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Firelight and the origins of spoken language

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Language and fire are hallmarks of the human condition, but most scholars treat them as independent traits. We develop a theory for the origin of language that links both touchstones of human evolution. First, we show that precursors to language were probably rooted in the gestural systems of living apes. Next, we show that attempts to explain the evolution of spoken language in utilitarian terms (a) are undermined by evidence of these abilities in other species and (b) overestimate the need for language to sustain daily practicalities of early small-scale social groups. Instead, we draw attention to the fireside niche as the likely site for the origin of language during oral storytelling. Fireside storytelling could: (i) resolve the conundrum of why load-bearing aspects of meaning shifted from gesture to speech, and (ii) promote hierarchical structure and a shift away from embodied gesture into arbitrary generative speech, enabling communication outside of direct experience and into social imagination: from our distant past and future, to other places and peoples. We examine visual properties of firelight to consider how it could enhance the effectiveness of storytelling. We generate testable predictions to address how firelight propelled the characteristically human expression of language.

1. Background

Darwin [1] described fire as 'the greatest [discovery], excepting language, ever made by man'. It is an oft-cited claim by those writing about the sequential origins of these traits. The past decade, however, has witnessed the integration of both topics into a unified vision of fire-mediated language evolution [2–4], a trend that parallels emerging evidence for temporal congruence in fire-use and the expansion of key brain features, such as Broca's area, between 2.0 and 1.5 Ma [5,6]. This development is notable for transcending the boundaries of several disciplines—evolutionary anthropology, comparative psychology, cognitive neuroscience and primatology—a factor that can impede progress. Another problem is mechanistic: how does fire promote language evolution? Here we put disparate literatures into conversation to highlight the testable properties of firelight and its potential influence on the origins of spoken language.

2. Ape communication

Great apes or hominoids—including humans—have a rich set of signals for communicating needs, emotions and goals. In this, they are not unique. Like many species, their repertoire draws on different modalities such as olfaction, sound, vision and touch. What is distinctive is their use of large sets of intentional signals to recognize and reshape the behaviour, and perhaps understanding, of others during social interactions. Humans accomplish this feat with

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language, whereas other apes rely principally on intentional gestures: a large, rich, multi-channel system of communication used to navigate the day-to-day goals of social life.

Language is not restricted to speech. Sign languages are language in its full form, but they are typically employed in situations where spoken language is inaccessible to some people. As a result, primate vocalizations—superficially resembling speech—offered a logical starting place for studying language evolution. Initially validated by findings on the informational content of referential alarm calls in monkeys [7,8] and indications of combinatoriality [9–11], this same body of work raised thorny questions. It demonstrated that primate receivers capably extract essential information, but it was unclear whether signallers produce calls with the intent of communicating information to receivers [12]. Most referential calls are 'alarm calls' produced in response to potential predators, a narrow usage that makes it difficult to establish the flexibility of calling in general—indeed, callers show few adjustments to the knowledge, attention or even presence of audience members [7,13–15]. Perhaps most crucially for research on the origins of language, this outcome has been replicated across monkey species [6,16], even if there is little evidence that apes have—or need—similarly referential vocalizations (although see [17]). In part, this absence may be owing to an under-appreciated level of plasticity in ape vocalizations [11,18], including intentional use of some alarm calls [19,20]. At the same time, there is some evidence for referential use of specific signals in non-primate species, such as fish [21]. Thus, intentional signalling can sometimes emerge under sufficient selective pressure on a particular use-case. Where ape gestures and human language continue to stand alone are in the scale of the system and in the flexibility with which we co-construct meaning with our communicative partners.

A recent estimate suggests that eastern chimpanzees have more than 140 [22] and mountain gorillas have more than 120 discrete gestural units [23], numbers that exceed the repertoires for any other signal type by an order of magnitude, including the gestures of monkeys [24,25]. Every ape has access to a largely shared repertoire of gesture units, with evidence of near-perfect overlap among closely related species [26,27], and use of presumed 'species-typical' gesture units by heterospecific apes living under atypical socio-ecological conditions (e.g. gorilla-like chest-beating by sympatric chimpanzees [28] or the expression of 'chimpanzee' gesture-actions by (social and terrestrial) captive orangutans [29]). The mechanisms underpinning these shared repertoires are debated [30–32], but the core forms of these units are unlikely to be learned [27] or to be a trivial consequence of similar body plans [33]. However, far from a family-wide repertoire resulting in a fixed rigid system, apes show substantial flexibility in gesture *use*, with evidence for variation in the frequency of use [26,34,35], nuanced articulation of specific forms [36], perhaps akin to dialects [37], and in the timing and patterning of gesture use [38,39].

