The Predictable Evolution of Letter Shapes

An Emergent Script of West Africa Recapitulates Historical Change in Writing Systems

Piers Kelly, James Winters, Helena Miton, and Olivier Morin

A familiar story about the evolution of alphabets is that individual letters originated in iconic representations of real things. Over time, these naturalistic pictures became simplified into abstract forms. Thus, the iconic ox's head  of Egyptian hieroglyphics transformed into the Phoenician  and eventually the Roman letter *A*. In this vein, attempts to theorize the evolution of writing have tended to propose variations on a model of unilinear and unidirectional progression. According to this progressivist formula, pictorial scripts will tend to become more schematic while their systems will target smaller linguistic units. Objections to this theory point to absent, fragmentary, or contrary paleographic evidence, especially for predicted transitions in the underlying grammatical systems of writing. However, the forms of individual signs, such as the letter *A*, are nonetheless observed to change incrementally over time. We claim that such changes are predictable and that scripts will in fact become visually simpler in the course of their use, a hypothesis regularly confirmed in transmission chain experiments that use graphic stimuli. To test the wider validity of this finding, we turn to the Vai script of Liberia, a syllabic writing system invented in relative isolation by nonliterates in ca. 1833. Unlike the earliest systems of the ancient world, Vai has the advantage of having been systematically documented from its earliest beginnings until the present day. Using established methods for quantifying visual complexity, we find that the Vai script has become increasingly compressed over the first 171 years of its history, complementing earlier claims and partial evidence that similar processes were at work in early writing systems. As predicted, letters simplified to a greater extent when their initial complexity was higher.

If all writing systems undergo observable historical change, is it possible to identify the underlying evolutionary processes and predict their trajectories? A long-discussed hypothesis holds that new scripts become visually simpler and more systematic as they are transmitted from generation to generation over historical time (Changizi and Shimojo 2005; Dehaene 2009; Trigger 2003:600–602). One of the greatest challenges in testing this claim is the fact that we do not have a complete record of the first writing systems, especially in the earliest years of their development. We address this problem by drawing on data from the Vai script of Liberia, a syllabary developed in isolation by nonliterates in ca. 1833 and still in use today. We find that Vai letters have become more compressed over the first 171 years of their history, and we suggest that this finding has broad applicability to the evolution of early writing systems.

One of the earliest to articulate a theory of the evolution of writing was Rousseau, who proposed that writing passed through three stages, from pictures, to whole words, and finally to alphabets. "The depicting of objects is appropriate to a savage people," he wrote in his *Essai sur l'origine des langues*, "signs of words and of propositions, to a barbaric people, and the alphabet to civilized peoples [*peuples policés*]" (Rousseau 1966 [1781]:17). This basic proposition was to remain largely unchallenged for nearly two centuries, but the sensational decipherment of Egyptian hieroglyphics on the part of Champollion (1824) generated a new wave of interest in the evolution of writing. Contrary to Champollion's expectations, the Egyptian hieratic script was apparently far cruder in its form than the monumental hieroglyphic script that had preceded it, which lent the impression that it was regressing to a more "primitive state" (Champollion 1836). In response, the sinologist Pauthier addressed the apparent contradiction of style and chronology in Egyptian scripts, maintaining that progressive schematization was a defining process in the evolution of writing. In an upgrade to Rousseau's tripartite model, Pauthier postulated a so-called figurative age of writing that was characterized by pictorial representations of objects, while in a subsequent transitory age, these iconic images become more conventional and abstract. In a final pure alphabetic age, only the simplest phonological elements were represented in graphic form. Alphabets were thus doubly compressed. Not only were they simpler in the outward shape of their scripts but also their underlying orthographic systems were reduced to the bare phonemic essentials. Illustrating this progression, Pauthier referred to documented changes in both Egyptian and Chinese writing systems toward greater abstraction and simplicity. In his estimation, the process could even be invoked as a method for dating paleographic inscriptions since it was a law that "suffered no exception" (Pauthier 1838:567). Later, the classicist Ritschl (1869)

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would seek to formalize a new "scientific paleography" that recognized that historical script change was not arbitrary but a matter of "internal development" governed by "certain laws and guiding impulses."[1]

Independently of the French and German tradition, Morgan and Tylor were to reinvent Rousseau's evolutionary stages of writing in the context of their more ambitious teleological model of human progress. For Morgan (1877), a society's use of alphabetic writing, as opposed to other systems, was diagnostic of its ascension to the highest status of civilization. Tylor (1878 [1865]:374) was even more explicit in linking technological changes, such as a shift from stonework to metalwork, with transitions from "picture-writing" to the alphabet. For the progressivists, therefore, there was an implied inverse relationship between the (perceived) complexity of a society's material culture and the outward simplicity of its writing system.

Although progressivism was to be roundly rejected from within anthropology, it found fertile ground in the field of grammatology. Taylor (1883*a*, 1883*b*), Clodd (1900), Ege (1921), Mason (1928), Gelb (1963 [1952]), and Cohen (1958) gave the social evolutionist framework a renewed impetus in their stadial formulas for the evolution of writing. Their chief theoretical differences lay only in the number of discrete stages that writing was supposed to pass through on the road to alphabetic abstraction.

Schematization as a General Law

Nineteenth-century European scholars often wondered whether the proposed principle of progressive schematization might be applicable to symbolic behavior more generally. Pitt-Rivers and Balfour assessed graphic artifacts collected in colonial settings—including New Ireland paddles, Peruvian pottery, and decorated spear shafts from the Solomon Islands—and attempted to arrange them in sequences from the most representational to the most schematic. This exercise was intended to illustrate how figurative forms become conventionalized through constant reproduction, with their superfluous features falling away in the process:

> Thus, the drawing of a stag would be made to convey information to people at a distance that there was a herd of deer in the neighbourhood to be hunted; and as the object of the drawing was no longer to depict truthfully the peculiarities of the beast, but merely to convey information, the amount of labour expended upon it would be the least that could be employed for the required purpose. All written characters have originated in this way; and no one now requires to be told how pictographic representations developed into hieroglyphic and subsequently into phonetic characters. (Pitt-Rivers 1906 [1875]:40)

Graphic communication systems, be they cave paintings or writing systems, were therefore seen to follow a principle of least effort. One of the presumed mechanisms for schematization was to be found in the imperfect reproduction of a graphic figure over successive iterations. Accordingly, Balfour (1893) emphasized the role of "unconscious variation" whereby "the changes are not intentional, but are due to want of skill or careless copying, difficulty of material, or reproducing from memory" (77). Reprising Pitt-Rivers, he maintained that figurative art must surely have been ancestral to modern alphabetic writing (Balfour 1893:98).[2]

Balfour was also the first to develop experiments for testing the effects of cultural transmission on items of symbolic culture. In Balfour's tasks, an experimental participant was asked to create a sketched reproduction of a picture, and this sketch was then copied by a second participant, and so on. According to his contemporary, the French philosopher Philippe (1897), these kinds of experiments revealed a "law of economy," by which "unnecessary details fall and disappear to make room for what is necessary for the whole," adding that such transformations must scale up to broader cultural changes at the population level (493).

Bartlett would later design similar pencil-and-paper tasks with the aim of testing the dynamics of human memory. Noticing that figurative images tended to become simpler and more conventionalized over successive "generations," he perceived a real-world parallel in the historical evolution of writing systems whereby "realistic pictures" eventually became "nonrepresentational conventional signs" (Bartlett 1995 [1932]:95). So taken was he by this observed correspondence that he was inspired to use Native American pictograms and Egyptian hieroglyphics as the primary input for a number of his experimental tasks (Bartlett 1995 [1932]:97, 180).[3] In a more recent

1. "The fact that historical changes within a script are not a matter of chance or arbitrariness, but rather are associated with an internal development that progresses according to certain laws or guiding impulses is surely indisputable: it is on this insight that the whole concept of scientific 'paleography' is based" ("*Dass die geschichtlichen Veränderungen einer Schrift nicht Sache des Zufalls oder der Willkür sind, sondern viel-mehr im Zusammenhange einer innern Entwicklung stehen, die nach gewissen bestimmenden Gesetzen oder doch leitenden Trieben vor sich geht, wird wohl im allgemeinen von niemand verkannt: wie denn auf dieser Einsicht der ganze Begriff einer wissenschaftlichen 'Paläographie' beruht*"; Ritschl 1869:1).

2. Perhaps the greatest champion for this theory was the epigrapher Arthur Evans, whose *Scripta Minoa* (1909) proposed a much deeper lineage for writing than any of his predecessors. While the Paleolithic archeologist Henri Breuil (1905) was prepared to suggest that stylistic transitions in Magdalenian rock art were analogous to the evolution of writing, Evans hinted at a much more direct historical pathway. Referring to Breuil's sketches, he wrote that "signs of curiously alphabetic aspect—at times even in groups—are seen engraved on reindeer-horns or ivory, or on the surface of the rock itself. . . . Certain signs carved on a fragment of reindeer horn are specially interesting from the primitive anticipation that they present of the Phoenician *alef*" (Evans 1909:3–4). Even today, a presumed relationship between geometric signs in rock art and modern writing continues to be entertained (see, e.g., von Petzinger 2016).

3. Bartlett (1995 [1932]) noted that in transmission chain experiments, "some element of an original complex gradually attains a more and more important position and comes to stand for all the rest. The long story of the development of the common alphabetical forms is a case in point" (271). It is

example, Garrod et al. (2007) developed Pictionary-style graphic tasks that detected a transition toward noniconic simplicity, leading them to speculate that similar processes must have underpinned the loss of iconicity in the cuneiform and Chinese writing systems over deep timescales. One preliminary attempt to compare complexity rates in natural writing systems was made by Hegenbarth-Reichardt and Altmann (2008), who applied a hand-coded method to show that a specific historical instantiation of the hieratic script was quantifiably simpler than the hieroglyphic script used in the same period.

A Revised Hypothesis on the Evolution of Letter Forms

A unifying argument across these disparate fields, from nineteenth-century paleoanthropology to contemporary transmission chain experiments, is that graphic forms proceed through a process of simplification that transpires in the course of their recollection and reproduction by individual writers and their transmission from one individual to another. However, the term "compression" is a more accurate descriptor than "simplification" for this process. In other words, through repeated interactions, a system of signs will become compressed so that the same amount of information is expressed with less descriptive effort. Although this proposition is well confirmed under controlled experimental conditions (Tamariz 2017), it not always clear how it might apply to the dynamics of real-world historical change in writing systems.

It is remarkable, after all, that the world's earliest independent writing systems have all exhibited extensive iconicity and that in many instances this iconicity diminished in later forms or derivatives of the script. As a counterobservation, one could point out that simple and nonfigurative symbols were already in wide use at the dawn of writing in Mesopotamia or that iconicity in Egyptian hieroglyphics was retained over the entire history or the script. Meanwhile, the Olmecoid scripts of Mesoamerica are apparently less figurative than the Maya script that postdates them archeologically (Downey 2014; Mignolo 1989), while the Maya script itself retained its complexity and iconicity. These, however, are not falsifying examples. We do not yet know whether the pre-Maya scripts of Mesoamerica were glottic writing (representing language) or whether they have a direct historical relationship to the better-attested Maya script, just as the abstract markings on neolithic Chinese pottery cannot be proven to be ancestral to early Chinese writing. As for Egyptian writing, there is no doubt that the more schematic hieratic script was derived from Egyptian hieroglyphics and not the other way around (Altenmüller 2005; but see Goedicke 1988:vii–viii). Moreover, hieroglyphics existed in a rich graphic context that included not just hieratic and demotic scripts but also an artistic tradition with a well-defined repertoire of figurative forms (Baines 2007).

