Middle Stone Age social connectivity: Can stone tools indicate the transmission of cultural ideas?

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Humans are unique in their ability to build complex social networks that foster cooperation, knowledge sharing and innovation. Evidence from the African Middle Stone Age provides some of the earliest signs of these connections, alongside increasingly sophisticated behaviours. Archaeologists study past social interactions through various proxies, with stone tools playing a central role. Yet the extent to which stone tools reliably reflect cultural transmission and connectivity remains debated. Similarities in toolmaking can indicate knowledge exchange and social ties, but they may also result from convergent evolution, whereby different groups independently arrive at comparable solutions to similar challenges. Recent research from southern Africa and beyond shows that applying middle-range theories and integrating contextual data help distinguish cultural transmission from convergence. This approach sheds new light on how knowledge and practices spread in early human societies, revealing the deep roots of cooperation and collaboration that continue to shape human societies today.

Significance:

In human origins research, stone tools provide some of the earliest evidence for how knowledge was shared and how social connections formed in early communities. Assessing whether similarities in these tools reflect cultural transmission or independent invention helps trace the roots of social networks, learning and innovation. Such insights are central to understanding the evolutionary pathways that made us human and continue to shape societies today.

Introduction

One of the defining characteristics of humans is our capacity to form social connections that facilitate transmission of knowledge, skills and innovations across generations.[1,2] Social connectivity refers to the network of relationships and interactions between groups, encompassing not only the transmission of knowledge and skills, but also trade, exchange, alliances and mobility.[2-4] These connections could be short-lived or enduring, localised or long-distance, and take many forms, from the movement of goods to the migration of entire groups.[4,5] Structured social networks have enabled knowledge sharing and supported coordinated management of essential resources.[6,7] They have also functioned as a form of risk buffering, allowing information to flow across distant communities and providing a 'safety net' during periods of resource scarcity.[4,5,7-9] By drawing on partners across multiple social spheres, from co-resident kin for routine activities to more distant kin for support during widespread stress, these networks enhanced cooperation and innovation while minimising vulnerability in unpredictable environments.[4,9]

Although it is difficult to determine precisely when sustained and reliable transmission of ideas and the formation of social ties first appeared[10], some evidence suggests that this process may have begun as far back as 3.3 million years ago[11]. By approximately 600 000 years ago, humans were already employing effective methods of communication, likely integrating hand signals with vocal sounds.[11] This capacity for clear information exchange set the stage for a turning period between 200 000 and 100 000 years ago, during the Middle Stone Age (MSA), when fully developed language, more sophisticated social learning, and stronger social connectivity emerged as *Homo sapiens* developed increasingly complex technologies and behaviours.[11,12]

Archaeological evidence for social connectivity comes from multiple proxies, including the distribution of beads in southern and eastern Africa[2,3], the long-distance movement of raw materials[13], and recurring patterns in stone tool technologies[6,7,14-17]. In Africa, evidence shows that more than 3 million years ago, early hominins were already producing and using stone tools to access and process essential resources.[18] The manufacture of these tools left enduring traces, enabling reconstructions of early human lifeways.[19] Some scholars argue that similarities in stone tool technologies across groups reflect cultural transmission through teaching, careful imitation and social learning, pointing to deep evolutionary roots of social connectivity.[14,17,20-22] Others caution that such similarities may instead represent "latent solutions"– behaviours independently reinvented rather than passed on through shared learning.[10,23-27] Comparable tool forms across regions could therefore result either from cultural transmission through migration or diffusion, or from independent convergence.[14,25,27-29] This debate highlights the challenge of distinguishing behaviours arising from shared knowledge from those emerging independently.[10]

Nonetheless, a growing body of research demonstrates that stone tools, when considered alongside contextual evidence, provide robust indicators of cultural transmission, showing how early humans shared knowledge and maintained social connections.[6,7,14,16,17,21,30-34] This review examines the extent to which stone tools can serve as proxies for cultural transmission during the MSA. By synthesising existing research and case studies, we demonstrate how material culture reflects the mechanisms of knowledge transfer, and how multiple lines of evidence together illuminate the nature, scale and duration of social connections among MSA populations. In doing so, this review contributes to a broader understanding of the emergence of early human social dynamics beyond the narrow confines of stone tool analysis.