A particularly characteristic feature of human language is its capacity to distinguish between timeless and occasion meanings (*sensu* Grice [40]). Timeless meaning provides a general meaning across uses of a word, but where language thrives is in our ability to generate variable meanings on distinct occasions, based on the shared understanding of signaller and receiver. Here, the same words and intonation can be used to *mean* something very different in each usage (the phrase 'nice shoes' means something very different when uttered just after someone says hello, as compared with just after being asked if they like their conversation partner's new hat). The informational content of most species' signals is highly fixed, as is the intentional use of a chimpanzee alarm call (or fish-hunting gesture)—ambiguity is problematic if the context is urgent and some consequences are dire. By contrast, great apes regularly incorporate the immediate socio-pragmatic context into their use of gestures; for example, the same object-move gesture can hold at least four different meanings (move closer, move away, etc.) depending on the characteristics of their partner, their shared history and the behavioural context [41–43].

(a) Gestural origin theory

Given that communication via flexible intentional context-embedded meanings is universal in great ape gestures, gesture has been proposed as the channel through which language-like meaning evolved in crown great apes, including humans [44,45]. The theory that human speech has roots in gestural communication emerged in the 18th century, when philosopher Bonnot de Condillac described language as developing from the 'language of action'. But the empirical foundation for gestural origin theory dates to the 1970s, when researchers began studying the communication systems of wild primates [44–47].

Recent work supports the importance of gesture in the origins of language, with evidence that language operates in tandem with (rather than completely replacing) the gestural system of apes. Young children express many of the same gestures that other apes use to communicate needs while language is coming online [48] and perhaps long after [49]; and language-competent adults continue to show understanding of the gestures produced by other apes [50], even when incorporated into conspecific human exchanges [51].

Our current understanding recognizes the fundamentally multi-modal nature of language and primate communication [52,53] and highlights the difficulty of drawing a sharp distinction over the use of different channels [54]. Most of the evidence suggests that non-human apes centre the load-bearing semantic aspects of language-like meaning in their gesturing, but other aspects of language use—such as combinatorial and compositional structures—are more readily detected in vocal systems [11,55]. Arguably, gestural sequences are unencumbered by the linear combinatorial structures of spoken languages and primate vocalizations, much like signed languages [46,56,57]. Still, the fundamental components of language—the sounds and movements, our ability to construct intentional, flexible meanings and to combine them in structured ways—are shared with every other great ape.

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3. Language: what is it for?

Given that non-human apes have the same tools in their communication toolkit (and seem capable of acquiring characteristically 'human' ones, when raised in human environments [58,59]), human language may have less to do with the structural tools available to us and more with how we use them, or what we use them for.

A range of human behaviours are thought to be language-dependent, but—while they undoubtedly benefit from and are enriched by language use today—most can be ruled out as the key initiating force of language evolution. Tool use—including tool manufacture—does not require language. Taxa as diverse as apes to octopuses, by way of various bird families (famously New Caledonian crows [60] and parrots [61]), construct tools to solve problems related to extractive foraging, hygiene and communication. Even the sophisticated stone tools of early hominins can be acquired without language, although it probably promotes learning [62]. Facilitating understanding through teaching is another characteristic use of language, but it is problematic to suggest it as the original catalyst of language evolution. Teaching is neither uniquely [63,64] nor universally human—and linguistic instruction and the active shaping of learning are features of Western, educated, industrialized, rich and democratic (WEIRD) cultures [65]. Pantomime may offer a practical preliminary alternative to language in teaching [66]. Written language is another powerful way to transmit information—separating us from the need for direct teacher–pupil contact—but it is a recent invention (approx. 6 ka [67]), and focusing on it elides over the important role of oral traditions in knowledge transmission.

Similarly, practical uses of language for social coordination—for example, cooperative hunting [68], confrontational scavenging [69], inter- and intra-community aggression, social politics and warfare [70]—fall at the same hurdle. Language undoubtedly facilitates the expression of these behaviours, but they are neither uniquely nor universally human. With their current system of communication, non-human great apes can acquire and share cultural understanding of material technology and communicative dialects [37,71,72]. They establish and maintain diverse non-kin social bonds—so much so that the endocrinological 'rewards' for participation in social behaviour such as grooming are dependent not on the activity, but on the nature of the social bond [73,74] and the anticipation of participation in risky activities, such as boundary patrols and hunting, is sufficient to trigger them (irrespective of outcome [75]). Apes hunt other species (including the possible coordination of differentiated roles [76]) and kill their own—sometimes over extended territorial back-and-forths [77,78]. They navigate nuanced social politics and show substantial group-to-group variation in how these are expressed, even within populations [79,80]. They appear to understand death [81,82] and show prosocial care—including of non-kin—when individuals are sick or wounded [83,84]. When raised in a human environment [58,59], apes acquire human expressions of symbolic communication and culture—including time, numerals and holidays—suggesting their apparent absence in wild populations is not the result of a firm physical or cognitive limitation.

Once again, we find ourselves at an impasse. Our search for a 'smoking gun' to differentiate the communicative abilities of humans and great apes continues to elude us, and yet we remain surrounded by evidence of human distinctiveness. For all their communicative and technological capacity, no other ape is inventing algebra, writing King Lear or probing interstellar space.