In short, a minimal hypothesis that early scripts evolve in the direction of visual simplicity is not, on the face of it, controversial. What could cause this bias is not quite as evident. We propose that it is driven by a least effort principle (inspired by Zipf 1949). This phrase is usually linked to the fact that spoken languages tend to minimize the total amount of effort that speakers invest in producing words by shortening frequently pronounced words, which are also the least informative (Piantadosi, Tily, and Gibson 2011; Zipf 1949). We endorse the general notion that symbols should minimize the effort of producing them, to the extent that this does not harm their information content. This principle is in line with the broader view that communicative signals face a trade-off between simplicity and informativeness. Applied to lexicons, the principle successfully predicts that fine-grained categorizations apply to the more salient, relevant, or frequently communicated elements, while coarse-grained categorizations are reserved for less important traits, in both natural languages and artificial codes evolved in the lab (Carr et al. 2017; Regier, Kemp, and Kay 2014).

We apply this principle to writing (departing from Zipf in doing so). Our version of the least effort principle states that writers are motivated to reduce their cognitive and motor exertion when tracing a letter, up to the point where further simplification would make the letter undistinguishable from other letters. This principle does not predict a continuous progress of increasing simplification, nor does it assume that all scripts should reach the same level of complexity over time. Quite the contrary. Simplification should stop around the point where it imperils legibility, making letters too difficult to distinguish from one another, and it predicts this because a decrease in legibility entails a potential increase in future effort. Where this point lies is likely to differ from script to script; letters are distinctive for various reasons in various scripts. The very pressure to stand out as a distinctive letter would be less intense in a small alphabet, compared to a 200-letter syllabary. Our hypothesis, thus, is quite compatible with the fact that the scripts used by the world's writing systems vary considerably in complexity. It can also accommodate the possibility that most scripts are not currently becoming simpler.

Character complexity is driven not solely by the cognitive and motor factors listed above but also by variable technological factors (e.g., means of letter inscription, etc.) or historical contingencies (weight of precedent; contact with other writing systems). We make no specific predictions about these culturally and historically contingent factors, except to stress that they may complicate the account given here in unpredictable ways, making the data noisier, so to speak. For this reason, our theoretical framework does not predict that two culturally distinct writing systems should necessarily evolve to reach the exact same degree of letter complexity over time (even assuming that both systems encode the exact same language in the exact same way). In particular, we cannot rule out the possibility that a script's initial complexity could cast a long

in this light that we should read his choice Egyptian owl hieroglyphic 𓅓 /m/ as the starting stimulus in a transmission chain, noting that it "may have been the basis of the form of our letter M" (180), as derived from the *M*-like beak and face. In fact, his participants transformed it into cat.

shadow over its subsequent evolution, making it likely that initially complex scripts stabilize at a higher level of complexity than ones that were initially less complex.

This still does not tell us why letter shapes should be overly complex from the outset. In theory, the mechanism just described could result in a process of complexification, where overly simple letters get enriched until they become sufficiently distinctive. We do think that, in theory, such a process should happen and that some actual examples may be found. Scholars have pointed to potential complexification processes at work in the Aztec and Mixtec scripts (Boone 1994; Downey 2014), certain Linear A inscriptions (Steele 2017:165), and later forms of Ogham (McManus 1996). Complexification, or inertia, may set in when writing systems are employed primarily for symbolic, aesthetic, or religious purposes or when the inscriptions are intended to be displayed for long periods of time.

Yet we also concur with the literature just reviewed: the trend usually goes from complex to simple. Why would this be? Here is one possible answer. The need for letters to be distinctive is immediately apparent to the eye of a script inventor. To estimate, and then to reduce, the precise amount of effort that goes into tracing a letter would presumably take longer. The differentials are minute, becoming significant only when a letter is repeatedly traced millions of time. It would thus make sense for script inventors to overlook the discrete costs of letter production and favor distinctiveness over simplicity. A related pressure leading to initial complexity is the fact that, from an inventor's point of view, ease of imagination and recall (pushing for distinctiveness) may matter more than ease of production.

In some ways, the process we are positing resembles cursivization, another well-known evolutionary trend that affects writing systems, the Egyptian and Latin scripts being the clearest examples (Coulmas 2003; Parkes 2008). Cursivization occurs when a script starts being written much more frequently and rapidly than it used to be—by copyist monks in the Latin case—linking letters together, producing rounded shapes and ligatures. Cursivization may or may not produce simplified shapes (it did in the case of Egyptian hieratic; Hegenbarth-Reichardt and Altmann 2008). In any case, it has much in common with simplification. It is a gradual process driven by a principle of least motor effort that may come into conflict with letter distinctiveness; in the Latin case, cursivization produced such ambiguous pairs as *p* and *q* or *n* and *m*. Cursivization is common, and its effects are recognizable in various unrelated scripts, but it is neither a universal process nor one that fashions every script into the same identical shapes.

The view that cultural change is somehow geared toward particular states has recently been defended by cultural attraction theory (Morin 2016; Scott-Phillips, Blancke, and Heintz 2018; Sperber 1996), a school of thought working within the broader framework of cultural evolution (Boyd and Richerson 1985; Cavalli-Sforza and Feldman 1981). Its goal is to identify attractors, that is, states that cultural dynamics tend to evolve toward unless they are in that state already. Attraction dynamics are well explored experimentally (Fehér et al. 2009; Kalish, Griffiths, and Lewandowsky 2007; Miton, Claidière, and Mercier 2015). We contend that letter shapes satisfying a principle of least effort are such an attractor: scripts should evolve toward that state unless they are already there.

Iconicity versus Visual Complexity

If, therefore, the material shape of writing is subject to processes of schematization, from iconic to abstract, how is such change to be measured or predicted? The problem faces a number of immediate challenges. First, the property of iconicity is hard to capture and measure objectively given the cross-cultural diversity of figurative traditions and their context-specific perceptions of verisimilitude. This inherent subjectivity of iconicity judgments is succinctly expressed by Morphy (1991), a visual anthropologist who has defined figurative representations as those that are "intended to 'look like' the object represented and to be interpreted as such by *those familiar with the iconographic code*" (52; emphasis added). Added to this is the problem that even within a single visual tradition, there is no robust way of determining whether a given sign is more, or less, iconic than another (but see McDougall, Curry, and de Bruijn 1999). We argue, however, that the tendency for graphic images in transmission experiments to lose iconicity over multiple generations is subordinate to a more fundamental transition from less compressible to more compressible. That is to say that the images (iconic or otherwise) become graphically optimized in terms of information storage, retrieval, and reproduction by human agents. We do not claim that graphic iconicity itself is an encumbrance with no role or affordance (see, e.g., Turoman and Styles 2017) but rather that the diachronic measurement of iconicity is neither feasible nor desirable, let alone the measurement of its presumed effects. In other words, whether an insider observer perceives a loss or maintenance of iconicity across the full history of a writing system is of far less relevance to whether the writing system, both the individual items and the set of items, is becoming more or less compressed over time or remaining stable.

Emergent Writing Systems and What They Might Tell Us

Probing for compression effects in ancient primary inventions of writing is difficult since there is no way of reconstructing the very early phases of the development of writing as it unfolded year by year from individual to individual.[4] In short, the surviving archeological record does not permit us to observe how incremental processes of change and variation, witnessed over very short time spans, might scale up to larger patterns over

4. As Silvia Ferrara (2014) put it, "Incipits of all script are invisible, as our points of departure are irrevocably not 'the first' attestations, but the 'earliest' that the vagaries of archaeological preservation has made available to us" (75).

generations, centuries, and millennia. And if we turn instead to later and better-documented periods in the history of writing, it becomes hard, if not impossible, to disentangle the effects of inheritance from other processes.[5]

One proposal, by no means original, is to turn instead to secondary inventions of writing generated via stimulus diffusion. These are systems created in near isolation by nonliterate inventors who borrowed the idea of writing but did not directly acquire its principles directly from literate teachers. Terminology for this special class of secondary scripts varies; however, we prefer "emergent scripts" (by analogy with "emergent languages") and define them as functional writing systems developed by nonliterates from minimal stimulus.[6]

Both Tylor (1878 [1865]) and Kroeber (1940) recognized the potential of emergent systems to illustrate general processes of cultural borrowing, diffusion, and change. Other scholars, meanwhile, argued that they might also serve as heuristics for probing the origin and evolution of writing itself across deep timescales (Dalby 1967; Diringer 1968 [1948]; Ferguson 1995; Gelb 1963 [1952]; Kotei 1972). Isolated reinventions of writing serve as naturalistic transmission experiments in script change since the nonliterate inventors taught their systems to new generations of nonliterates who have in turn passed their knowledge to subsequent generations. Writing has been reinvented under these conditions at least seven times in recent history. The best-known example is that of the Cherokee script developed by Sequoyah in 1821. This was followed soon after by the Vai script (Liberia, ca. 1833), the Bamum script (Cameroon, ca. 1896), the Alaska script (1901–1905), the Caroline Islands script (1905–1909), the Masaba script (Mali, 1930), and Pahawh Hmong (Vietnam, 1955–1971).

Of these scripts, we contend that the Vai script of Liberia (fig. 1) is the best candidate for historical analysis. The script was created by at least eight men (Forbes 1851) who had probably been exposed to the Arabic and Roman scripts but were not literate in either of them and certainly did not apply them as models, unlike the Cherokee syllabary that took direct inspiration from the Roman alphabet.[7] While Roman and Arabic scripts were certainly used in West Africa by a literate minority in the early nineteenth century, no influence is discernible in early or later forms of the Vai letters. Indeed, a powerful indication that the inventors of Vai were not literate in the segmental Roman and Arabic scripts is the fact that the Vai writing system is a syllabary (Daniels 1992:88). Although the Vai script was sporadically taught in local schools, its transmission has remained largely informal and noninstitutionalized for most of its history. Until recently, those who wished to learn the language had to seek out a literate individual to teach them on a voluntary basis (Bai Leesor Sherman, personal communication; Scribner and Cole 1981). The teaching itself follows no prescribed method: there is no recitation order or any common reference syllabary, meaning that apprentices learn-by-doing (Konrad Tuchscherer, personal communication). Thus, if certain characters are not needed in a communication, there may never be occasion to learn them at all.[8] The fact that the number of graphemes in the system did not substantially expand or contract from its inception up until the present day means that the pressure for distinguishability of letters has not appreciably changed over its history. Vai is also a wholly secular writing system that has always been used for ordinary communicative purposes, such as letter writing and household administration, as opposed to display or ritual. For all these reasons we might expect that Vai writers have used their scripts under conditions of relative freedom, giving variation and change the best chance to emerge. Finally, the script has been independently documented on at least 16 separate occasions between 1834 and 2005, meaning that almost all of its history is recorded and does not require any interpretive reconstruction.

