Levels of Structure
Within Chinese Character Constituents

James Myers

Abstract. It is already known that Chinese readers and writers decompose characters into four structural levels: basic components, complex strokes, simple strokes, and stroke features. These levels parallel word-internal structure in spoken and signed languages (respectively, morphemes, complex segments, segments, and segmental features). In this paper I consider evidence for a level intermediate between basic components and strokes: the stroke group. Like syllables, stroke groups are targeted by stress-like prominence and analyzable in terms of analogs to onsets, nuclei, and codas. They also seem to compete with each other for space within a component, as syllables do within morphemes. Though the analogies between stroke groups and syllables are weaker than the linguistic analogies for other character levels, the stroke group concept may help improve our understanding of a hitherto understudied aspect of writing systems: stroke interactions.

1. Introduction

Myers (2019) is a sober defense of an outrageous idea, the idea that Chinese characters conform to a genuine lexical grammar. In it I argue that Chinese script has direct analogs to morphemes, affixation, compounding, reduplication, inflectional agreement, idiosyncratic allomorphy, regular allomorphy, prosodic structure, stress, stress clash, weight, distinctive features, and feature spreading. The arguments are backed up with evidence from quantitative corpus analyses and psycholinguistic experiments, and in general I tried to be cautious in advancing only those claims that seemed reasonably well-established empirically.

In this paper I take a somewhat more, shall we say, speculative approach. Namely, while in the book I mused on whether certain types of stroke groups in Chinese characters are analogous to syllables, I did not

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push the idea. The primary purpose of this paper is to see how far this idea can go anyway.

Before we begin, I should say that, like Myers (2019), this paper focuses on traditional characters, but I do occasionally allude to simplified characters, which have almost exactly the same grammar. I also focus only on structures and patterns in modern characters that are hypothesized to be mentally active in contemporary readers and writers; despite its importance to other aspects of character analysis, etymology is thus irrelevant here.

Chinese characters have long been recognized as having multiple levels of representation. For example, the character in (1a) consists of the complex constituents in (1b-c), synchronically interpretable in terms of meaning and/or pronunciation. The constituent in (1c), in turn, consists of the basic components in (1d-e), where that in (1e) is not synchronically interpretable, but appears in other characters like those in (1f). The component in (1e) can be further decomposed into the strokes in (1g), including simple strokes, like the vertical stroke that forms its left edge, and complex strokes, like the rotated-L shape that forms the upper right corners of its two boxlike substructures.

(1) a. 館 *guǎn* ‘public building’
b. 食 *shí* ‘meal’
c. 官 *guān* ‘government official’
d. 宀 *mián* (roof-related semantic marker)
e. 𠂤 (synchronically lacking meaning and pronunciation)
f. 師 *shī* ‘army’ 遣 *qiǎn* ‘dispatch’
g. 丨㇕一㇕一

As will be reviewed in section 2, all of these levels have been demonstrated to be mentally active in the minds of modern readers and to have relatively self-evident analogs to levels in the internal structure of spoken and signed words.

Section 3 then explores the proposed level of stroke groups, which lies between the levels of components and strokes, and points out several similarities they share with syllables. For example, the component in (1e) above contains two boxes, each composed of more than one stroke, and joined together rather than being separate components. Since the lower box in (1e) is larger than the upper one, it is being treated as a whole by some sort of enlargement process. This process is argued in Myers (ibid.) to be like stress, making the targeted stroke group analogous to a stressed syllable. The fact that the box is treated as a whole is also consistent with how its strokes interact (i.e., are arranged with respect to each other), and to a large extent, interactions within stroke groups prove to be analyzable in terms of analogs to syllable-internal structure like onsets, nuclei, and codas. Moreover, stroke groups seem to compete with each for space within components, much as syllables do within morphemes.

Section 4 ends the paper with some conclusions.

2. Levels of Structure in Chinese Characters

In spoken and signed languages, morphological and phonological structures each consist of hierarchical levels, though the two types of hierarchies themselves parallel each other. For example, in the American English pronunciation of the word in Figure 1, the division between morphemes does not correspond precisely to that between syllables (σ), because the /t/ is ambisyllabic between the strong (stressed) and weak (unstressed) syllables, as defined by the metrical foot $[SW]_F$ (the moras reflect segmental duration and syllable weight; see, e.g., Hayes, 1989). This prosodic structure also causes the /t/, lexically specified with the feature [-voiced], to be realized as [+voiced] [ɾ].