4. Storytelling: a uniquely human use of communication

Our use of language to navigate the mundane logistics of social life does not (need to) differ dramatically from the communication of other apes. But once our daily needs are taken care of, we continue to sit and talk long into the evening hours. In 2014, Wiessner [2] made the provocative suggestion that social fire was the fundamental driver of human evolution. She recorded the conversations of Ju/'hoansi foragers and highlighted a crucial difference between daytime topics (mundane practicalities, gossip) and fireside conversation. Overwhelmingly used for storytelling, fireside conversations were, she argued, key drivers of human sociality: they were fuel for imagination and the formation of individual and group identities, cultural norms and belief systems. There was no fundamentally new ingredient in the human mix. But the use of language for storytelling so fundamentally reshaped our social worlds that it made us who we are today: *Homo narrans*, man the storyteller. Given that shifts in our communication can shift our perception of the world and of each other [85,86], affecting our choice and use of words and language, and with it our ability to describe important aspects of group and individual identity, then it follows that the incorporation of controlled fire into our social lives served as a catalyst that initiated a rapid acceleration of how we think about the world, others and ourselves.

But what if we could go one step further? Suppose that the non-linguistic communicative systems shared by modern apes, including humans, are sufficient to sustain the mundane practicalities of life in a small-scale prosocial society. Then, perhaps, language itself emerged in the context of fireside storytelling.

Our supposition offers a plausible explanation for the difficulty in establishing uniquely human features or combinations of capacities not present in the communication of other species. If language developed into the form we recognize today during storytelling as a mechanism for social bonding at the group level, then storytelling language—but not other forms of communication—should be characterized by patterns that promote collective behaviour in humans and other species. But, to date, research has focused on comparing the everyday practical communication of non-human species with similarly practical uses of language by humans and finding substantial overlap in the ways in which we achieve those 'mundane' daily goals and navigate our basic social needs. When we compare like-with-like in our uses of communication, we find many of the same underpinning mechanisms. But if our human use of language emerged during fireside storytelling, then storytelling should differ from other uses of language—and from 'mundane' communication of other apes—in predictable ways. To investigate this possibility, we need to

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describe the structures and features of storytelling and compare them with how other species establish, share and shape social identities during communication.

Storytelling is described as 'a collaborative conversational activity focused on the production of narrative discourse' [87,88], with audiences functioning as a passive receptacle, or an active participant, guiding the narrative [89,90]. Anthropologists and linguists have paid ample attention to storytelling, calling attention to universal properties [91], such as metaphor [92–94], its evolutionary and cultural significance [87,95,96] and to the features that distinguish it from other forms of discourse [97–100]. New neural-imaging techniques highlight why we find stories so compelling: unlike mundane speech, where we focus on decoding information, a far greater proportion of our brain, across diverse regions, is activated when listening to stories [101]. In addition to the prefrontal areas responsible for listening and processing, stories activate areas associated with reflection and creativity, and storytellers and listeners experience shared neural entrainment [102,103]. As work shifts toward story*telling* [87,104] (supplementary material), it also opens a void: no one has quantified the core structural differences between storytelling and mundane speech in ways that are suitable for cross-species comparison. Here we generate testable predictions, enabling us to investigate the hypothesis that language emerged in fireside storytelling.

(a) Rhythm

One highly tractable area of speech production is its rhythmic patterning, prosody and tempo. These features have been intensively studied in music, using qualitative and quantitative approaches to explore variation and identify human universals [105,106], as well as points of commonality with other species to suggest deep evolutionary roots [107,108]. The study of rhythm in music and performance has also been used to explore synchronization and coordination of behaviours, such as drumming and song, powerful facilitators of social connectedness in both humans and apes [109]. Quantitative studies of rhythmic patterning and tempo during speech have focused on everyday conversations [110,111], often during experiments, where strangers in laboratory settings exchange scripted information [112]. New studies aimed at generating more naturalistic automated expressive speech hint at measurable variation in pitch range and speech in storytelling [113], but most studies of expressive storytelling speech remain qualitative [114,115], making comparisons challenging. Storytelling sits at the intersection of informational and narrative aspects of everyday speech and the performative components of music or song, topics with established methodologies. We are well equipped to detect quantitative distinctions in the tempo and patterning of everyday speech and storytelling.