The Vai script remains in active use today among Vai speakers; however, the devastations of the Liberian Civil Wars (1989–1997, 1999–2003) and the West African Ebola crisis (2013–2016) have had some impact on its domains of use and the distribution of its users. Prior to these events, the script had a more prominent role in formal communications between Vai chiefdoms, especially in the coordination of elections for the

5. It is often noted that writing systems have a bias toward inertia. The clearest demonstration of this can be seen when a writing system developed by speakers of a given language is later appropriated for use by speakers of a language with dissimilar phonological or morphological rules. In many cases, features of the system designed for the first language are retained for the new language, despite increased costs in terms of accuracy and learnability. Consider how the Minoan syllabic system was appropriated for Mycenean Greek, despite the latter's preponderance of consonant clusters (Mattingly 1992), or the fact that Turkish was, for centuries, represented in the Arabic script, which is well suited to Semitic languages, with consonantal roots and inflecting vowels, but not to the phonotactics of Turkish. However, when writing systems are actively reformed to accommodate the phonologies of their new languages, these reforms often result in the more precise specification of phonological units, e.g., from Sumerian cuneiform to the more phonetic Akkadian cuneiform or in the shift from the Phoenician script (specifying consonants) to the Greek alphabet (specifying both consonants and vowels).

6. Note that the term "emergent" is not defined historically, so there is no categorical cutoff point distinguishing emergent scripts from primary scripts on the basis of periodization; indeed, several ancient scripts are argued to have been emergent, including Linear A and Old Persian Cuneiform. Daniels introduced the term "unsophisticated grammatogenies" (Daniels 1992:85) for such scripts, which we believe is misleading since it lends the impression that they were naively or deficiently constructed.

7. Although unsuccessful attempts have been made to detect influences from systems as disparate as Arabic, Hebrew, and Chinese (for a summary see Kelly 2018), the Vai script is very much a closed writing system (Houston 2004*c*) with no discernible interference from other writing traditions.

8. Momolu Massaquoi (1899) complained that before he drew up his standard chart of Vai signs, "each man . . . began the study of the characters where he liked and ended where liked, few ever mastering the whole" (578). However, Tuchscherer's observations confirm that these efforts had limited impact on traditional ad hoc learning methods.

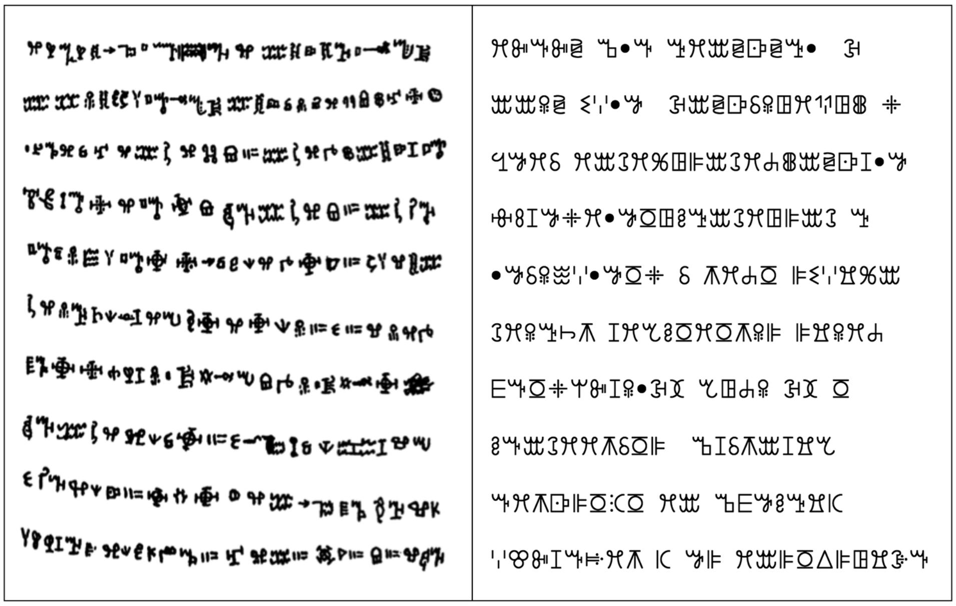

Figure 1. *Left*, the earliest surviving record of the Vai script, dated 1834. *Right*, the same text written in the modern (2005) version of the script. The left-hand image is cataloged as "New invented native alphabet of Western Africa Recd. April 18, 1834 from Messrs Wilson and Wynkoop," MS. Vai 1, page 1. Houghton Library, Harvard University. It is reproduced by permission of the United Church of Christ Wider Church Ministries. The right-hand image is rendered in the Unicode standard using the Dukor font developed by Jason Glavy. (Not all 1834 graphemes are attested in 2005; spaces indicate omissions.)

Traditional Council of Chiefs. During the Ebola crisis, meanwhile, the Vai script was mobilized within Cape Mount as a medium for promoting health and quarantine regulations. Vai program officers used the script to display warnings and directives on public placards and to distribute messages among Vai communities. Another significant change in recent years is the fact that the script is now being taken up by learners who are not ethnically Vai. This has been noticed among students at the University of Liberia campus in Sinje, Grand Cape Mount County.

An Analysis of Compression in the Vai Script

Drawing on manuscript sources, we proposed to measure compression in the Vai script as it has evolved between 1834 and 2005. The Vai script has roughly 200 graphemes (inventory sizes vary slightly depending on the source and historical time period) representing CV syllables of the Vai language and some logograms.

The Vai script has previously been treated as a case study for exploring synchronic distributions of complexity in writing systems (Rovenchak, Mačutek, and Riley 2009; Rovenchak, Riley, and Sherman 2011). These studies attempted to find correlations between the frequency of given graphemes and their complexity, with inconclusive results. They relied on manual coding of overt features within individual graphemes, as developed by Altmann (2004) and Peust (2006). A single point, for example, is assigned a value of 1, a straight line a value of 2, an intersecting line a value of 3, and so on. Our study, however, analyzes the graphemes in terms of their descriptive and perimetric complexity by means of semiautomated computational processes. Descriptive complexity refers to how simply an image can be described in mathematical terms, while perimetric complexity captures the size of an image's perimeter independent of its scale. These methods have the advantage of circumventing the potential subjectivity of hand coding and have precedents in other studies (e.g., Caldwell and Smith 2012; Miton and Morin 2019; Pelli et al. 2006; Tamariz and Kirby 2015).

Our measure of perimetric complexity is taken from Watson (2012) since this procedure has proven effective at measuring relatively simple images, including the graphemes of writing systems. Descriptive complexity, meanwhile, is measured by recording the file size of images that are compressed to a zip format (following Tamariz and Kirby 2015).

Analysis of Historical Data Set

Our data set consists of individual Vai graphemes from 16 sources dated between 1834 and 2005, as tabulated by Tykhostup and Kelly (2018). Each source is constructed so that the set of graphemes is associated with a date (e.g., 1909) and an author (e.g., Migeod). Tykhostup and Kelly's aim was to provide a meaningful comparative data set for the history of the Vai script such that any transformations of individual graphemes might be tracked over 171 years. All available archival sources were consulted in order to assemble the data set presented in that paper; however, texts that were either undated or too short were necessarily excluded. It should also be noted that the final source is a Vai Unicode proposal (Everson, Riley, and Rivera 2005). Though modeled to some extent from earlier materials (especially Kandakai et al. 1962), we regard this latest instantiation of the script as a dateable source that is no less historically significant for being a digital document. Tykhostup and Kelly did not have access to dated manuscripts after 2005, which is why more recent sources are not included.

The data, while extensive in comparison to other emergent scripts, are not exhaustive and are limited to what has survived in the documentary record. Notable gaps include the period of the two world wars and the Liberian civil wars (1989–2003). It is plausible, for example, that variant graphemes branched off to create new lineages that became extinct and were thus not represented in surviving archives. We cannot know the degree of compression in these hypothetical lost lineages. For the purposes of analysis, our data set is further limited to the life histories of only the best-attested Vai graphemes. Thus, a Vai grapheme is included in the data set if (*a*) it is attested in at least 90% of the historical sources and (*b*) there are surviving examples in both the earliest sources (1834 to ca. 1845) and the most recent source (2005). This reduces our analysis to 61 graphemes (although not all 61 are attested in each source). Such a constraint weights the sample in favor of more frequent syllables in the Vai language since these are more likely to turn up in documentary sources.

To ensure consistency and accuracy, each grapheme was extracted from a digital image of the original manuscript source, opened in Adobe Illustrator, and then virtually traced as a vector over the exact contours of the original image, a method widely used by epigraphers to ensure the accurate comparative analysis of inscriptions (Parker and Rollston 2016). Further, we applied a consistent stroke width and placed each letter within a bounded area of 1,121 × 776 pixels. Next, each grapheme was exported in both .png and .svg formats. For all images, the foreground color of the grapheme was white, and the background color was black. All 2,128 processed images, including the originals, are permanently archived in an open-access, open-data Figshare repository.[9] As .svg images are vector based, the graphemes are represented by 2D points that are connected via lines and curves to form shapes. We then apply two measures of visual complexity for each instantiation of the 61 graphemes across 16 time periods.

Perimetric complexity (henceforth, PC) measures the complexity of binary pictures by taking the squared length of the inside and outside perimeters of a grapheme P, divided by the foreground area A and by 4π (Pelli et al. 2006; Watson 2012):[10]

$$C = \frac{P^2}{4\pi A}.$$

Our second measure takes the vector representation of drawing (.svg file) and then applies the DEFLATE compression algorithm to remove any redundancies (following Tamariz and Kirby 2015). This method approximates the descriptive complexity (henceforth, DC) of each grapheme: the amount of information required to losslessly describe a grapheme in terms of vector paths and anchor points.

Preregistered Predictions

Our general hypothesis is that repeated episodes of transmission amplify a bias for simplicity and that this impacts the visual complexity of Vai graphemes. It is important to note that our hypothesis is principally concerned with the evolution of each individual character as opposed to the set of characters (Claidière et al. 2018). As such, we ignore factors such as an increased similarity between characters within a set and instead focus on whether a particular grapheme becomes more or less visually complex. In particular, we test three predictions:

Prediction 1: Visual complexity will decrease over successive generations.

Prediction 2: The complexity of graphemes with higher visual complexity will decrease more than those with initially lower scores.

Prediction 3: Variance in complexity among characters should decrease with successive versions of the script.

These three predictions were preregistered on the Open Science Framework on September 9, 2017.[11] Our predictions were meant to apply to two distinct studies: the present study, based on historical data, and a transmission chain experiment. The results of the transmission chain experiment will be published separately. This paper also reports on follow-up analyses that were not preregistered but were suggested by reviewers.

Does Visual Complexity Decrease over Successive Generations?

To test our first prediction, we constructed two distinct analyses for the dependent variables of PC and DC. Both analyses were performed using a mixed effect model (Bates et al. 2014), with individual characters being considered as the basic unit of analysis, nested inside the year of the script. For instance, the character ꕭ ‹ga› as instantiated in the 1868 version of the script counts as a single data point. Year is used as the sole predictor in our model.[12] This allowed us to test whether changes in our dependent variables are predicted by the progression of time. We expected a negative effect for both analyses (i.e., both PC and DC decrease over time). Last, it is likely the case that individual characters will follow different trajectories through

9. All materials can be accessed at https://figshare.com/articles/Comparison_chart_of_Vai_script/5398537.

10. We use the Watson instantiation of PC because it controls for the limited resolution of the visual system, unlike the measure derived from Pelli et al. (2006).