Stone tool technology and cultural transmission

Cultural transmission encompasses the transfer of knowledge, ideas, beliefs and behaviours across generations through instruction and mimicry.[35] Cultural transmission can be vertical, horizontal or oblique.[36-39] Vertical transmission occurs when cultural knowledge is inherited across generations, typically from parents to children, ensuring the stability of complex toolmaking techniques as young learners observe and refine skills taught by experienced individuals.[37,40] Horizontal transmission occurs among peers within the same generation, facilitating the rapid spread of innovations within social groups.[35,38] Oblique transmission involves the transfer of knowledge from non-parental adults, such as mentors or community leaders, allowing for both the preservation and adaptation of cultural traditions over time[39] (Figure 1; Table 1).

Cultural transmission operates through various mechanisms: direct (content-based) transmission, where traits are adopted for their effectiveness or memorability; indirect transmission, where traits are copied from admired or successful individuals; and frequency-dependent transmission, where traits spread due to widespread use (e.g. conformity).[36] These mechanisms, together with biases like payoff bias, interact with ecological and social contexts to shape how knowledge is transmitted across generations.[10] Observational learning and imitation also play key roles in the spread of cultural ideas, shaping behaviour across generations.[37] This learning process involves acquiring behaviours by observing others, while imitation is the direct replication of observed actions, often without understanding their underlying principles.[36] However, some recent work has also questioned the extent to which imitation and other high-fidelity learning processes can be identified in the deep archaeological record, highlighting ongoing debate.[10,23]

At broader spatial scales, cultural transmission operates through diffusion or dispersal (migration) as mechanisms that facilitate the spread of knowledge between populations.[25] Diffusion involves the transfer of knowledge and practices between neighbouring groups, often leading to the replication of techniques and the integration of more accessible or prominent elements of toolkits.[25] Migration entails the physical movement of populations, which then transmit their technological knowledge in new contexts, typically resulting in the imitation and accurate transmission of complex, sequential techniques.[14,25,28,29,41] For example, core reduction in stone toolmaking involves the controlled extraction of flakes from a solitary core in successive stages, illustrating how multi-step knowledge could be reliably transmitted.[14,28,29] However, caution is needed when using these terms, as the mechanisms of cultural transmission are rarely clear-cut in the archaeological record. Overreliance on diffusion or migration can obscure other possibilities, such as indigenous autonomy or hybrid processes that combine multiple pathways of knowledge transfer.[42] Distinguishing between these processes is critical for archaeological interpretation; while cultural transmission occurs at the individual level through teaching, imitation and observation, these larger-scale mechanisms shape patterns of social