(b) Narrative structure: a beginning, a middle and an end

In *Poetics* [116], Aristotle offered this succinct definition: a story has 'a beginning, a middle and an end'. The back-and-forth of conversation, in which the outcome is rarely predetermined, is exchanged in rapid-fire turns [117,118], produced so quickly that receivers' brains are already planning a response before the speaker pauses [117]. The timing of these turns is highly similar in chimpanzee gestural exchanges—including the frequency of 'interruptions' before the 'speaker' is finished—suggesting homologous communicative devices for aligning conversation [39]. Stories, however, are often told to an audience, and in settings that require long-form structure and some planning from the outset. Receivers may still respond actively, with gestures and sounds of encouragement, or formalized call-and-response, but a lack of interruption for extended periods indicates attention, allowing the speaker to plan and execute extended forms of structural narrative. If modern language emerged during storytelling, the grammatical structure of storytelling should differ from everyday conversation in its use of hierarchically embedded long-form structure, for example call-backs and repeated patterns. Our understanding of this transition may be helped by investigating the ways in which tempo and structuring of behavioural signals vary in contexts where apes appear to discriminate longer-form 'performance' for an audience (as in displays or perhaps 'rain-dances') from use of similar signals in back-and-forth exchanges.

(c) Content

Finally, in addition to variation in rhythm and patterning, storytelling differs from everyday speech in content. For example: stories benefit by containing some—but not too many—counter-intuitive elements: when the balance is right, they are more faithfully transmitted across tellings [119]. If modern language emerged during storytelling, the content of storytelling should differ from everyday conversation, particularly in features that make human language characteristically different to other species' communication: more arbitrary, more generative and more abstract. At present, there is no evidence that apes engage in storytelling-like activities, but hints that they may be capable of 'pantomime' to convey meaning may offer an important bridge [66,120]; for an expansion of this point, see the supplementary material.

5. The fireside–language connection

There are recent calls to investigate the role of storytelling during language evolution, including the importance of the fireside niche [3,4]. But these arguments focused on how storytelling shaped an existing proto-language already markedly and qualitatively different from the communication of other modern great apes. Like Wiessner, these authors view fireside storytelling as a final step in the evolution of language as we use it today, rather than the generative catalyst. They describe firelight as a social niche exerting a strong selective pressure on proto-language, modifying a vocal apparatus refined by laughter and song [3].

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By contrast, we suggest that a pre-storytelling proto-language would have more in common with the communicative capacities of modern apes than with the language we use today. And that social fires catalysed our motivation to create social identities in new ways—and that doing so pushed a system of communication more similar to that of other apes, towards the structure and use of modern language.

Planer & Sterelny [4] make the case for a proto-language in practical communication, prior to storytelling, in part because they argue that core language-capacities, such as joint action and reading of others' minds, are uniquely human and readily done during daytime activities. This perspective underestimates the level of sophistication present in other primates' cognition and communication. Seyfarth & Cheney [9,121] have long highlighted that independently of what is expressed in primate signalling, there is an underlying linguistic syntactic structure to their conceptualization of social interactions, which includes the capacity for hierarchical structures and propositional relationships (combining identities, motives and causal relations). In this regard, primates show precursors to what Bruner describes as 'narrative' thought: a landscape of action that includes agents, intentions, goals, situations and instruments [100]. In apes, there is increasing evidence for a theory of mind [122,123], along with the ability to engage in referential communication [19,124], plan actions and needs in advance [125,126], and coordinate behaviour and communication to navigate cooperative tasks: all essential precursors for storytelling [127].

At the same time, Planer & Sterelny's arguments for the emergence of proto-language in practical communication may have overestimated the level of language-like communication needed to navigate daily routines within a very familiar set of individuals in a familiar location. King [128] highlights the modern examples of musical improvisation between bandmates, or a long-together couple making breakfast in their home—both complex practical tasks that can be achieved with little explicit communication between deeply familiar partners. Even if an unplanned event occurs, deep familiarity with another individual and the task at hand allows me to predict how you are likely to respond and adjust accordingly.

We agree with Planer & Sterelny [4] that displacement is rarely incorporated into modern ape communication (although they seem capable of the concept [59]). Chimpanzees live in groups of approximately 50–70 individuals, often close kin or social partners of decades, in a territory they have occupied all their adult life, with predictable variation in daily and seasonal routines. They have detailed mental maps of local food resources, including stage of ripeness [126], and may not need to 'tell' a familiar partner at the time of day they are usually hungry, with the event-typical levels of speed, stress and energy, that they want to travel together for co-feeding to a nearby fig tree. A glance or pause of affirmation or coordination may be the only 'explicit' information cue (much as all we need to do is knock on the door of an office mate around 11 am for them to grab their coffee cup without a spoken word). A similar system of communication may have allowed early hominins to navigate the mundane needs of a small-scale camp life.

We suggest that (*contra* [4]) the firelight niche is well suited to the evolution of language displacement. End-of-day social fires might have provided one of the first opportunities to gather the social group together—as readers familiar with camp life will recognize, they provide an ideal opportunity to exchange news of what happened while apart, as well as what needs to happen tomorrow. Ideal first steps towards a more abstract system of communication.