11. The preregistered document can be consulted at https://osf.io/8gw5a/.

12. Year was transformed so that it starts at 0 (i.e., 1834 = 0). This transformation preserves the absolute change in time (e.g., 1834 = 0, 1845 = 11, 1848 = 14, etc.)

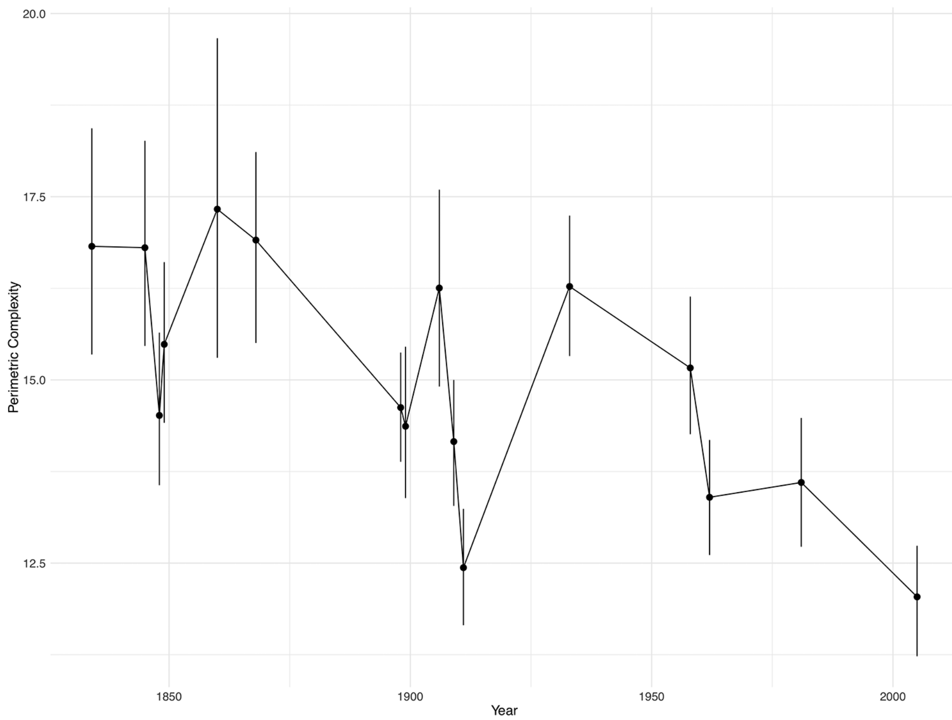

Figure 2. Mean perimetric complexity from 1834 to 2005. Error bars correspond to 95% confidence intervals (bootstrapped).

time; to control for this variation, we specified character as a random intercept (i.e., different versions of the character within a year are free to vary on the intercept) and included a random slope for year (which accounts for the fact that characters can vary year on year in terms of complexity).

Figures 2 and 3 show the respective averages for PC and DC, respectively. In both cases, we observe a general trend toward a decrease in visual complexity, which is confirmed by the model results for both PC (intercept: $\beta = 16.128$, year: $\beta = -.019$) and DC (intercept: $\beta = 517.196$, year: $\beta = -.100$). The negative coefficients in these models are significant when compared to null models (i.e., without year as a predictor).[13] The significant effect of year tells us that this negative trend is robust, even when accounting for individual variation in changes to character complexity over time. To illustrate, if one character happens to increase in complexity over time, then the model controls for this fact in determining the overall effect of year. Conversely, the model also accounts for any steep decreases in complexity for individual characters, which means that our results are not simply an artifact of a single character disproportionately influencing the average trend.

13. To assess the fit of the models, we used Akaike information criterion (AIC) and Bayesian information criterion (BIC). AIC and BIC are estimators of model fit, taking into account the number of parameters for a given set of data (i.e., the trade-off between a parsimonious model and an accurate model). The main difference between the two is that BIC penalizes violations of parsimony more stringently than AIC (see tables 1, 2).

Do Graphemes with Higher Visual Complexity Decrease More Than Graphemes with Initially Lower Complexity?

Simplifying effects are predicted to be dependent on the initial complexity of the grapheme. Specifically, our claim is that graphemes with initially high visual complexity are more likely to decrease than graphemes that start with low complexity, the rationale being that low-complexity graphemes are already extremely optimized and unlikely to deviate much in terms of complexity, as observed in transmission chain studies, where compressed items stabilize at a certain point of optimization (Tamariz and Kirby 2015:182). Conversely, graphemes with initially high complexity are not optimized for simplicity and are thus predicted to decrease over time (assuming a directional effect for simplicity). To test this prediction, two ordinal ranks were constructed for both PC and DC, based on their respective scores for 1834. This provides us with a baseline for the initial grapheme complexity. The ranks go from 0 (lowest score) to 37 (highest score) for PC and from 0 (lowest score) to 31 (highest score) for DC.[14] Ordinal measures were used for both year and rank to mitigate differences in scale causing convergence errors. As with the first prediction, we conducted separate mixed effect regression analyses for PC and DC but have now added rank as an interacting predictor with year.

14. For DC some of the characters share exactly the same file size. As such, these characters receive the same rank.

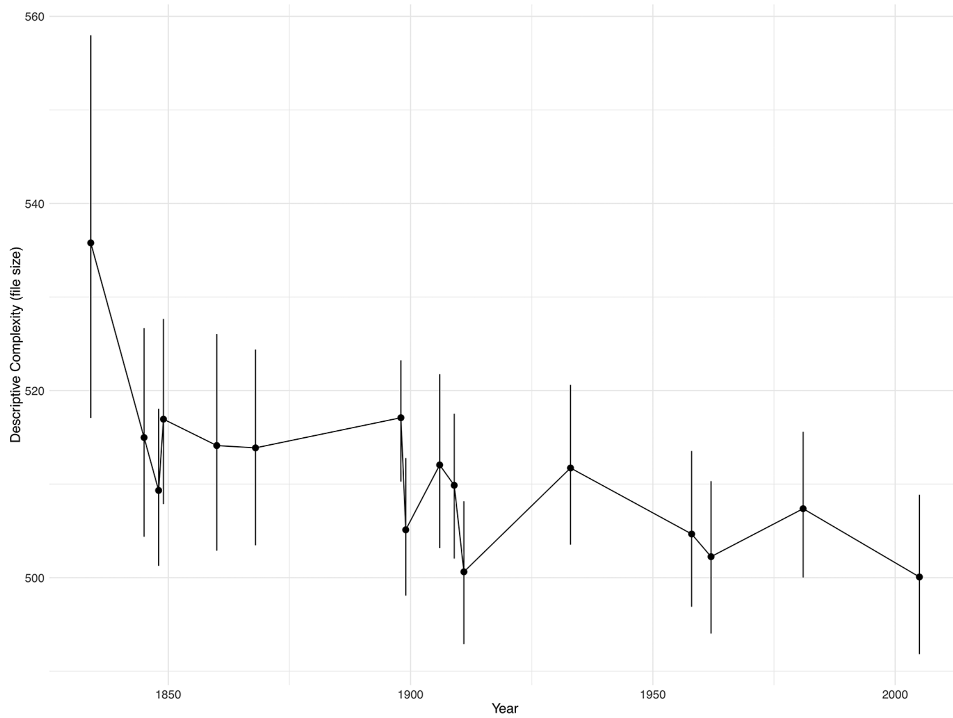

Figure 3. Mean descriptive complexity from 1834 to 2005. Error bars correspond to 95% confidence intervals (bootstrapped).

It seems that adding initial grapheme complexity (complexity rank) as an interacting predictor does improve the model fit for both PC and DC when compared to a model with only year as a predictor. Furthermore, the interaction between year and initial grapheme complexity for PC (intercept: $\beta = 9.95$, year × complexity rank: $\beta = -.01$) and DC (intercept: $\beta = 450.91$, year × complexity rank: $\beta = -.20$) indicates that later years and higher initial grapheme complexity correspond to decreases in PC and DC (figs. 4, 5). This supports our general hypothesis that differences in visual complexity are important in determining the change in complexity over time: graphemes with initially higher complexity are likely to follow a steeper decrease over time than graphemes with initially lower complexity.

Does Variance in Complexity among Graphemes Decrease with Successive Versions of the Script?

To test for a decrease in variance in complexity with successive versions of the script, we used a Levene's test for homogeneity of variance (1) on all samples from 1834 to 2005 and (2) between the first (1834) and the last (2005) available data sets. On all samples, the Levene's test indicated unequal variances for both DC ($F_{14, 1{,}048} = 1.83, P < .05$) and PC ($F_{14, 1{,}048} = 2.21, P < .01$). In testing for a decrease in variance between our first and last available data sets, we observed that variance was higher in 1834 than in 2005 for both DC and PC (figs. 4, 5). This decrease is significant for DC ($F_{1, 97} = 4.09, P < .05$) but not for PC ($F_{1, 97} = 2.66, P = .11$), as shown in table 3.

All three of our predictions were confirmed by our results. Visual complexity decreased over successive generations, and graphemes that started out with higher visual complexity decreased more than those that began with lower visual complexity, leading to a lower variance in complexity over time. We now turn to the context and potential causes of those results.

The Context of Compression

Our study reveals that historical changes in the Vai script are far from random. Instead, Vai letter forms undergo a process of compression that can be detected from the earliest years after the script's invention right up until the twenty-first century. As we have seen, most studies explain compression effects in terms of transmission dynamics. As cultural items are transmitted from one user to another, they pass through a memory and learning bottleneck (Bartlett 1995 [1932]; Mesoudi and Whiten 2004; Tamariz and Kirby 2015). The most learnable characteristics are retained, while features that are harder to recall or reproduce will tend to fall away. Later generations of learners inherit a refined set of items that they, in turn, may continue to optimize until a degree of equilibrium is achieved. Equilibrium is here understood as the result of a trade-off between simplicity and distinctiveness, whereby the requirement that each letter be distinctive puts a cap on the amount of simplification that a letter can undergo. Each of these pressures applies to individual letters, even though the pressure for distinctiveness will vary depending on the number of letters in the system. In the present case, however, the size of the grapheme inventory did not alter

Figure 4. Perimetric complexity of each Vai character from 1834 to 2005. Each facet corresponds to the initial 1834 ranks in terms of perimetric complexity (i.e., 0 is the highest rank, and 37 is the lowest rank). Characters (A to YE) are color coded.