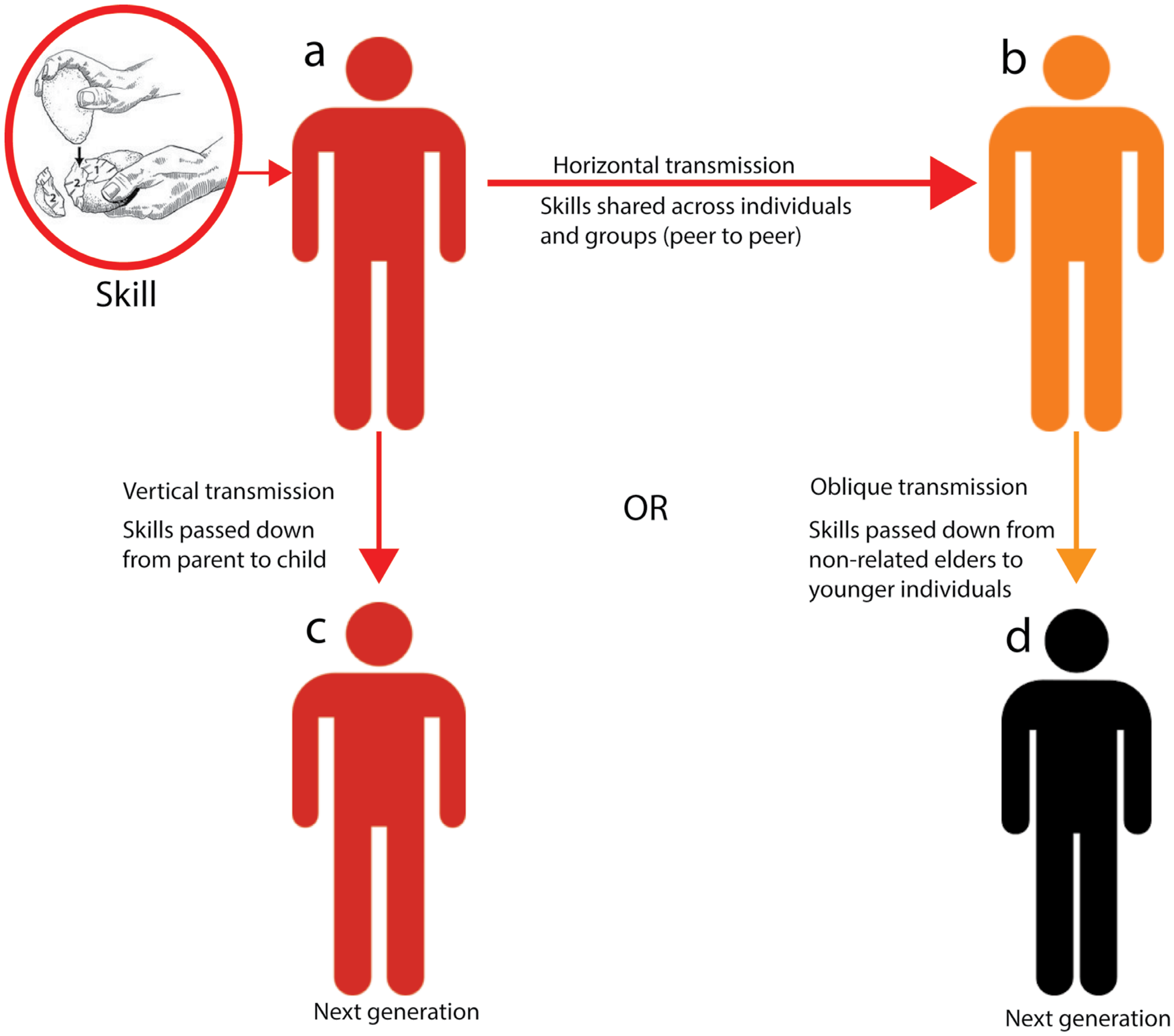

Figure 1: An Illustration of vertical, horizontal and oblique cultural transmission, showing how knowledge, skills and behaviours are passed from parents, peers and non-parental adults.

Table 1: Summary of cultural transmission types, highlighting their sources of knowledge, rates of cultural change, and balance between stability and innovation

Type of transmission	Source of knowledge	Rate of cultural change	Stability vs innovation	References
Vertical	Family, parents, direct lineage	Slow and gradual	High stability, low innovation	Cavalli-Sforza and Feldman[37]; Shennan[40]
Horizontal	Friends, same age group, neighbouring communities; can include newcomers via migration	Rapid	High innovation, cultural variation	Boyd and Richerson[35]; Lycett[38]
Oblique	Mentors, experts, skilled individuals	Moderate	Balance of stability and adaptation	Mesoudi and O'Brien[39]

connectivity observed across the landscape. Differentiating between diffusion and migration is therefore essential, as what is sometimes labelled as social connectivity may reflect either the borrowing of ideas across networks or the relocation of groups carrying technological knowledge.[25]

Several models have been proposed to study how early humans passed on cultural knowledge using stone tools as evidence. One widely used framework is Tostevin's[14] Behavioural Approach to Cultural Transmission (BACT). This model links theoretical perspectives with archaeological evidence to explore how knowledge transfer about toolmaking was shared within and between groups. By drawing on experimental studies[43], BACT helps us understand not only the skills involved in stone tool making but also the flexibility and social organisation of early humans.