(a) Gesture to speech

For all that we continue to access and make use of our gestural inheritance [48–51], humans default to expressing language through speech. One long-standing suggestion was that the arbitrariness of speech (a classic linguistic 'design-feature' [129]) offered an advantage over gesture in freeing the signaller from the restrictions of an iconic system [130]. However, arguments for the arbitrariness of speech are undermined by increasingly widespread evidence for iconicity in spoken languages (outside of onomatopoeia [131,132], see also the supplementary material) and the usefulness of gesture for generating novel signals and meanings [133]. Another enduring argument is that increasing tool-use preoccupied the hands at the expense of gestural communication. Not only does (regular tool-users) chimpanzees' use of gesture challenge this suggestion, but the fraction of each day spent chewing food (approx. 37% in chimpanzees; 7–10% in *H. habilis* and *H. erectus* [134]) undercuts the idea that our mouths were more readily available than our hands.

An alternative suggestion is that vocalization would offer a transmission advantage in low and flickering light. All gestures are visual signals. A substantial proportion of the ape-wide gesture repertoire includes audible and tactile components, but the contribution of different modalities remains unclear, and even spoken language suffers when visual components of multi-modal production are obscured [54]. Dunbar [3] and Planer & Sterelny [4] highlight that if fireside talk was a crucial driver of human social expansion, it may resolve the long-standing conundrum of when and why load-bearing aspects of semantic meaning shifted from gesture to speech. They do so by suggesting that firelight is too dim for effective gestural communication. The potential advantages of speech as a flexible, nuanced means of reliable signal production under firelight conditions is another testable hypothesis.

6. Storytelling and the firelight niche

Several authors have called attention to the qualities of firelight and its effects on vision and storytelling, describing a 'firelit niche' [2] or 'fireside niche' [4]. This latter concept has the advantage of breadth, combining the two products of fire—a chemical reaction that emits heat and light—into an integrated sensory experience. But it suffers from familiarity. It is a milieu so readily envisioned that it is described without formal measurement (figure 1*a*). Germane here is the hypothesized effect of firelight on

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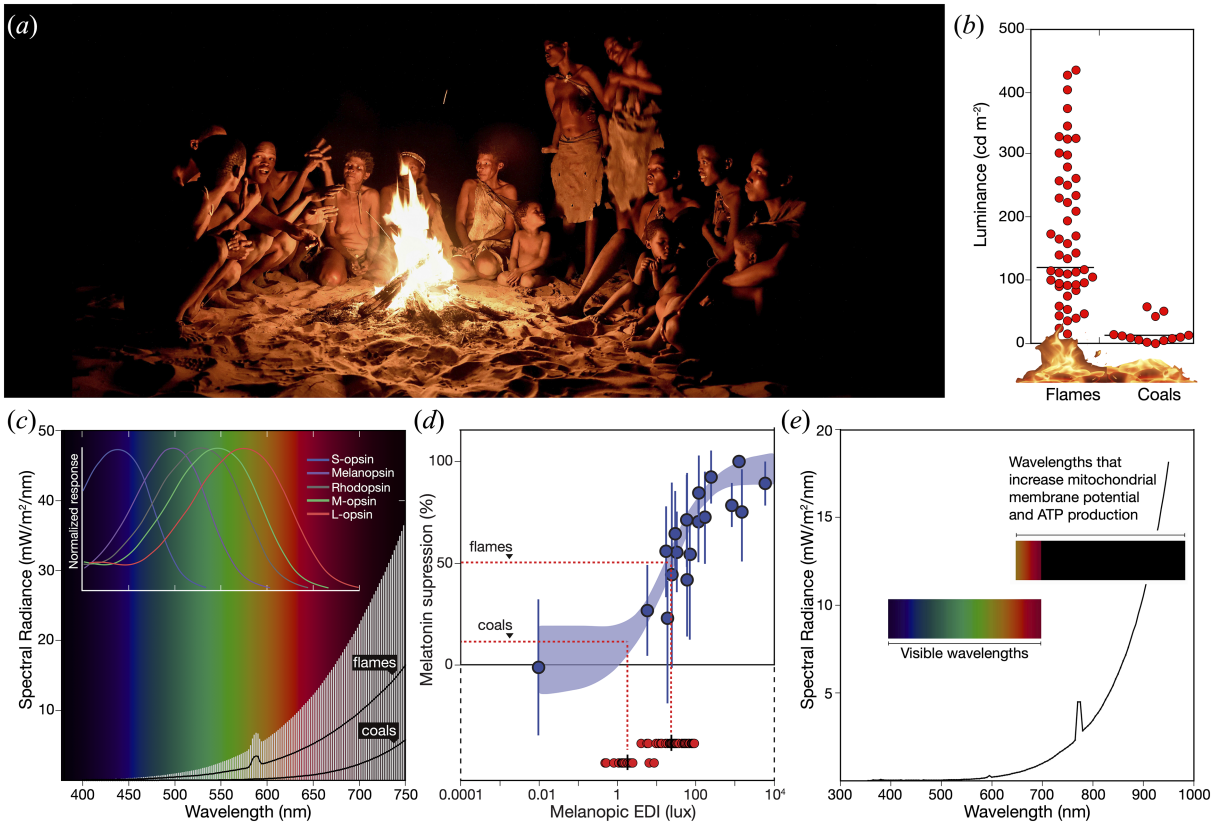