Figure 5. Descriptive complexity of each Vai character from 1834 to 2005. Each facet corresponds to the initial 1834 ranks in terms of descriptive complexity (i.e., 0 is the highest rank, and 31 is the lowest rank). Characters (A to YE) are color coded. Note that some characters started at the same level of descriptive complexity and therefore receive the same rank (e.g., rank 11).

significantly across the history of the system. Our study therefore suggests that the compression account is highly plausible in the case of the Vai script. We have shown, for example, that the most complex letters, such as (Fig. 6), undergo the most dramatic changes toward simplification. Meanwhile, letters that start out as relatively simple shapes tend to remain unchanged. Accordingly, high levels of visual complexity would appear to act as a hindrance on the transmission of the script. Of relevance here is the finding from Pelli et al. (2006) that PC is inversely correlated with efficient object recognition. Thus, Vai graphemes that have lower PC will be easier for readers to process and vice versa. However, since our study relies on naturalistic data outside of a controlled laboratory setting, it is well worth reflecting further on the historical context of Vai writing to consider whether there might be other complementary—or even contrary—pressures at play across the life history of the script.

A Coordination Problem for Nonliterate Inventors

For nonliterates to invent a writing system from scratch is an extraordinary cognitive achievement. Writing systems have been described as cognitive tools for the analysis of linguistic sound in the way that they model, and sometimes reify, phonological and morphological structure (Ferguson 1995; Harris 1986; Mattingly 1987, 1992; Watson and Horowitz 2011). Without such tools at their disposal, nonliterate inventors must figure out how to segment strings of spoken language into meaningful units, lacking any means of taking notes or drawing up sound values in a reference chart. As such, the eight men who developed the script in the 1830s would have had to rely on their collective memories to recall the agreed-upon sounds associated with each sign. With over 200 individual syllabograms, this would have required a great deal of mental effort and coordination. The script development process itself can be imagined as a kind of hypertransmission event involving intensive interactions, reproductions, conscious memorizations, and negotiated adjustments. It is likely that the inventors exploited cognitive shortcuts wherever possible. Perhaps the most fundamental was their decision—deliberate or otherwise—to model single syllables as opposed to either segments or multisyllabic words. The fact that nonliterate inventors are inclined to invent syllable-centric systems is well established (Daniels 1996), a phenomenon that reflects the fact that syllables have a denser psychological reality than phonemes (Port 2007; Treiman and Tincoff 1997). Other properties of the Vai writing system as it is found in the earliest records also appear to be purpose built for learnability. Certain characters, for example, have been modeled on traditional symbols already in use by Vai speakers, while others exploit iconicity to reference the morphemic values of a given syllable. Examples are GUN ‹bu› (representing shot pellets), WATER ‹ʤi›, and MONEY ‹kpɛ›. Importantly, these signs served double duty as both logograms (signs standing for whole words or morphemes) and syllabograms (signs standing for syllable sounds). In the earliest decades of the Vai script, at least 21 such logograms are attested.[15] Perhaps these logograms, with their iconic relationship to meanings, were simply easier to invent and recall. Moreover, their relative iconicity may have demanded a greater attention to form, resulting in higher visual complexity. Thus, in the early history of the script, a strategy of logography coupled with (visually complex) iconicity may have promoted the learnability of the script, especially among those who were already well versed in Vai figurative traditions. As the system developed over time, however, the logograms fell out of use, such that only three were still attested by 1981. In other words, Vai writers discarded their logographic scaffolding, allowing phoneticism to take over. This in itself would amount to a significant compression process that cannot be captured by measuring visual complexity alone.

Table 1. Model comparisons for perimetric complexity (PC) and descriptive complexity (DC) using Akaike information criterion (AIC) and Bayesian information criterion (BIC)

	AIC	BIC	Pr(>χ^2)
PC:			
Null model	5,596.4	5,621.2	
Year	5,574.5	5,604.3	1.013e-06*** <.001***
DC:			
Null model	9,808.9	9,833.7	
Year	9,800.7	9,830.5	.00138** <.01**

Note. A null model, e.g., PC ~ 1 + (1 + year | character), was compared to a model where year was entered as a predictor, e.g., PC ~ year + (1 + year | character).

Table 2. Model comparisons for descriptive complexity (DC) and perimetric complexity (PC) using Akaike information criterion (AIC) and Bayesian information criterion (BIC)

	AIC	BIC	Pr(>χ^2)
DC:			
Year only	6,383.7	6,410.9	
Year × complexity rank	6,361.2	6,397.5	1.817e-06*** <.001***
PC:			
Year only	3,551.8	3,579.0	
Year × complexity rank	3,524.3	3,560.6	1.445e-07*** <.001***

Note. Each comparison involved a model with year specified as the only predictor (year only), e.g., PC ~ year + (1 + year | character), and year interacting with the initial complexity rank, e.g., PC ~ year × complexity rank + (1 + year | character).

Institutions and Standardization

At least three attempts have been made to standardize the Vai script. The first was made in 1899 by Momulu Massaquoi, a descendent of the Vai script's principle inventor and a prominent

15. Drawing on progressivist models, a number of scholars speculated that an ideographic or pictographic system must have prefigured the development of the phonetic Vai script (Diringer 1968 [1948]; Kotei 1972; Massaquoi 1911).

Table 3. Variance in descriptive and perimetric complexity in 1834 and 2005

	1834	2005
Descriptive complexity	3,994.98 [2,174.54–5,815.42]	1,089.64 [699.73–1,479.56]
Perimetric complexity	24.57 [13.38–35.77]	10.83 [6.95–14.70]

Note. The values in brackets indicate bootstrapped 95% confidence intervals.

Liberian intellectual and official. In this year he produced a standard chart of the Vai script for use in schools (this is represented by the point just prior to 1899 in figs. 2 and 3). Twelve years later he published another chart that he claimed to be a direct reproduction of the 1899 script but that in fact shows numerous subtle variations (see 1911 in figs. 2 and 3). More successful was the standardization campaign at the University of Liberia in 1962, involving 11 consultants and an official Standardization Committee. For the first time all variant graphemes were eliminated, and the committee settled on one sign per syllable. The final standardization event was the Unicode proposal of 2005 (Everson, Riley, and Rivera 2005), resulting in the Vai script being accepted into the Unicode Standard three years later. Those who compiled the proposal relied on the 1962 standard together with modifications that reflected modern use. As we can see from figures 2 and 3, each standardization event, in 1899, 1962, and 2005, coincided with a decline in both DC and PC, suggesting a possible causal relationship.

Domains and Media

The shift from a reed stylus in protoliterate Mesopotamia to a wedge-tipped stylus in the mid-third millennium necessarily resulted in a more compact and consistent cuneiform script, just as the advent of paper in early second-century CE China preceded the emergence of more uniform styles of Chinese writing. In like manner, technological changes in writing apparatuses may have influenced the rate of compression in the Vai script. Vai was first written using pens cut from reeds with ink derived from the leaves of certain species of bush. By the end of the century, Vai writers in the interior were still using reed pens and organic inks; however, those living on the coast who had better access to foreign products were writing with commercial pens and pencils on imported European paper (Delafosse 1899:30). The Vai script was also represented on surfaces other than paper. Vai men were renowned as silversmiths, and surviving artifacts and commentaries indicate that the script was inscribed on silver ornaments. Vai has also been carved into wooden tablets, furniture, and lintels, a practice that continued well into the twentieth century. Examples of the Vai script, apparently written with a ballpoint pen, surface in the 1970s (Scribner and Cole 1981), and by the twenty-first century Vai appeared in digital form as a font. It is possible that a shift from more rudimentary writing materials to modern pens and digital fonts contributed to the simplification of the script. Fonts, after all, must conform to precise dimensions and have standardized

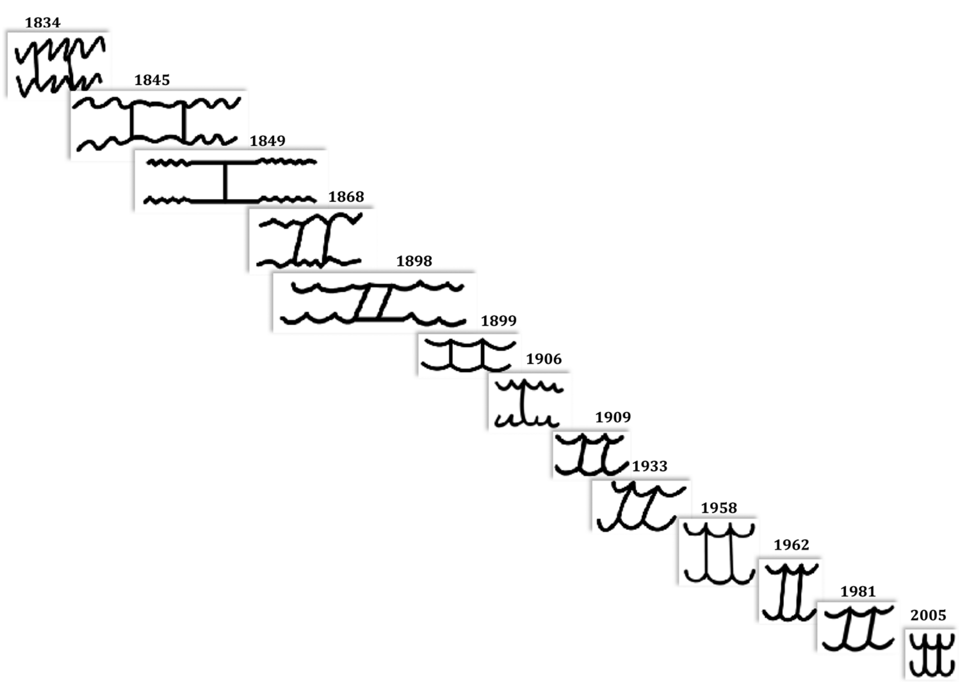

Figure 6. Evolution of the complex symbol ꕬ ‹ga› between 1834 and 2005.

gradients for horizontal, vertical, and oblique strokes. However, the fact that Vai continued to compress over the entire length of the nineteenth century, at a time when there was little change in writing media, indicates that shifts in writing technology cannot be the full story. Even the transition from a handwritten system to a font, between 1980 and 2005, does not show a dramatically steeper decline in visual complexity than comparable time periods elsewhere in the history of the script (see figs. 2, 3). Thus, while it is a possibility that letter inscription technology has influenced the compression of the script, this cannot explain our results.

After its invention, the Vai script gained popularity and became circulated more widely among Vai speakers entering into new contexts, domains, and genres. Accordingly, changes in the dominant genres of Vai writing may also influence compression. Elsewhere, religious texts, or documents glorifying royal lineages, are often characterized by an abundance of visual detail. Consider, for example, the richness of Christian illuminated manuscripts, Islamic calligraphy, the Maya codices, or the monumental temple inscriptions of Egypt. These kinds of texts are not designed primarily to be read so much as displayed for the admiration of literate and nonliterate alike (Ferrara 2015; Guillaume-Pey 2016; Houston 2004*a*; Olivier 1981). By contrast, mundane or secular genres of writing often take a more simplified form, as witnessed in the bureaucratic handwriting of the hieratic and demotic scripts, or the Simplified Characters of modern China first promoted by the ultra-secularist May Fourth Movement. As it happens, the earliest recorded genres of Vai manuscripts are quite diverse and include such documents as ordinary business transactions, historical chronicles, and ornamental engravings (Creswick 1868; Payne 1860). At the end of the nineteenth century there are reports that the script was used for letters, travel diaries, and the recording of popular stories (Delafosse 1899:29; Massaquoi 1899:578). Only in the twentieth century was it used in more prestigious genres such as autobiographies, compilations of aphorisms, and translations of canonical literature, including the Koran, the Bible, and even the Iliad (Dalby 1967; Massaquoi 1911). However, the more prosaic uses, such as letter writing, record keeping, the compilation of shopping lists, and the drafting of technical plans, are also known across the twentieth century and may have persisted from the script's earliest years. As Singer (1996) put it, "The basis for the enduring popularity of Vai [writing] has been its personal uses rather than more public ones" (594). Consequently, nothing in the history of the script indicates a decisive shift in genres of Vai writing, or changes in writing tools, that might otherwise explain the reduction in its visual complexity.