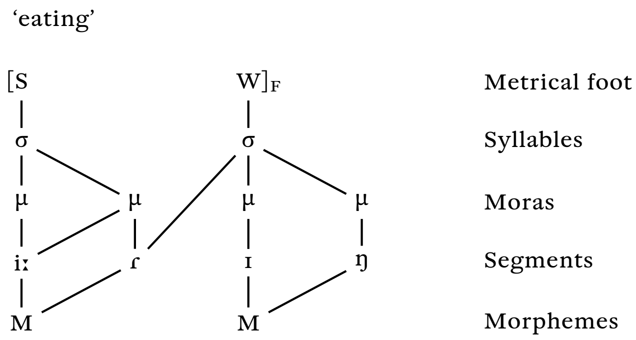

Figure 1. Autosegmental analysis of an American English word

The goal of this section is to review evidence that Chinese characters also have a hierarchical structure. Even ancient Chinese linguists recognized that characters are composed of interpretable components, which in turn are built using a small inventory of strokes, but as shown in sections 2.1 and 2.2, these levels have more recently also been thought of as corresponding to morphemes and segments, respectively. In 2.3 I review arguments from Myers (2019) suggesting that both of these levels also interact with something like the metrical structure of spoken and signed phonology.

2.1. Components

The best-studied level of Chinese character structure is the component. The most transparent of these is the semantic radical, which prototypically relates to the meaning of the whole character, as illustrated in (2a). Characters also often have a so-called phonetic component, which hints at the character’s pronunciation, though most of these are also complex constituents containing more than one component, as illustrated in (2b).

(2) a. 婚 *hūn* ‘marry’ 女 *nǚ* ‘female’
b. 昏 *hūn* ‘dusk’ 氏 *shì* (a surname) 日 *rì* ‘sun’

All characters can ultimately be decomposed into basic components, forming an inventory much smaller than that of characters. As estimated by Hue (2003), educated traditional character readers know over 5,000 characters, and Unicode contains many tens of thousands, but estimates for the number of basic components in traditional characters ranges only from around 250 to around 650 (see Myers, 2019, Section 1.2.2.3). The component inventory cannot be definitively fixed in part because the character inventory is not fixed, and in part because not all components are interpretable (see, e.g., Slaměníková, 2018). For example, the character in (3a) clearly contains the (uninterpreted) component in (3b), but the rest of the character is not found anywhere else in the traditional character system; the character in (3c) is the simplified equivalent of (3a). Chuang and Teng (2009) treat (3a) as an atomic component, whereas Lu, Chan, Li, and Li (2002), who also cover simplified characters, treat the bottom portion as a component in its own right; Wikimedia Commons[1] instead decomposes it into the components in (3d). For consistency in this paper, I will pretend that the inventory of 441 traditional character components proposed by Chuang and Teng (2009) is definitive.

(3) a. 單 *dān* ‘single’
b. 口 *kǒu* ‘mouth’
c. 单 *dān* ‘single’ (simplified system)
d. 甲 *jiǎ* ‘shell’ 一 *yī* ‘one’

Like morphemes, character components are the minimal potentially interpretable units, even if, like morphemes, not all are actually interpretable synchronically, as in English *result*, *resist*, *consult*, *consist* (see Aronoff, 1994 for the notion of “morphology by itself”). Also like genuine morphology, character decomposition is often recursive, as illustrated above in (2). Such parallels have often been noted (Ladd, 2014;

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[1] `https://commons.wikimedia.org/wiki/Commons:Chinese_characters_decomposition`.

Feldman and Siok, 1999), but Myers (2019) takes them further, noting, among other things, that the formal and functional properties of semantic radicals have much in common with those of inflectional affixes, and that component reduplication, as in the top of (3a), shares formal and functional properties with its namesake in spoken and signed morphology (see also Behr, 2006).

