicity, which is now understood to be a fundamental property of language (*6*, *7*, *11*).



Newly hatched chickens associate rounded shapes with the word “bouba” and spiky shapes with the word “kiki.”

PHOTO: LOCONSOLE *ET AL.*

The lexicons and grammars of sign languages show ample evidence of iconicity, as do many of the gestures used by people when they speak. Iconicity also shapes spoken languages to a much greater extent than previously appreciated. For example, iconicity is present in ideophones, which are a distinct lexical class of depictive words found in many, if not most, of the world’s spoken languages, with some containing hundreds or thousands of these words (*4*, *11*). Ideophones go far beyond the sound-based iconicity of onomatopoeic words (words that resemble the sounds they refer to, such as “buzz,” “ping,” or “meow”). They express a wide array of vivid meanings related to sensory, motor, emotional, and cognitive experiences. Examples include “kibikibi” (energetic) and “bukubuku” (flabby, obese) in Japanese and "fwefwefwe" (springy, elastic) and "saaa" (cool sensation) in Siwu, a language spoken in Ghana (*11*). The ability to coin and appreciate these semantically diverse words is not adequately explained by a discrete set of predisposed cross-modal associations such as the bouba-kiki effect.

Although the bouba-kiki effect cannot account for the wide-ranging manifestations of iconicity found in spoken words, it could have played a role in grounding the first vocal symbols because of the extent to which it is innate and universal across humans. Loconsole *et al.*'s findings in chickens seem to amplify this possibility, which suggests that the effect is deeply ingrained in human phylogeny. Notably, however, the bouba-kiki effect is not an especially strong case of iconicity in speech sounds. For example, a cross-cultural study that included speakers of 28 languages spanning diverse cultures and language families reported a stronger and more consistent association between a trilled /r/ sound with a jagged, "rough" line and a lateral approximant /l/ with a flat, "smooth" line (*12*) than a comparable study of the bouba-kiki effect (*2*).

Beyond these specific associations, the human capacity to communicate with iconic vocalizations—nonlinguistic vocal sounds that depict or resemble their meaning—is expansive. For example, in another cross-cultural study, speakers of different languages were able to interpret new vocalizations created to communicate 30 meanings that included various entities (e.g., child, deer, fire, fruit), actions (e.g., eat, cut, hide), and properties (e.g., big, many, sharp) (*13*). Such findings demonstrate the vast and open-ended human talent for vocal charades, a skill that distinguishes them from all other animals.

As good as they are at vocal communication, humans might be even better at playing charades with their hands (*14*) or through drawing (as in the game of Pictionary). Even if the basis for the bouba-kiki effect is phylogenetically ancient, as shown by Loconsole *et al.*, it is but a single manifestation of the near-boundless human capacity for iconicity that transcends any particular medium of communication. Therefore, although the study of innate cross-modal correspondences such as the bouba-kiki effect may uncover general principles of sensory perception, a broader framework of iconicity is needed to illuminate the origins of language. □

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SOCIAL SCIENCES

AI raises the productivity bar

Understanding how AI affects productivity has implications for labor markets

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Artificial intelligence (AI) is often assumed to democratize productivity by lowering the cost of production, especially for less-experienced workers (*1*, *2*). An opposing view is that AI concentrates productivity among the experienced. These competing expectations arise because they rest on different definitions of productivity. If it means generating more text, figures, or lines of computer code, then AI should benefit novices more by making the production of such output cheaper. But if productivity depends on whether the output has market value and keeps people employed, then AI should benefit experienced workers more by amplifying the value that they bring from their accumulated knowledge, skills, and judgment. On page 831 of this issue, Daniotti *et al.* (*3*) report that entry-level software developers show little productivity gain when using AI compared with their experienced counterparts.

Software development is one domain where empirical evidence on the impact of generative AI is accumulating quickly, thanks in large part to the wealth of trace (time-stamped) data available from GitHub, a public platform where developers store and manage code. Although measuring productivity from public repository trace data depends on many assumptions, the scale of such data is orders of magnitude larger than self-reports or controlled experiments, thus offering considerable statistical power. Daniotti *et al.* analyzed millions of open-source changes to Python files on GitHub using a machine learning model (classifier) trained to recognize AI-generated code. The authors show that adoption of generative AI has grown rapidly, accounting for roughly one-third of Python functions written by late 2024. They also found that only experienced developers—those with 6 or more years of GitHub activity—show a measurable rise in commit rates (a measure of software development velocity that can be interpreted as a proxy for productivity), whereas junior developers show little gain. If this finding were to hold broadly for production-grade software beyond the public Python files of the study, it would mean that even as AI use spreads quickly, the capacity to convert generated code into working software does not grow with it.

The findings point to a potential threshold model of human-AI productivity in which the quality of human input translates into productivity gains only after a minimum amount of expertise is reached. When content can be generated cheaply, productivity depends less on producing output and more on integrating AI-generated material into complex systems. Below this threshold, it may be that more generated content simply absorbs working time—output must still be read, edited, and maintained at substantial cost (*4*). Once the threshold is crossed, however, AI could accelerate productive work by reducing execution time. In this sense, AI does not lower the productivity bar but raises it.

In software development, human input takes two kinds of judgment. One is evaluation. Junior developers often treat AI-generated code as tentative solutions—they insert outputs into projects, keep them if they run, and revisit problems only when something breaks (*5*). This workflow generates false positives—code that appears functional in isolation but fails under real-world complexity or accumulates technical debt (*6*). Experienced developers, by contrast, draw on accumulated knowledge of abstractions, design patterns, and failure modes to predict how code