Relevance of Findings to Other Writing Systems

Long before the proclamation of Liberia as a freed-slave commonwealth in 1838, Vai merchants acted as agents in the cross-Atlantic slave trade, with networks stretching from the Pepper Coast into the interior. Later, as the freed slaves migrating from the United States became established as the ruling ethnicity, the indigenous Vai were pushed to the political margins but remained active in warfare and trade, including clandestine slaving. The relative autonomy of the Vai-speaking people over centuries of colonial contact may go some way to explain how they resisted domination from literate populations but were porous enough to permit their script to be documented at regular intervals by outsiders. Such a delicate balance of contact and isolation has resulted in a rich archival legacy that is not available to the same degree for the other emergent systems invented independently in the Americas, the Pacific, and Southeast Asia, not to mention elsewhere in West Africa.

These less described emergent scripts, not discussed here, nonetheless exhibit certain similar characteristics. On the phonological level, all emergent scripts that are known to us have targeted syllables as the central unit of phonetic representation, with varying degrees of primacy. Further, they have emphasized the representation of consonants while underspecifying vowels (Kelly 2018). Logosyllabograms—or signs standing for monosyllabic morphemes—have also featured widely in the earliest beginnings of many emergent systems wherever the documentation has survived.[16] With the exception of the short-lived Caroline Island Script, later generations of writers worked with smaller and increasingly phonetic sets of graphemes, as logograms were gradually abandoned or repurposed. As we have seen, the Vai script decreased in visual complexity over the first 171 years of its history, and it remains to be seen whether this process is also detectable within other emergent scripts. It is nonetheless clear that the Bamum script of Cameroon and the Pahawh Hmong script of Vietnam went through discrete phases at the hands of their nonliterate inventors, resulting in fewer strokes per character in later versions of the scripts. It would appear, therefore, that emergent writing systems may well confirm the more material aspects of the progressivist hypotheses supported by Gelb, Tylor, Taylor, and others, even if their rigid and unilinear stadialism must be abandoned. That these thinkers also assumed that writers of simpler or more phoneme-based scripts were intellectually and morally superior presents another unfortunate—some might say fatal—distraction from a much better-founded insight.

16. Historians maintain that Sequoyah first developed a logographic system for Cherokee before launching his fully syllabary in 1821 (Walker and Sarbaugh 1993). In the earliest years of its development in ca. 1896, the Bamum script of Cameroon was composed of 460 logograms but transitioned through five stages until it became a fully phonetic system of 80 signs (Dugast and Jeffreys 1950:24). The Alaska script developed between 1901 and 1905 relied first on indigenous pictograms with no phonetic values before its inventor reformed it as a syllabary. The Caroline Islands script (1905–1909) was phonetic from the beginning but included many iconic logograms. Similarly, Pahawh Hmong (Vietnam, 1955–1971) became increasingly precise but was phonetic from the outset, with a small set of logograms used only for numbers and certain common words. The earliest drafts of the Masaba script (Mali, 1930) are lost, and the surviving documents show a fully phonetic script (Kelly 2018).

Just how well emergent systems track the trajectories of ancient primary inventions of writing remains to be explored. That the Vai script was created in a conscious act by named inventors does not invalidate it as a historical heuristic. As many paleographers now claim, the first writing systems are also likely to have been developed by small groups of individual specialists in the space of single generation (Boltz 1986:28; DeFrancis 1989: 216; Ferrara 2015; Glassner 2003; Handel 2016; Houston 2004*b*; Michalowski 1994; but for a contrary view see Bottéro 1995). There is, after all, no such thing as a natural writing system in the same sense that we understand natural languages. All writing necessitates a degree of deliberate engineering. It is nonetheless remarkable that emergent writing systems appear to change much faster than other scripts, a phenomenon recognized by Gelb (1963 [1952]:21, 210–211), who suggested that their short histories emulate the evolution of writing across deeper timescales. Contrary to Gelb's teleological approach, we suggest that this apparent rapidity may be a consequence of the stimulus diffusion dynamic: since their inventors already knew what writing was capable of—including organizing populations, asynchronous communication, trade facilitation, and status and identity marking—this foreknowledge gave them greater impetus to develop and optimize their system.

Though writing was not developed to address the bureaucratic needs of states, it is nonetheless true that it would become instrumental in the regulation of state activities. One characteristic of early state complexes is a movement toward increasing uniformity and standardization of material culture. As Norman Yoffee has noted, the progressive standardization of writing in Mesopotamia coincided with other incremental uniformities in state-associated material culture, including the standardization of calendars, ration bowls, weights and measures, legal discourse, and irrigation systems (Yoffee 2001). Thus, if compression effects are found in ancient writing systems, these may well be subordinate to larger political convergences toward forms of statewide legibility understood in its broadest sense (Downey 2014; Scott 1998). The relative extent to which any such individual changes may be blind or intentionally coordinated cannot be probed.

By contrast, the inventors and earliest generations of Vai users belonged to smaller-scale chiefdoms on the outer margins of a growing colonial complex; the first official standardization efforts were not enacted until Vai populations had become integrated into the Liberian colony. Even though it has never been deployed to fulfil the demands of mass production within a complex state infrastructure, the Vai script has nonetheless transitioned toward greater visual simplicity and regularity across all phases of its history.

Limitations of the Study

One of the advantages of Vai as an object of study is the fact that its grapheme inventory of around 200 letters has remained fairly stable over its entire history. However, this fact also places limits on its heuristic value. The cuneiform, Egyptian, and Chinese systems have witnessed significant fluctuations in inventory size over their much longer histories, with implications for visual complexity. As Isaac Taylor (1883*b*) put it, "A change in any one letter constantly produces related changes in other letters—they have to be differentiated in order to maintain an adequate dissemblance" (365). Thus, as grapheme inventories of writing systems expand and contract at different points in their history, we can expect individual graphemes to maintain or increase their complexity in order to ensure that no two graphemes look too alike within a limited design space. As Watson's (2012) analysis indicated, individual letters of the comparatively small Roman alphabet are, on average, much simpler than those of the much larger Chinese script. Expansions and contractions to grapheme inventories also raise the question of system-wide compression effects and how they might be detected.[17] System-internal effects, in which similarities and distinctions between letters become structurally organized within the system as a whole, could not be investigated in our study. However, if adequate concordance tables were available for sequential phases of ancient writing systems, this would present an opportunity to detect system-wide compression by measuring and controlling for grapheme inventory size. Such a study would help to bring precision to the question of how individual graphemes within a fluctuating system must strike "compromise between reduction of effort and distinctiveness" (McArthur 1992:341).

Conclusion

As we have seen, scholars have long drawn attention to incremental processes of simplification in historical writing systems, and some have suggested that these dynamics might also be found in emergent systems created by nonliterates. Our study of the emergent Vai script has detected clear compression effects over the first 171 years of its existence, corroborating the simplification hypothesis. These effects are witnessed in the fact that visual complexity decreases over successive generations of users and that graphemes with higher visual complexity decrease more than graphemes with initially lower complexity. Further, we have demonstrated that the overall breadth of variation in Vai graphemes decreases with time. In other words, the complexity rates of Vai graphemes become increasingly uniform with respect to one another. We have argued that historical considerations, such as standardization campaigns and changes in writing technology and genres, cannot by themselves explain the consistent reduction in visual complexity over the life of the script. Following the lead of earlier paleographic theorists, we suggest that systematic compression may well be a central dynamic underpinning the early evolution of writing systems.

17. Again, Taylor (1883*b*) preempted this question when noting that "of an opposite tendency [to differentiation] is the principle of assimilation, which often produces curious superficial resemblances among letters belonging to the same alphabet, affecting, more especially, contiguous letters such as m and n, p and q, E and F" (365).

Acknowledgments

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Comments

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Any attempt at the rigorous study of African indigenous scripts must contend with three challenges: first, the firmly engendered orthographic thought-habits resulting from the ubiquity and prolonged usage of the Latin alphabets in the Western hemisphere; second, the complex conceptual adjustments that must be made in order to unlearn and then learn an entirely novel orthographic philosophy; and, third, the often esoteric origins of these indigenous scripts and the traversal of various realms of meaning across which the symbols function, realms that may not always be accessible to common human experience. The publication by Kelly et al. throws these three challenges into sharp relief. On the one hand, as prisoners of our own (Latinized) orthographic experiences, a lot of thought habits need to be broken in order to engage this study. On the other hand, the syllabic nature of the Vai script reveals a rather uncommon manner of thinking about (and doing) orthography. In addition, the association of the Vai script with the Liberian house of chiefs points to its esoteric origins.

At the heart of Kelly et al.'s paper lies the examination of the theory that states that "through repeated interactions, a system of signs will become compressed so that the same amount of information is expressed with less descriptive effort." Kelly et al. tested this theory by using the Vai script as a case study. Their efforts dwelled upon an aspect of script metrics: the measurement of script complexity. In concluding, they maintained that "all three of our predictions were confirmed by our results. Visual complexity [of the Vai script] decreased over successive generations, and graphemes that started out with higher visual complexity decreased more than those that began with lower visual complexity, leading to a lower variance in complexity over time." The authors note, however, that not all scripts seemed to conform to the theory in question. They cited the example of the hieratic Egyptian script, which became "far cruder in its form than the monumental hieroglyphic script that preceded it" while making allowance for the fact that "most scripts are not currently becoming simpler." Such an exception comes as a surprise, because one must be able to test all existing scripts against the stated theory if one is to assign a definitive truth value to the theory.

At this juncture, the discourse may benefit immensely by opening itself to more dialectical possibilities. In other words, this theory (like all scientific theories) must wrestle with the conceptual behemoth known as underdetermination. Further examination of the nonconforming scripts requires a decision: either to investigate holist or contrastive (Stanford 2017) forms of underdetermination as source(s) of nonconformism or to make appropriate modifications to the theory itself. The wider applicability of the theory to other indigenous scripts remains an inviting exercise. However, the question as to why the Vai script appears to obey the stated theory, and why the Egyptian hieratic does not, must remain a work in progress.

The theory subsists in the web of belief, and it is to this web of belief that we must turn when deviations from theory are observed. After all, "when the world does not live up to our theory-grounded expectations, we must give up something" (Stanford 2017:4). The investigative enterprise of verifying a theory requires much caution, so that one does not fall for the temptation of putting one metric on a pedestal when it is not very clear which metric to investigate. The web of belief opens up multiple paths of inquiry: should we further interrogate our own orthographic thought-habits? Where should we make necessary conceptual adjustments? When and where should we embrace nonmonotonic reasoning? Has a particular script maintained symbol complexity for the sake of aesthetics and the transmission of meaning? Do the symbols have their origins in irreducible artifacts, mentifacts, and sociofacts (Fantini and Fantini 1997:56–59)? How should we navigate the boundary separating the esoteric realm of meaning from the nonesoteric realm of meaning? Could it be the case that the theory exhibits multiple degrees of truth when applied to multiple indigenous scripts?