There is copious evidence that readers and writers mentally activate character components (see Myers, 2019, Chapter 5, for a thorough review). Taft and Zhu (1997), for example, found that characters were recognized more quickly if they contained higher-frequency components, even if they were unrelated in meaning and pronunciation to the character as a whole; Chen and Cherng (2013) drew related conclusions from handwriting experiments. Such observations are consistent with corpus modeling. For example, Li and Zhou (2007) showed that characters share components to the precise degree that one would expect if characters were generated from components via a general grammar rather than via exemplar-driven analogy (see also Fujiwara, Suzuki, and Morioka, 2004; Haralambous, 2013).

One particular sort of corpus-based generalization will prove particularly relevant to the present study, since it was first observed in syllables and other phonological units: Menzerath's law (Menzerath, 1954), also called the Menzerath-Altmann law (Altmann, 1980). Informally, this law states that the more constituents within a constituent at the next-higher level (e.g., syllables within a morpheme), the simpler they tend to be. In other words, the lower-level units compete for space within the higher-level unit.

This law applies to character components as well. As shown for Japanese Kanji by Prün (1994), and for simplified Chinese characters by Bohn (1998), the more components a character has, the fewer their mean number of strokes; independently, Chen and Liu (2019) showed that this generalization also holds for components in a multi-character word (probably, I speculate, because longer Chinese words tend to be transliterations of foreign borrowings, which tend to reuse the same small set of relatively simple characters).

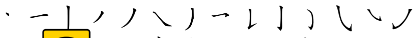
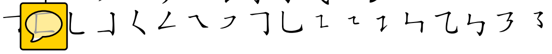
Formally, Menzerath's law is an inverse power law, as in the simplified version in (4) given in Prün (1994, p. 149), whereby the mean size or complexity y of the lower-level constituents is correlated (inversely, given the negative b) with the complexity of the upper-level constituent x (in terms of the number of lower-level constituents), nonlinearly, so that the difference in constituent size for one versus two constituents is larger than that between two versus three, and so on.

(4) $y = ax^b, \ b < 0$

As Prün (ibid.), Bohn (1998), Chen and Liu (2019) have all noted, the fact that the law applies to character components suggests that they represent a genuine level of description. It thus provides a tool for testing for the potential psychological reality of character levels even without running a psycholinguistic experiment.

2.2. Strokes

All writing is composed of strokes, that is, marks left via continuous contact between writing instrument and writing surface. Modern Chinese script has a set of basic linear strokes that can be used in their basic forms, concatenated with each other (i.e., changing stroke axis without lifting the writing instrument), and/or slightly modified (via curving and/or hooking), as shown in (5) (strokes that fit more than one category are repeated).

(5) a. Simple strokes: 
b. Complex strokes:  
c. Curving: 
d. Hooking: 

As has often been observed (Wang, 1983; Peng, 2017; Myers, 2019), strokes are like phonological segments in being basic units that are readily analyzable in terms of distinctive features, as opposed to the multi-stroke morpheme-like components that they compose. Watt (1980) observed a similar three-level contrast (morpheme = letter, stroke, feature) in the Roman alphabet.

No matter how Chinese stroke features are formalized, they serve to encode axis (horizontal, vertical, main diagonal [\], counterdiagonal [/]), curving, and hooking. Though strokes are visual marks, they also require encoding in terms of motoric gestures, much as evidence for character components comes from both perceptual and production experiments (see Myers, 2019, Sections 1.3.1.4 and 5.2.1.2, for more on amodality as a sign of the grammar-like nature of the Chinese character system). Individual stroke direction is mostly from left and/or top to right and/or bottom (for reasons that will be discussed in a later section). This gives the so-called dot, the simplest of all strokes, its default direction along the main (falling) diagonal (see first stroke in (5a) above). Since the counterdiagonal axis cannot be drawn simultaneously left to right and top to bottom, the Chinese stroke inventory offers two distinct strokes: that in (6a) is written top to bottom but right to left, whereas that in (6b) is written from left to right but bottom to top.

(6) a. 才
b. 孑

The inventory of complex strokes is limited by the same stroke direction constraints: the axis direction changes at the endpoint (right or bottom) of the previous portion, as in (7).