Figure 1. The fireside niche is a dynamic light environment and social space. (*a*) Storytelling by firelight among the Ju/'Hoansi-San of //Xa/oba, Namibia. Photographer: Fabian Von Poser, reproduced with permission. (*b*) Variation in the luminance of flames and coals. Horizontal lines represent median values. (*c*) Variation in the emission spectra of flames and coals. Dark lines represent median spectra; vertical white lines represent ±1 s.d.. The inset illustrates normalized absorbances of selected photopigments. (*d*) Blue circles: published data on light exposure and melatonin suppression (whiskers represent ±1 s.d.); red circles: melanopic equivalent daylight illuminance (EDI) lux values of coals (mean = 1.8 melanopic EDI) and flames (mean = 30.4 melanopic EDI); dashed lines connect the mean values with approximate levels of melatonin suppression. (*e*) Firelight emission spectrum. Mitochondria absorb near-infrared wavelengths, improving performance. Time in the firelight niche could have extraordinary photometabolic benefits, reducing need for calories and sleep, while offsetting cognitive processing costs. Complete details in the supplementary material.

language evolution, and the argument that it produces a 'smaller, less varied, less well illuminated [visual world]' [4]. Measuring the properties of firelight is a research priority, but it is also challenging. Firelight exists in a state of living flux—colours and light changing moment to moment.

(a) Firelight and luminance

The luminance of firelight is central to discussions of language evolution, in part because its dimness is viewed as an impediment to gesture [3,4,135]. Yet, the illuminance of campfires—ranging from 19 lux at 40 cm to 3 lux at 2 m (see the supplementary material)—is sufficient for resolving the spatio-temporal subtleties of vision-mediated communication, such as gesture. Our own preliminary data affirm this view, with luminous intensities at 1 m ranging from 3–61 cd m^{-1} [scintillating coals] to 18–435 cd m^{-1} [flickering flames] (figure 1*b*). The firelit niche is, therefore, photopic and extremely variable—individuals nearby may be clearly lit, whereas those farther from the fire are less so, and individuals across the fire may be entirely obscured—not by darkness, but by the fire itself (figure 1*a*). Such conditions provide ample light for intimate conversation or gossip with neighbours, but may impede communication throughout the fireside niche, a factor expected to favour oral storytelling. A problem with focusing on luminance alone, however, is that it overlooks variation in colour.

(b) Firelight and colour

Few phenomena are more effective at exciting the human visual system. The colour of firelight is extremely well-matched to the peak sensitivities of our long-wavelength cones (figure 1*c*), although it is a spurious coincidence. The evolution of our red-sensitive L-opsin between 40 and 35 Ma [136] long pre-dates the origins of controlled fire between 1.9 and 1.8 Ma [5,137], but the outcome is a visual system serendipitously pre-adapted for the firelight niche. Even so, our exposure to this niche raises questions concerning its detrimental effects on sleep [137]. Firelight extends waking hours by approximately 4 hours in foraging societies

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[138], an obvious impediment to sleep, whereas its luminance hints at the suppression of melatonin, the 'hormone of darkness' [139] critical for regulating sleep–wake cycles [140].

Melatonin is inhibited by the activation of melanopsin, an intrinsically photosensitive retinal ganglion cell. Excitation begins at light levels equivalent to indoor lighting, or approximately 214 cd m^{-2} [141], a threshold readily exceeded in the firelight niche (figure 1*b*). But melanopsin is maximally sensitive to blue light (λ_{max} = 480 nm) [140], meaning its activation depends on the colour of ambient light. This trait motivated us to calculate the melanopic equivalent daylight illuminance (EDI) of firelight (figure 1*d*), a new standard for assessing the quality of light environments that regulate circadian rhythms, sleep and alertness (see the supplementary material). At its brightest, the melanopic EDI of firelight exceeds 10 lux (figure 1*d*), suggesting some level of melatonin suppression. But diminishing firelight falls squarely in the optimal range for sleep preparation (less than 10 lux), with glowing embers providing the best light of all (figure 1*d*). Taken together, the firelight niche, or at least its later stages, would appear well suited for vision and the upregulation of melatonin, extending the day for important social interactions with few adverse consequences. Testing its impact on communication is an essential step.

(c) Firelight and flux

Neither luminance nor colour exists in a steady state—they pulsate, giving firelight its appearance of 'behaviour'. This degree of flux (flicker) holds relevance for human communication, as rhythmic oscillation between photopic (cone-active) and mesopic (rod-and-cone active) light levels is taxing for vision, increasing receptor noise and lowering acuity. Our duplex retinas need several minutes to adapt to liminal light conditions (a reason that car accidents to spike at dusk [142]). So, it follows that luminous *flux*—rather than luminance, *per se*—is the property of firelight that may have disadvantaged gesture and favoured spoken communication.