The BACT model recognises stone toolmaking as a complex skill that requires planning and careful decision-making.[14] Much of this skill was likely learned through teaching, imitation or observation rather than discovered independently.[14] The BACT model identifies several aspects of toolmaking that reveal how knowledge was passed on: shaping core stones in different ways, preparing surfaces to control how pieces are removed, following consistent strategies for flake removal, maintaining the overall shape and structure of the core, and producing tools with recognisable designs that reflect cultural traditions.[14,15] For analysis, BACT compares stone tool assemblages based on how the initial pieces were prepared and how the final tools were shaped.[14] To track cultural influences, assemblages are classified using three terms: the substrate (earlier tools or traditions), the acculturator (tools or groups that influenced changes in later traditions), and the product (the resulting set of tools combining features of both).[14] BACT also incorporates broader theoretical ideas, such as how toolmaking was shaped by what was visible in the landscape and the social interactions between people, connecting detailed tool analysis to wider social behaviour.[14] This approach has been further applied in the eastern African context, at sites in Kenya and Tanzania such as Nasera and Koobi Fora, using controlled stone tool experiments as contextual data to study knowledge transfer in MSA technologies.[17] Analyses suggest that examining broader strategies for making tools, rather than individual flakes, provides reliable indicators of cultural transmission, allowing researchers to study how skills were learned, shared and modified over time.[17]

Beyond the BACT framework, stone toolmaking is recognised as a cognitively challenging task that requires precise motor control and careful planning, making it a practice that is learned and passed from experienced makers to novices.[44-47] To better understand how this knowledge was transmitted, researchers are moving from analyses of entire groups to identifying individual toolmakers in the archaeological record through measurable aspects of their techniques.[45] Comparative studies of novices and experts have highlighted clear indicators of skills, including the efficiency with which material is removed and the symmetry of the resulting tools.[45] These findings shed light on the learning processes and cognitive skills of early humans.[45]

In addition, a widely contested example of cultural transmission is the Levallois technique, a method of preparing a stone core so that it can produce flakes of a predetermined, consistent shape. This approach involves carefully shaping the core in advance, allowing early humans to control the size and form of the flakes they removed, which could then be used as tools.[46,47] Some researchers argue that similarities in Levallois tools across Africa, Europe, and the Near East suggest that these skills were learned from experienced makers, reflecting social learning and apprenticeship. The consistency of these tools suggests that replicating Levallois technology required specialised knowledge passed across generations.[46,47] Supporting the use of the Levallois as a marker of cultural transmission, studies in eastern Africa, Arabia, and the Levant show the long-distance spread of this technology.[33] These sites reveal the persistence of centripetal Levallois, a method in which flakes are removed toward the centre of the core to create a prepared surface for a final flake.[33] The repeated use of this technique and the consistent core shapes indicate that knowledge was transmitted across generations among mobile hunter-gatherer groups.[33] These findings demonstrate a shared technological tradition originating in eastern Africa and spreading across vast distances.[33] However, the interpretation of Levallois as evidence of cultural transmission is highly debated, with some suggesting that the technique may have emerged independently through convergent evolution.[24,48] Hence, further methodological refinement is needed, as no consensus currently exists on whether the Levallois technique reflects convergence or transmission.

Further evidence of knowledge sharing comes from the long-distance movement of raw materials. In Africa, MSA people transported obsidian, silcrete and other raw materials tens to hundreds of kilometres from their sources to toolmaking sites.[32,49,50] For example, silcrete raw material at White Paintings Rockshelter in the Kalahari was traced to sources over 220 km away, despite suitable local stone being available.[13] Similarly, at Olorgesailie in Kenya, early *Homo sapiens* engaged in long-distance raw material transfers by 300 000 years ago.[50]

In southern Africa, MSA studies using stone tools to explore knowledge sharing and social networks have grown substantially over the last decade.[6,7,30,31] It is argued that environmental changes may have shaped social connections and technological practices.[6] During colder periods, communities were more interconnected, whereas warmer periods saw the emergence of localised groups with distinct traditions.[6] For example, during Marine Isotope Stage (MIS) 5, sites such as Blombos, Cape St. Blaize and Klasies River show regional differences in toolmaking, reflecting local adaptation and limited interaction.[6] In MIS 3, sites including Sibhudu, Umhlatuzana, Rose Cottage and Sehonghong produced more specialised tools within relatively isolated populations.[6,51] At Sibhudu and Umhlatuzana, hollow-based points[51], stone tools with a concave base designed to be hafted onto a handle or shaft, may be seen as a classic case of convergence[52]. These points closely resemble those found in distant regions during the Palaeolithic, suggesting that similar functional requirements can lead to similar tool designs, independently, rather than through direct cultural transmission.[52]