African indigenous scripts remain a vast, untapped repository of semiotic and symbolic information, and many questions remain to be asked. Indeed, the study of these scripts must evolve into a rigorous science that makes allowances for fuzzy and even nonlogical notions that contribute to the formation of meaning. A constructivist hermeneutic might need to be embraced that gives room for the contextual uniqueness of each indigenous script. It may well be imperative to focus on understanding how specific scripts function in context rather than on the generalizability of findings. We may have to admit that measures of phenomena are often subjective and that data collection methodology may be subject to individual bias. Given the continued use of these indigenous scripts, their continuous examination by means of ever-rigorous phenomenological inquiry, together with techniques of never-ending language learning (Mitchell et al. 2018), remains an imperative.

Researchers may need to engage each and every indigenous African script before seeking sweeping generalizations. Studies in indigenous orthography remain relevant in light of the fact that Unicode proposals have been submitted as preludes to the digitization of several indigenous African scripts. We may be witnessing the dawning of the much-discussed concept of Afrofuturism. A different orthographic future is possible when we refuse to remain prisoners of our orthographic past. We remain grateful to Kelly et al. for their pioneering investigations.

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The paper by Kelly, Winters, Milton, and Morin reports an interesting approach to the analysis of script complexity from a historical perspective. The authors apply two different methods to calculate complexities of the graphic shapes of symbols. The study is based on manuscripts written in an indigenous West African syllabary used for Vai, a Mande language currently spoken in Liberia and Sierra Leone. The manuscripts cover a rather large time span of over 170 years. The Vai syllabary has a special role for studies of writing systems in view of several factors, including a comparatively long-preserved written tradition and the influence as a stimulus for the emergence of new writing systems in the region in the first half of the twentieth century (cf. de Voogt 2014; Tuchscherer and Hair 2002).

The notion of complexity, especially when dealing with graphic images, while being rather intuitive, is not easily quantifiable. The most straightforward approach applied for written symbols is perhaps stroke count known, for example, for Chinese characters. Traditional definitions of strokes, however, do not distinguish between simple straight lines and curvier shapes. A more elaborated method suggested by Altmann (2004) consists of assigning different weights to points, straight lines, and arcs as well as various types of connections. Rovenchak, Mačutek, and Riley (2009) and Rovenchak, Riley, and Sherman (2011) applied this approach for the Vai syllabary.

The results for both perimetric (based on the relation of contour lengths and the area of the symbol) and descriptive (based on the amount of information to store character shapes in vector form) complexities confirm several authors' initial suggestions about the simplification of character shapes in time. It is a pity that only references to the Figshare repository are given and no illustrations appear in the article text. An example for the perimetric complexity would be especially helpful. Unfortunately, I was not able to locate any numerical data for complexities calculated using the two approaches considered by the authors except for those visualized in figures. It would be interesting to compare different approaches to the complexity definition. In particular, one may ask the following questions. (1) Do the orderings coincide with the available definitions of complexities (perimetric, descriptive, and the approach by Altmann [2004])? Namely, is the order of characters sorted by increasing/decreasing complexity the same? If not, what causes the differences? (2) What are the correlations between perimetric or descriptive complexity and character frequency? Do they significantly change with time?

The latter question is linked to the suggestion that simpler shapes would be utilized for more frequent characters and vice versa. So far, such tendencies were confirmed—within the complexity definition of Altmann (2004)—for two indigenous African writing systems, Vai syllabary and Nko alphabet, but the correlation was rather weak compared with artificial systems like Morse code (Rovenchak, Riley, and Sherman 2011).

Kelly et al. make a nice point mentioning two concurring processes driving the evolution of character shapes: a balance should be achieved between simplification of shapes, up to indistinguishable, and efforts to distinguish those. A good example of such processes is reflected in *iʿjām* (consonantal pointing) of the Arabic letters. The Vai syllabary, like the majority of young writing systems, is certainly far from the point where the second process enters into play. Mechanisms behind the simplification were in particular mentioned by Delafosse (1899), who noted that—in the absence of printing—shapes of characters, especially those used less frequently, undergo deformations caused both by individual handwriting style and by memory flaws.

The authors report, among other results, significant drops in the mean character complexity for years 1899, 1962, and 2005, when the Vai syllabary underwent standardizations. This result, as far as it follows from the paper, is based on their data set of 61 graphemes (attested in at least 90% of the historical sources and found in both the earliest and the latest sources). It would be interesting to analyze how the mean complexity changes for the entire syllabary containing over 200 graphemes. Note that standardizations, although they eliminate variant shapes, might increase the set of characters. This is especially pronounced in the standard syllabary by Massaquoi (1911), where an entire six new series are introduced for syllables with foreign initial consonants (Everson, Riley, and Rivera 2005).

The authors claim at least seven instances of the invention of writing in recent times "by illiterate inventors"; of those, three occurred in Africa, namely, Vai (Liberia, 1820s), Bamum (Cameroon, 1890s), and Masaba (Mali, 1930). It is not clear, though, whether two other Mande syllabaries from the 1930s, Kpelle and Looma, fall into this category. The former might be interesting along the lines of the authors' study, as at least two lists of characters were published separated by several decades (Lassort 1951 via Dalby 1967; Stone 1990).

Beyond those seven recent inventions, some others can be considered, as commented in particular by Kelly (2018). For sure, the list could be expander even further to include, in particular, Chukchi writing by Tenevil or Tynevil (Davydova 2015; Jensen 1969), several scripts in Alaska (Schmitt 1951; Stern 2004:124), and Apache symbols by Silas John (Basso and Anderson 1973). The majority of those scripts, however, are not documented sufficiently well—if documented at all—to provide data for the complexity studies.

No doubt, the best choice for the next study of complexity changes would be the Bamum script (Dugast and Jeffreys 1950; Schmitt 1963). The easiest approach might be to use standardized shapes of characters contained in the Unicode proposals and the Unicode charts themselves (cf. Everson, Riley, and Tuchscherer 2009). There are not too many examples of writing systems in evolution available, so any chance to analyze this issue should be implemented as carefully and comprehensively as possible.

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Evolution of Items and Evolution of Systems

Kelly and colleagues present a unique analysis—prefaced by an enjoyably thorough introduction—showing an increase in compressibility (or a reduction in complexity) in the letters of the Vai script of Liberia over nearly two centuries. This is a lovely real-world example of cumulative cultural evolution: the optimization—or adaptation, or attraction—of letter shape influenced by the least effort principle. While the target article briefly discusses evolution at the level of whole alphabets, it very much focuses on how individual letters evolve. However, the evolution of each letter is dependent on that of every other letter in a script. The evolution of a set of letters therefore entails the emergence[18] of system properties that make sense only at the level of the whole set. This commentary highlights evolutionary processes affecting whole scripts, rather than letters, and outlines a systematic taxonomy of cultural evolutionary pressures affecting items and systems.

Writing systems can be used for artistic, decorative, and other purposes, but their main function is communication through reading. In this respect, letter shape is subject to three cognitive pressures—efficiency of production, recognition, and learning—and influenced by the linguistic environment (e.g., sound-letter mappings). Regarding individual letters, production efficiency, or the least effort principle, favors, as the target article shows, simple, compressible letter shapes. The opposed recognition efficiency pressure is met when the shape of a letter is clear and each letter is written neatly and completely. Learning efficiency is best achieved when letter shapes are memorable. Iconicity (e.g., the shape of a letter resembles a referent whose name starts with the sound of that letter) can boost the memorability of individual letters. Over the course of learning and usage, letters become symbols (Garrod et al. 2007), which are highly resistant to change over repeated episodes of learning and reproduction (Tamariz and Kirby 2015).

Regarding letter systems (alphabets, scripts, fonts), production efficiency could favor shapes that streamline the transitions between letters during writing. It might also favor similar shapes, which minimize motor learning and memory load, to the extent that—if this were the only pressure in operation—all the letters might end up looking the same. Recognition pressures, once again, counter production pressures, but at the system level, they encourage distinctiveness of letters in the script.

Existing letter systems are adaptive states, or attractors, that satisfice specific pressure combinations. Unintelligible handwriting (fig. 7*a*) is adaptive when production pressures such as time constraints and least effort trump recognition pressure (e.g., in quick notes meant to be read only by the writer; for signatures). Simultaneous production and recognition efficiency pressures favor letter systems that are resistant to simplification, that is, distinct from each other even if produced in haste: letters *p*, *i*, and *t* (fig. 7*b*) are more adaptive than *m* and *u* (fig. 7*a*) in this respect. Decorative scripts are not affected by the least effort principle—legible scripts (fig. 7*d*) are adaptive for large readerships, and illegible scripts (fig. 7*c*) may emerge in attractor basins in which recognition is not important.

The intended readership therefore modulates recognition pressures but also learnability. The number of adult language speakers in a population correlates with language compressibility (Lupyan and Dale 2010); smaller populations develop more obscure languages than large populations (Wray and Grace 2007). If these findings are applicable to literacy, scripts would evolve to be more compressible when they are commonly learned and used by adults or large groups than by children or small groups.

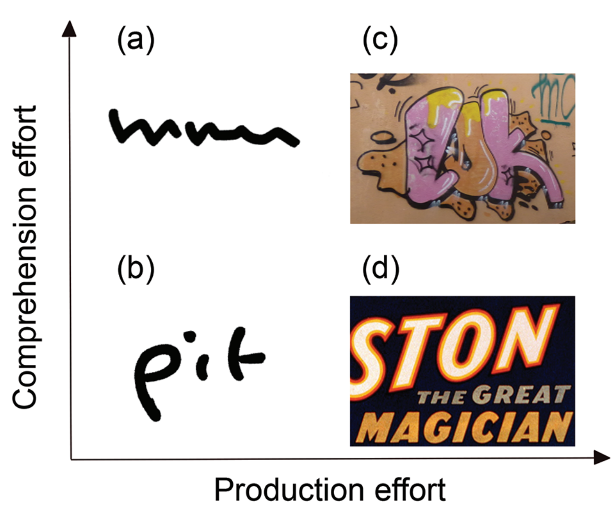

Figure 7. Handwritten samples involving different degrees of comprehension and production effort. The words "mum" (*a*) and "pit" (*b*) are fast spontaneous handwriting. Panel *c* is a graffiti signature, and panel *d* is a detail from a poster.

18. My use of "emerge" and "emergent" is different from that in the target article. The authors call secondary invented systems like Vai "emergent scripts" by analogy with emergent languages. This choice of terminology is defensible to the extent that secondary invented writing systems, like emergent Sign languages, appear in individuals who did not have the system beforehand. However, I find the term misleading in the context of cultural evolution, where "emergent" typically involves self-organization and unintentional processes, very much the opposite of what happens during the deliberate invention of scripts. My use of "emergent" in this commentary is in line with the former meaning.