The luminous flux of firelight is caused by the cyclical formation, upward propagation and shedding of the toroidal vortex surrounding the flame. Measuring flicker frequency is challenging. High-speed video cameras have transformed recent efforts, but the methods have always involved laboratory conditions and varied from measuring whole-flame brightness to specific colours in RGB colour space [143–145].

Flickering firelight may hold special importance for storytelling. Wiessner [2] described fireside talk as putting storytellers and listeners 'on the same emotional wavelength', but without elaborating how. Neurons in the visual cortex tend to synchronize their firing to the frequency of flickering light, leading to electrical signals in the brain captured by electroencephalography (EEG). This pulsating modulation of brain activity is called photic driving [146]. The strength of this effect varies with flicker frequency, and a strong synchronizing EEG response is termed resonance. It follows that flickering firelight could act as a central point of shared stimulus for collective neural entrainment—we might, quite literally, be resonating with the rhythms of firelight, and by extension with each other. Wu *et al.* [143] reported a fire flicker rate of 2.5 Hz, a value in the delta range of EEG neural resonances (0.5–4.0 Hz) and corroborated by our own measurements of campfires (figure 2). Intriguingly, delta waves are associated with improved performance in cognitive functions such as attention and memory [146], factors that would serve the purposes of storytelling. Work to establish the impact of flickering firelight on human social behaviour is another key step.

On a phenomenological level, flickering firelight may create a microworld of attention. It is a familiar concept in studies of change blindness, when visual processing privileges bright, moving, central stimuli and another factor favouring oral storytelling over gesture.

(d) Firelight and the infrared

The fireside niche includes thermal radiation (heat) from infrared wavelengths (figure 1*e*). Given that the absorbance of longer wavelengths (660–1000 nm) by mitochondria improves their membrane potential and increases adenosine triphosphate (ATP) production, it is plausible that one of the greatest benefits of fireside storytelling is photometabolic. Nightly exposure to firelight may have conferred profound energetic advantages during human evolution, reducing the need for dietary calories and sleep while offsetting the cost of cognitive processes, including those exemplified in storytelling [127].

7. More than just-so stories

The ability to engage in powerful acts of social cohesion under twilight and at night when other tasks are challenging, would represent a substantial advantage as we harnessed the power of firelight to extend our days. If fireside storytelling was an important shaper of human sociality, there was no need for fundamentally new ingredients in the human communicative toolkit for language to emerge. Instead, shifts in our *use* of communication led to shifts in our perception of the world and of each other. Stories can serve as tools to extend our social minds. Our integration of controlled fire into our social lives may have acted as a catalyst that initiated a rapid acceleration of how we think about the world, others and ourselves.

In addition to testing predictions about the differences in mundane and storytelling speech, and the efficacy of gestural and vocal channels of communication under firelight, we can investigate the impact of firelight on human social behaviour and storytelling, and whether the physical properties of firelight promote collective synchronization and social bonding. Durkheim [147] anticipated firelight's potential effects on behaviour, claiming: 'collective emotion cannot be expressed collectively without some order that permits harmony and unison of movement, gestures and cries fall into rhythm and regularity'.

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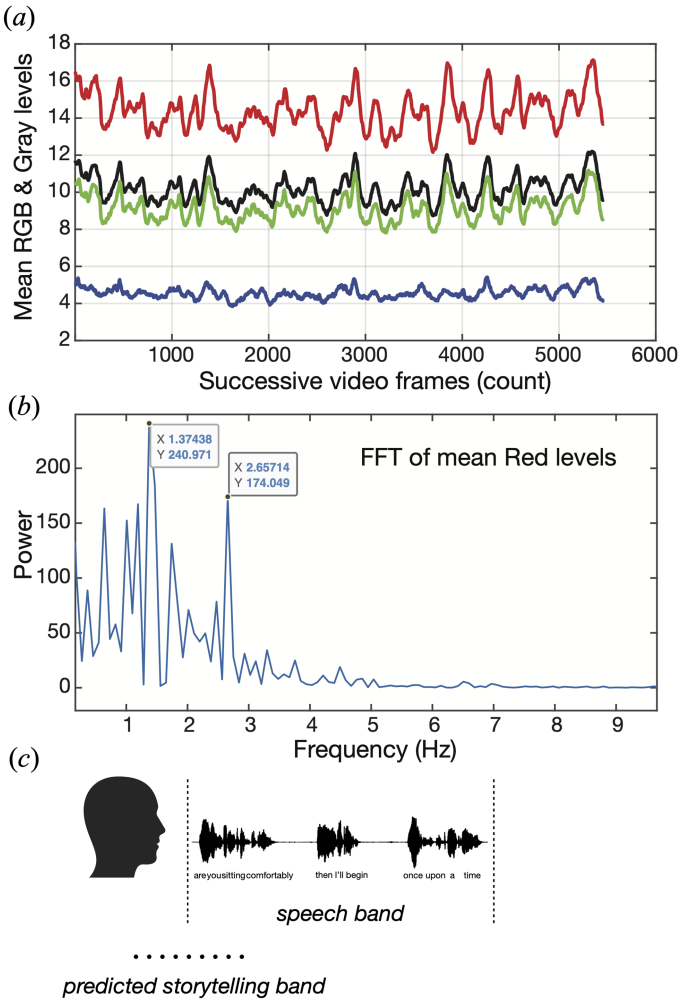