In contrast, other tool types, such as backed tools – small, often sharp, tools with a blunted edge for hafting or handling – indicate cultural transmission and are found both at individual sites and more broadly across southern Africa.[31] High frequencies of scraping tools at sites such as Rose Cottage and Sehonghong may reflect smaller more isolated groups[6], although additional research is needed to explicitly link these patterns to population size or demographic structure. However, demonstrating population increases or decreases is often challenging due to multiple interacting variables.[6] Collectively, these observations suggest that convergent evolution and cultural transmission are not mutually exclusive, and more refined analytical methods are required to disentangle their respective contributions. During colder periods like MIS 4 and 2, broader social connections are evident, with standardised tools appearing across multiple sites (including Blombos, Hollow Rockshelter and Sibhudu), indicating strong long-distance social networks.[6] These patterns suggest that environmental conditions may have influenced knowledge sharing, with harsher climates encouraging wider interaction and resource abundance allowing regional differentiation.[6]

During MIS 5, patterns of cultural transmission in southern Africa varied depending on the environment and geography. In the Lesotho highlands, at Melikane Rockshelter, communities adapted to a mobile lifestyle shaped by local conditions, producing long, thin blades.[30] Compared with sites across South Africa (including Blombos, Border Cave, Diepkloof, Klasies River, Pinnacle Point and Sibhudu), clear regional differences emerge.[30] Despite facing similar climates, highland groups at Melikane were largely detached from low-elevation populations, limiting the spread of technological knowledge and suggesting population fragmentation during this period.[30] By contrast, in the Kalahari Basin and surrounding areas, studies using BACT show that MIS 5 communities at sites such as Ga-Mohana Hill North Rockshelter, Erfkroon, Florisbad and White Paintings Rockshelter shared similar approaches to making stone tools and produced comparable toolkits.[7] This similarity indicates ongoing knowledge exchange and social connectivity, which may have helped groups cope with the harsh Kalahari environment.[7] In such marginal settings, social networks likely acted as 'safety nets', allowing communities to share information, coordinate resources and reduce risk.[4]

Cultural transmission versus convergence

Interpreting similarities in stone tool technologies across regions requires distinguishing between cultural transmission – through diffusion or dispersal – and convergence (Figure 2; Table 2).[25] While these processes produce similar outcomes, studies often assume that shared tool forms reflect knowledge transfer. Yet similar tools can also emerge independently when groups work with comparable raw materials under similar environmental conditions. Relying solely on tool resemblance risks oversimplifying the complex processes shaping technological evolution in the MSA.[24-27,53]

Examples of convergence in the southern African MSA include Nubian Levallois technology in the arid Tankwa Karoo.[60] At Tweefontein site, Nubian cores and points occur alongside post-Howiesons Poort tools