(7) a. ㇆ 司
b. ㇕ 口
c. ㇄ 匠

Strokes have undoubted psychological reality. Readers and writers tend to be consciously aware of them because they are explicitly referred to in lexicographical and pedagogical traditions, but they affect automatic processing as well: stroke number is routinely taken into account in reading experiments to control for visual complexity, and there is some evidence that it matters in writing experiments as well (Wang, Huang, Zhou, and Cai, 2020).

As demonstrated by Bohn (1998), Menzerath's law also applies to strokes, further reconfirming their psychologically real status. Stroke complexity was quantified on a scale that counted the number of linear segments and also hooking, so that both strokes in (8a) were given a score of two, on up to a maximum score of 5 for the stroke in (8b) (four segments plus a hook). Bohn found that the more strokes there were in a character component, the lower was the mean stroke complexity, in accordance with an inverse power function.

(8) a. ㇕ ㇚
b. ㇡

2.3. The Prosodic Structure of Chinese Characters

Building on research like that sketched above, Myers (2019) argues that parallel to the traditional hierarchy of strokes building components building characters, there is also structure analogous with prosody, specifically metrical feet. In spoken language, metrical feet are supported by a vast array of data, including perception experiments (Cutler and Clifton, 1984), production experiments (Levelt, Roelofs, and Meyer, 1999), and corpus analyses (Myers and Tsay, 2015), and there are similar data from signed languages as well (Crasborn, Kooij, and Ros, 2012).

The notion that written forms have a visual analog to prosody is also advanced in works like Evertz (2018) for spelling in the Roman alphabet. However, while the visual prosody of letters is claimed to correlate with that of the spoken phonemes they represented, the prosody that Myers (2019) sees in Chinese characters is completely unrelated to any of the spoken languages written with them, but relates solely to visual form.

At the heart of the analysis is the prosodic template in (9), realized in its full form as in (9a) and reduced as in (9b-d). This template places a single strong (S) position (head) in the bottom and/or right of a character or a component, with the remaining positions being weak (W). The lower right position is emphasized because strokes within a component and components within a character all tend to be written from left to right and top to bottom, and final gestures are given greater emphasis, not just in writing (e.g., in Western handwriting: Wann and Nimmo-Smith, 1991) but also in speech (Beckman and Edwards, 1990) and signing (Sandler, 1993).

(9) a. $\begin{bmatrix} & \mathrm{W} \\ \mathrm{W} & \mathrm{S} \end{bmatrix}$

b. $\begin{bmatrix} \mathrm{W} \\ \mathrm{S} \end{bmatrix}$

c. [W S]

d. [S]

This stress-like prominence is visually obvious in the different sizes of the reduplicated components in (10), where the larger component is at the bottom (10a) or right (10b). Note also that component reduplication involves doubling, either along one axis (10a-b) or along both (10c), again similar to the prosodically constrained reduplication of spoken language (McCarthy and Prince, 1998) and signed language (Berent and Dupuis, 2017).

(10) a. 昌 多 炎
b. 林 玨 比
c. 品 森 犇

This prominence generalization is sometimes clear even when the components are different, as in (11).

(11) a. 大：奧～奇
b. 田：富～畢

Myers (2019) argues that the prosodic weakness of the leftmost and topmost positions also explains (synchronically) the preference for semantic radicals to appear in these positions. This is because semantic radicals tend to be small along the relevant dimension (i.e., left-edge radicals are thin relative to the horizontal axis while top-edge radicals are flat relative to the vertical axis), as in (12).

(12) a. 彳：很
b. 艹 (derived from 艸)：花

The same correlation between position and size is also observed within basic components, as illustrated in (13) with some from the inventory proposed for traditional characters by Chuang and Teng (2009). Note that among the parallel strokes, the longest is that at the bottom (13a) or right (13b).

(13) a. 二 干 土 彳 彡
b. 丌 川

These generalizations have exceptions. Characters with small right-edge or bottom-edge semantic radicals do exist, like those in (14a), and there are an even smaller number of components with prominent top-most horizontal strokes, as in (14b). The existence of exceptions is also stresslike, however: the strong preference of English for strong-weak stress (*button*) and unstressed suffixes (*eating*) is not nullified by exceptions (*baton*, *unwell*).