Learnability pressures act more slowly than production or recognition pressures because learning a script happens only once in each individual. Script memorability, compressibility, and, therefore, learnability may be facilitated by style—the presence of elements and other features shared across letters. This can be tested with transmission chains of participants copying either a set of distinct abstract drawings with or without a homogeneous style. If style helps learning, the drawings will be better preserved in the former chains. Whether learning causes the emerge of style can be tested with a set of distinct abstract drawings copied either by different participants in a transmission chain or repeatedly by the same participant. If learning promotes style, common features would emerge in the chains but not in the individuals.

The memorability of script systems may also be enhanced by systematic letter-sound mappings. H. Jee, M. Tamariz, and R. Shillcock (unpublished manuscript) recently found that letters with similar graphical forms tend to map onto similar sounds (that share subphonemic features). The strength of systematicity varies across natural alphabets and fonts. The Korean Hangeul script, which was intentionally invented with pedagogical purposes in 1443, had the highest sound-shape systematicity, while artificial scripts such as Star Trek's Klingon were not systematic. Systematicity increases the compressibility of scripts, which strongly suggests that this property emerges, like the simplification of individual letters, in response to learnability pressures. The combination of production, recognition, and, especially, learnability pressures likely contributed to the coevolution of rich pedagogical traditions and teaching systems for literacy. The above considerations highlight the importance of taking into account pressures acting at the item and system level in order to understand the evolution of cultural systems such as alphabets.

Reply

That was all very well to draw once or twice; but when it came to drawing it six or seven times, Taffy and Tegumai drew it scratchier and scratchier.

Many of the other pictures were much too beautiful to begin with, especially before lunch, but as they were drawn over and over again on birch-bark, they became plainer and easier. (Kipling 1912 [1902])

The understanding that early sign forms steadily simplify over time has been taken for granted for such a long time that it has even inspired its own literal "Just So" story, *How the first letter was written*, in Kipling's famous compendium. The aim of our paper was to test just how well this theory performs in the real world by examining the near-complete history of a script.

Our three respondents have each provided thoughtful commentaries that illuminate the possibilities as much as the limitations of the study. It is gratifying to be able to address a collection of insights that range in scope from the technical and methodological right through to the dazzlingly philosophical.

Henry Ibekwe has understood that the study grows out of an African invention that has its own unique context, conditions, and implications. For the most part scholars have sidelined these concerns while perpetuating what Ibekwe terms "thought-habits," or a set of biases that resist critical introspection. As we understand it, Ibekwe's challenge is to render visible the hegemony of alphabetic and especially Roman orthographies across most of the world and to reengage with the indeterminate and esoteric dimensions of indigenous African sign systems. Only by provincializing Western orthographies can we make meaningful progress toward understanding indigenous written communication and, by implication, writing at large.

We maintain that this call to action is not antithetical to our study, even if we have not pursued this line of reasoning to its fullest. Indigenous inventors have developed emergent scripts in diverse environments, from the sub-Saharan tropics to the Arctic, the Pacific, and uplands of Asia. Common to all of these inventions are their origins, via stimulus diffusion, in a milieu of sustained contact with expanding literate empires. Accordingly, these new scripts can be understood as intellectual and political responses to the imposition of external powers that imported a new technology in the guise of writing. But emergent scripts are neither blank slate inventions nor wholesale cultural appropriations. Nonliterate inventors devised their linguistic mappings on the basis of native-speaker intuitions about their languages, unclouded by the biases introduced by prior literacy. Moreover, they often repurposed indigenous graphic repertoires without necessarily divesting them of all of their prior semantic conventions. In this light, the esoteric sources of inspiration deserve careful and sympathetic treatment. Similarly, the fact that new scripts have regularly assumed roles in religious movements and chiefdoms is revelatory of the relationship between writing, power, and restricted knowledge.

Our study was less ambitious and focused instead on testing the general theory that sign shapes simplify over time, by formulating a very specific set of hypotheses for the Vai script. The choice of Vai was not arbitrary. It is the only stimulus-diffusion script to have been documented moments after its Big Bang (or the point at which Vai signs were made to model linguistic values) and then regularly sampled at short intervals up until the present. Our predictions—that visual complexity will decrease, that the most complex graphemes will experience the steepest declines, and that the level of variability in complexity will homogenize—were confirmed. While these predictions were directed at the Vai script alone, Champollion's observation that hieratic was "cruder" than the monumental script is, in fact, wholly consistent with the predicted trajectory, contrary to Ibekwe's reading of it. Ibekwe's point that we should "focus on understanding how specific scripts function in context rather than on the generalizability of findings" is well taken. Yet context, contrary to the cliché, is not everything. In fact, our study reveals how much can be learned when the historical context as well as our expectations of function are momentarily set aside, to allow more light to shine on a single aspect: visual complexity. No amount of probing for ever-more historical or cultural determinants (per Downey 2014, e.g.) will explain the systematicity of the changes we see in Vai writing or the striking parallels with compression processes elsewhere, including in controlled settings. Such are the diminishing returns of a strictly relativist approach.

Andrij Rovenchak, by contrast, has directed his attention at measurements of complexity and their analysis. As he notes, we did not dwell on the fine-grained methodological details of our complexity measures as much as we might have. That is because the tools used here replicate measurements that we already used in two other studies (Miton and Morin 2019, 2021) and were borrowed from an earlier study (Tamariz and Kirby 2015). Comprehensive descriptions of perimetric and algorithmic complexity measurements (including schemas) are to be found there. Rovenchak is also right to remark that the original version of the paper did not link to the data used for the study, but this has been corrected in the final published version (see https://osf.io/qvfub/files/). His questions provide us with an occasion to stress the robustness and consistency of our measurements. Descriptive and perimetric complexity are generally substantially correlated with each other, as assessed with nonparametric correlations (Miton and Morin 2019, 2021). This is in spite of the fact that the two tools have almost nothing in common, the first being based on the compressed size of digital files, the second based on the contour length of images. Each measure has its advantages and drawbacks: descriptive complexity is the less intuitive of the two but is also arguably less sensitive to biases inherent in font properties such as line thickness (see especially Miton and Morin 2021). In the Vai data set, we once again observe substantial levels of correlation between perimetric and descriptive complexity. We computed nonparametric correlations (Spearman's rho) for each of our 16 sources. The resulting values range between 0.35 for the script's twelfth iteration and 0.77 for the script's first iteration, with an overall correlation of 0.52 ($P < .0001$). This study strengthened our confidence in the measures' validity but also justified our choice to cross-check these measures with each other.

We did not attempt to replicate Rovenchak's valuable study on the relationship between letter frequency and complexity (Rovenchak, Riley, and Sherman 2011). We doubt that sufficiently reliable and unbiased frequency estimates could be obtained across all the periods that we study. Furthermore, we believe that Rovenchak et al.'s original finding is essentially correct—that is, the correlation may be there, but it is weak—and that it would be replicated with new data. The weakness of this effect means that testing it on a relatively small sample of letters would likely result in an underpowered test. We came to realize the frailty of frequency-complexity correlations in a high-powered, systematic study of graphic complexity in heraldic emblems. We collected data on the complexity and frequency of use of thousands of heraldic symbols (figurative and nonfigurative) across two corpora, showing that the correlation between complexity and frequency can be, overall, positive instead of negative and is subject to substantial historical fluctuations (Miton and Morin 2019).

We concur with Rovenchak that it would be interesting to test our findings diachronically against the full Vai syllabary of over 200 graphemes as opposed to the 61 included in the study. Among other things, this would give us a window into how complexity relates to frequency and to explore how our study stacks up against the frequency studies of Rovenchak, Mačutek, and Riley (2009) and Rovenchak, Riley, and Sherman (2011) with respect to historical change. Unfortunately, this cannot be achieved without sacrificing statistical robustness. Our data set was constrained by the following criteria: a grapheme was included if it was attested in at least 90% of the historical sources and there were surviving examples in both the earliest sources (1834 to ca. 1845) and the most recent source (2005). Unless undiscovered and dateable Vai manuscripts come to light that can fill these historical gaps, the question must remain open. Rovenchak raises the possibility that the same methods might be applied to other emergent scripts, citing Bamum, Kpelle, Looma (Loma), Chukchi, the Alaska script(s), and western Apache. However, gaps in the data that can be controlled for with the well-described Vai script are altogether insuperable for these other systems. Apart from Bamum, there simply is not enough dated material that would allow for any meaningful diachronic analysis. Further, the inventors of the Kpelle and Loma scripts were plausibly literate in Arabic or Roman or perhaps even Vai (Dalby 1967:31, 51), meaning that, in theory, their scripts were born in a precompressed state. Chukchi and western Apache are not glottographic in the strict sense, which makes them rich and fascinating in their own right but not useful as comparators. In our view, the most suitable emergent scripts for diachronic analysis are the Bamum script of Cameroon (dateable across six periods), the Pahawh Hmong script of Vietnam and Laos (four periods), and the Pau Cin Hau script of Myanmar (three periods). The recently reported Lisu script of Yunnan-Tibet (Sun and Han 2020) offers another tantalizing prospect if enough manuscripts are available. Cherokee writing is dateable across at least six periods, but the casting of a typeface early in its history may be a confounding factor in its evolution.

In her engaging and thoughtful response, Monica Tamariz stresses the interdependence of letters and the importance of properties that can be studied only for entire written words and sentences. We fully agree with the view that written shapes need to strike a balance between competing pressures, some favoring higher complexity because it enhances letter distinctiveness, others favoring simpler shapes that are easier to produce. Like Tamariz, we see extant letter shapes as "attractors." In other words, the way that extant writing systems solve the trade-off between distinctiveness on the one hand and ease of production and recognition on the other hand constitutes a stable point in the space of possible solutions. Letter shapes tend to evolve toward this point and remain there when it is reached. This view of written symbols as optimizing a trade-off between competing pressures is in line with a well-established approach in linguistics:

lexical categories, for instance, have been shown to solve a trade-off between economy and precision (Regier, Kemp, and Kay 2014).

Tamariz's insightful comment raises the question of whether our predictions concerning complexity at the letter level could scale up and be tested at the level of entire scripts. Her contribution, as we read it, suggests that the level of entire scripts may not fundamentally differ from the level of single letters in this specific respect. Indeed, there are few ways that a script might become more complex if the letters composing it do not also become more complex. This could happen if a script changes its semiotics radically, through a drastic change in the way that shapes are made to map onto sounds, if, for instance, an alphabetic script turns into a logosyllabary or if a script that made little use of diacritics starts using them systematically. The system types of writing systems are, however, fairly stable in general, making such changes rather unlikely. In the case of Vai, these can be ruled out. That being said, we fully agree that a more systemic view of complexity would be highly enriching and is worth pursuing, as Tamariz suggests here and as was also suggested (from a very different point of view) by Ibekwe.

A question looms large when writing systems are seen from such a perspective: the issue of sound/letter mappings, judiciously raised by Tamariz. As she notes, the kinds of linguistic units that written symbols encode (phonemes, syllables, morphemes, etc.) weigh on their learnability and compressibility. We would add that it is the most important determinant of letter complexity when compared across scripts (Miton and Morin 2021). We are impatient to discover her new findings on the iconic relationship between letter shapes and the sounds they encode, an intriguing phenomenon (Turoman and Styles 2017) that this reply can only barely touch.

—Piers Kelly, James Winters, Helena Miton, and Olivier Morin

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