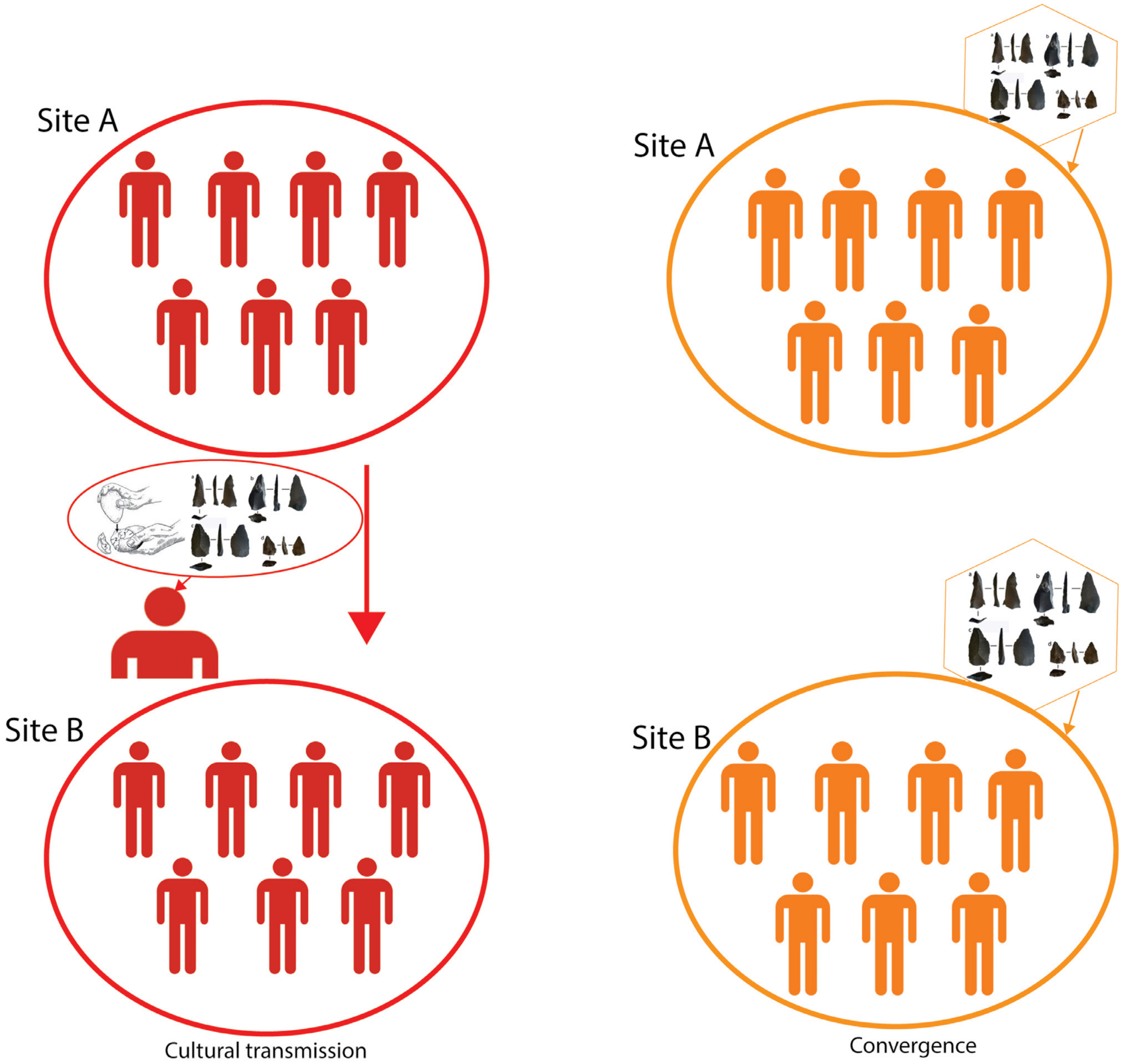

Figure 2: A schematic illustration of cultural transmission versus convergence.

Table 2: Criteria for distinguishing cultural transmission from convergence in stone tool analysis

Cultural transmission	Convergence
	Similar tools appearing in different regions without clear connections. If the same tool type is found across vast distances with no evidence of contact, it may be the result of convergence rather than cultural transmission.[24,25,55]
Spatial and temporal continuity in tool production. If a particular tool type or method of making tools continues within a geographically connected region over time, it may be the result of cultural transmission rather than convergence.[6,17,33]	**Tool types known to be reinvented.** Some tools appear repeatedly across time and space, suggesting that they were practical solutions to common problems rather than the result of direct transmission.[27,53,56]
Consistent patterns of reduction strategies across sites. If similar methods of tool-making are found across multiple locations, it may be the result of cultural transmission rather than convergence.[7,14,21,30]	**Variability in methods of tool-making within the same tool or core type.** If a tool or core type class shows significant variation in manufacturing methods across regions, this may indicate convergence rather than cultural transmission.[46,57,58]
Similar tool types and reduction strategies tied to feasible dispersal corridors or interaction zones. If similar tool types and manufacturing methods are found along plausible dispersal or trade corridors, or in interaction zones, it more strongly supports the idea of cultural transmission rather than convergence.[33,54]	**Tool types appearing in unrelated cultural or ecological contexts.** If a particular tool form or production method emerges in geographically or temporally distinct settings with different environmental pressures, it may be the result of convergence rather than cultural transmission.[59]
	Low-frequency or isolated occurrences of similar tools. Tools that appear rarely or in isolation across sites may indicate convergence rather than cultural transmission.