Figure 2. Firelight flicker rate quantified through high-speed video capture. (*a*) Each frame separated into RGB colour-space. (*b*) Spectral analysis identifies the dominant flicker frequency—here 1.4 and 2.7 Hz. (*c*) The open-close mouth rhythm of speech ranges from approximately 2 to 7 Hz. Detailed methods in the supplementary material. If the dominant flicker rate of firelight modulates human social behaviour, we would expect storytelling speech to show a slower tempo, reflecting the rhythmic structure of firelight.

Participation in shared, rhythmic activities is recognized for its role in promoting prosocial behaviour, empathy and joint action [148], and both firelight and the collective use of rhythm are frequently found at the heart of human social ceremonies. For example, the use of rich multi-layered percussive tempos provides essential structure for coordinating and synchronizing song and dance across cultures [105,149]. One feature of rhythm is its ability to facilitate social synchrony. Behavioural synchrony between individuals provides a key mechanism for promoting social cohesion and increased cooperation [150]. Easily observed examples include our natural tendency to fall into step [151], but heart rates and even brain activity can synchronize between social partners. When behaviour is synchronized, it creates a deep sense of social connection, predicting increased rapport and cooperation, and creating lasting connection [148,152].

The flicker of firelight—also found at the heart of many social rituals—could offer a shared source of visual input mediating group-level behavioural synchrony (as seen during dance [153]). In addition to rhythm facilitating social connection in general, the specific flicker rate of firelight may be a key facilitator, particularly for storytelling. If neural entrainment to firelight flicker occurs, preliminary data on firelight flicker rates suggest frequencies that would suppress alpha wave activity in ways associated with promoting social performance [154]. If storytelling emerged in a fireside niche, then storytelling today may have echoes of our shared neural responses to firelight: the tempo of fire flickering could have provided a foundational structure for the 'rhythm and regularity' of storytelling speech. While there is, to date, limited quantification of the difference in speech tempos during conversation and storytelling or narrative speech, once we have these data, it is a testable hypothesis to assess whether storytelling speech shares rhythmic properties with firelight. In a tantalizing commonality, our preliminary data suggest that the dominant flicker rate of firelight is 2.7 Hz, which sits within the slow end of speech rhythms (figure 2*c*).

Another area ripe for investigation is the presence and structure of behavioural synchrony between fireside storyteller and audience. New methods exploring pupil dilation and even brain wave oscillations suggest that physiological synchronization is a powerful indicator of social bonding [155,156]. These findings could be combined with measures of the tempo and rhythm of speech production to investigate the impact of different types of speech on social bond formation. Collective experiences of behaviour synchronized by firelight could offer a mechanism for social bonding at scales beyond grooming [150] or dyadic

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conversation. If fireside storytelling represents a powerful mechanism for social cohesion, we should see strong markers of behavioural synchrony between storyteller and audience that differ from typical conversations, including gossip and daytime exchanges.

8. Conclusion

We propose a new perspective on the evolution of language, one in which fireside storytelling provided the key catalyst for the emergence of a protolanguage that developed into the characteristically human expression of linguistic communication. We do so by integrating diverse disciplines and offering preliminary data that offer hints of support for our hypothesis and demonstrate how we can address the question of language evolution with a data-driven approach. We generate six testable predictions:

- there will be systematic shared differences across languages in the tempo and patterning of storytelling, compared with everyday speech;
- storytelling will embed structure at the narrative scale compared with everyday speech;
- storytelling, but not everyday speech, depends on features that make human language characteristically different from other species' communication: arbitrariness, generativity and abstraction;
- gestural comprehension will be negatively impacted under firelight, compared with stable low-light conditions, and to a greater degree than speech comprehension;
- storytelling speech will be closer than everyday speech in rhythmic structure to the flicker rate of firelight;
- storytellers and hearers will experience greater neural and physiological synchrony compared with participants in everyday conversation and gossip.

Our review risks over-romanticizing firelight, and evolutionary scenarios have a justifiably poor reputation. But if testable predictions are constructed carefully and regarded sceptically, they can inspire debate and generate new evidence-based lines of enquiry into the origins of human language, a story we never tire of telling.

Ethics. This work did not require ethical approval from a human subject or animal welfare committee.

Data accessibility. Original data and code can be found on Zenodo [157].

Supplementary material is available online [158].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. C.H.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, resources, writing—original draft, writing—review and editing; N.J.D.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, resources, writing—original draft, writing—review and editing.

Conflict of interest declaration. We declare we have no competing interests.

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