Table 3: Potential drivers of human connectedness

Core drivers of human connection	Description	Examples
Adaptive social networks (survival and resource sharing)[4]	Social connections develop as a crucial adaptation to harsh environments, enabling cooperation in locating and sharing vital resources[4]	• Formation of communities and alliances • Collective resource gathering (water, food, shelter) • Trade, migration, and communication networks for survival[4]
Psychological need for social bonds (cognitive and emotional resilience)[8]	Humans are wired to seek social interactions that provide emotional security and reduce stress, especially in challenging conditions[8]	• Sense of belonging and identity • Emotional and psychological support • Reduced anxiety and loneliness through companionship[8]
Trust and cooperation dynamics (strengthening social stability)[54]	The quality of social connections determines long-term cooperation, conflict resolution and social stability[54]	• Trust and mutual aid in times of crisis • Conflict resolution[54]

dating to MIS 3, suggesting local adaptation rather than cultural diffusion, despite Nubian technology being typically associated with North Africa, Arabia and the Levant.[60] Similarly, evidence from the sites Uitpanskraal 7 and Mertenhof shows that Nubian stone tool production methods, usually linked with the later part of the Pleistocene epoch in northern regions of the African continent and *Homo sapiens* dispersals during MIS 5, were also present in southern Africa by MIS 3.[56] The temporal and spatial patterns of these occurrences support convergence rather than cultural transmission or population movement.[56] In addition, early blade production across South Africa, Kenya and Israel (~500 000–400 000 years ago) shows similar forms but distinct methods and wide geographic separation, further indicating independent development.[55]

Understanding similarities and differences in stone tool technologies is challenging because multiple factors influence how traditions are passed on and how technologies change.[25] Humans are known not only for sharing knowledge but also for innovating, constantly refining tools to meet specific needs and local circumstances.[19,35] Differences in the types of stone raw materials available, for example, can lead to changes in tool design, making it difficult to determine whether the variation reflects resource constraints or independent invention.[57]

One way researchers have tried to address this problem is by examining technological complexity.[25,28,46] The idea is that more complex methods of making tools, such as techniques requiring several interdependent steps, are less likely to appear independently in different locations.[14,47,58] While this reduces the chance of mistaking coincidence for cultural transmission, it is not foolproof.[10,25] Even complex technologies can develop in parallel, and the very definition of 'complexity' is often unclear.[10,23,25]

Increasingly, stronger approaches aimed at identifying stone tool assemblage traits that distinguish cultural transmission from convergence, and thereby offering new ways to assess past social connectivity, are emerging.[6,7,14,17,30] These approaches have moved beyond simply comparing tool types and now employ advanced methods to provide clearer evidence of cultural transmission.[14] For example, techniques such as geometric morphometrics[46], detailed analyses of tool production, and the integration of contextual data with theoretical models such as the BACT framework, which links tool use with social behaviour and environmental context, offer promising ways forward[7,14,17]. These methods provide more robust insights, although their interpretation still depends on the frameworks researchers apply. Therefore, a critical, methodologically rigorous approach that integrates multiple lines of evidence, accounts for alternative explanations, and acknowledges the limits of current techniques remains essential. By refining these methods, researchers can move beyond broad generalisations and gain a deeper understanding of social learning in past human societies.

Drivers of human connectedness

Several studies identify three main drivers of human connectedness: adaptive social networks, the psychological need for social bonds, and trust and cooperation dynamics (Table 3).[4,8,54] The most cited explanation is adaptive social networks, whereby environmental pressures drive the formation of social ties. In harsh environments – such as the Kalahari[7] during interglacial periods or resource-scarce times such as glacial phases in southern Africa – social connections may have facilitated cooperation, knowledge exchange and resource sharing, acting as survival strategies.[6,61] Ethnographic studies of hunter-gatherer societies in harsh environments, including the Arctic, support this, showing how dispersed groups maintained social ties for survival.[4] Conversely, during interglacial phases, when resources were more stable and abundant, populations were more fragmented, reducing the need for extensive cooperation.[5,6,8,9,30,61]

While environmental pressures explain some aspects of connectedness, they do not account for intrinsic human innovations. Psychological factors, such as the desire for belonging, trust and emotional security, likely shaped social networks independently of ecological conditions.[4,54] Cooperation and mutual support also evolved from shared risks, collective defence and cultural transmission.[54] Across diverse environments, hunter-gatherer societies relied on trust-based interactions, trade and social bonding to reinforce group identity, maintain alliances, and transmit knowledge across generations.[54] Thus, human social networks emerged from the interplay of environmental, psychological and cooperative factors, providing a nuanced understanding of connectivity across ecological and cultural landscapes.[4,54]

Synthesis and discussion

Research is making important strides in differentiating cultural transmission and connectivity from convergence; for example, through approaches such as geometric morphometrics[46] and frameworks like BACT, which assess the sequential stages of tool replication and offer a more direct route to evaluating the cognitive and social investments involved[7,14,17]. These methods enable a more precise assessment of the learning processes underlying stone tool making and help to determine whether similarities arise from shared traditions or independent innovation. However, further advances are still needed, particularly in integrating lines of evidence beyond stone tools.

Moving forward, progress lies in refining methods that disentangle convergence from cultural transmission. Beyond simply documenting similarities, future research should investigate the mechanisms of knowledge transfer. Controlled experimental studies on imitation, copying and teaching, combined with middle-range theory, can provide valuable benchmarks for identifying the social learning processes embedded in toolmaking and help determine whether technological similarities reflect genuine transmission or independent convergence.[14,15,43] At the same time, greater consistency in data collection and recording is needed.[62] Variations in theoretical perspectives and analytical priorities often hinder meaningful comparisons, limiting the reliability of broader interpretations.[62] Given the durability and widespread presence of stone tools in the archaeological record, structuring data sets for meaningful comparison is essential.[62] Standardising methodologies and prioritising compatible analytical frameworks would enhance our ability to detect and interpret patterns of social learning more effectively and to distinguish them from convergence.[62]

Another promising direction is to combine stone tool studies with direct evidence of symbolic and social exchange, such as beads, ornaments and the movement of raw materials.[2,3,13] These artefacts were often circulated between groups and can provide clearer insights into networks of interaction than stone tools by themselves.[2,3,6] Recent work demonstrates this potential, using ostrich eggshell beads to show long-distance exchange networks and how climate-driven barriers influenced shifting connections.[2,3] Such interdisciplinary approaches illustrate how artefact style, provenance and mobility can be combined with isotopic and environmental data to reconstruct the scale and dynamics of past social networks.[2,3] Taken together, these integrated lines of evidence provide a more holistic picture of cultural transmission and human connectivity in the MSA and beyond.

Future progress will depend on developing standardised data sets that integrate technological, symbolic and environmental evidence, as well as demographic factors, for more reliable cross-site comparisons.[6] Archaeology can also target proxies for the social and psychological drivers of connectivity highlighted in ethnographic and theoretical studies.[5] For instance, the persistence of symbolic artefacts may indicate group identity and belonging, while raw material distributions can reflect trust, cooperation and risk-buffering strategies.[5,8] By linking archaeological patterns to reciprocity, identity and emotional security, we can move beyond purely ecological explanations and better capture the social and cognitive processes underlying cultural transmission.[5,8]

Conclusion

African MSA stone tool assemblages provide key evidence for early human social networks and cultural transmission. While similarities across regions suggest knowledge exchange, distinguishing inherited traditions from independent adaptations remains challenging. Advances such as BACT and geometric morphometrics improve our ability to assess whether patterns reflect social learning or convergence. Future research should include controlled experiments, and integrate analyses of symbolic artefacts, raw material movement, palaeoenvironmental data, spatial modelling, and high-resolution chronologies to understand the social, cognitive and ecological drivers of technological transmission. Standardised data sets and compatible analytical frameworks are essential for cross-site comparisons, while interdisciplinary approaches linking archaeological patterns to social and psychological processes offer deeper insight. Combining refined stone tool analysis with symbolic, environmental and experimental evidence provides a holistic understanding of cultural transmission and connectivity in the MSA.

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Data availability

There are no data pertaining to this article.

Declarations

We have no competing interests to declare. We have no AI or LLM use to declare.

Authors' contributions

P.C-M.: Conceptualisation, methodology, investigation, validation, writing– original draft, writing – review and editing. S.A.: Validation, writing – review and editing. J.W.: Validation, writing – review and editing. All authors read and approved the final manuscript.

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