(14) a. 戈：戰
b. 士

Some of the above components also illustrate an analog of prosodically conditioned allophony, namely curving of the vertical stroke on the left edge. Further components showing this are given in (15).

(15) 廾 井 片 用

The curving generalization seems to have more lexical exceptions than prominence, as illustrated with the components in (16).

(16) 巾 冉 冊

However, as first observed by Wang (1983), such exceptions are more likely in horizontally wider constituents, where, for example, the characters in (17a) have more horizontal strokes (making them "taller") than the corresponding ones in (17b) (making them "wider").

(17) a. ⺆：周 月
b. 冂：同 冊

Myers (2019) confirms that this tendency is indeed statistically significant, then goes on to propose an explanation: curving is only possible in a prosodically weak position, and wider components contain two prosodic templates rather than one, putting the left edge in a strong (head) position. This analysis is illustrated in (18). Curving in a weak position is thus similar to vowel reduction in unstressed syllables.

(18) a. 月 [WS]
b. 冊 [S][S]

In addition to statistical analyses of character databases, the psychological reality of the character prosodic template has also been supported in a series of experiments. Myers (2016) demonstrated that readers generalize constraints on reduplication shape to nonce characters. Myers (2019) showed that readers find nonce components more acceptable if the largest stroke is at the bottom or right, and prefer a curved vertical stroke to appear at the left rather than elsewhere. Myers (2020) found that readers prefer nonce characters to have thin rather than wide left-edge semantic radicals, whereas widening right-edge semantic radicals did not reduce acceptability much, presumably because doing so made the nonce characters conform better to the regular prosodic template.

Note that because metrical feet and the proposed character prosodic template are defined by their shape, Menzerath's law does not apply. It would make no sense to ask if feet are smaller in longer words, because feet always have the same number of syllables (if available), and the same is true for the proposed character template.

3. Stroke Groups As Orthographic Syllables

As spelled out in (19), spoken and signed syllables have a number of well-established properties.

(19) a. In a syllable, sonority (energy) increases to a peak and then falls.
b. Syllables are perceptually highly salient.
c. Syllables are targeted by foot-level processes like stress.
d. Articulatory gestures are more closely coordinated within than across syllables.
e. Nuclei are obligatory, onsets are favored, and codas are disfavored.
f. Syllables compete for space in morphemes (Menzerath's law).

Properties (19a-b) do not seem to apply to stroke groups. Whereas we can say that /pro/ makes a good syllable and */rpo/ a bad one (and likewise for <pro> vs. *<rpo>, as reviewed in Evertz, 2018) because of the intrinsic sonority of the segments (and letters), there seems to be no way to rank Chinese strokes in an analogous way. Strokes do differ in energy (as reflected in size), but as we saw in the previous section, this is predictable from position, making this phenomenon analogous to stress and not sonority. Moreover, there is as yet no evidence that stroke groups are perceptually salient, that is, that readers are sensitive not just to components and strokes but also to some intermediate level.

Nevertheless, section 3.1 argues that property (19c) does apply to stroke groups: the character template is built on syllable-like units. Section 3.2 then provides arguments that the related properties (19d-e), concerning syllable-internal structure, apply as well. Finally, Section 3.3 demonstrates property (19f): the applicability of Menzerath's law.

3.1. Stroke Groups and Prosodic Regularities

If regular prominence at the bottom and right is analogous to stress, enlargeable constituents should be analogous to syllables. As we have seen, these include certain simple components, like those in (20a), and certain individual strokes, as in (20b).

(20) a. 昌 多
b. 二 土 川 井

Yet regular enlargement also affects groups of multiple strokes, not just individual ones, even if they do not form full components. I illustrate this in (21) with a variety of examples: (21a-c) show enlargement of the lower of two linked boxes, (21d) shows something similar with other duplicate sets of strokes, and (21e) shows a cross-character contrast in enlargement of box versus (linked) stroke.

(21) a. 串 弗 虽
b. 亀
c. 官
d. 出 飛
e. 由 甲

At the same time, not all individual strokes are subject to prominence. As illustrated in (22), prominence does not affect the bottommost horizontal stroke if this ends (at the right) at another stroke (22a) or makes contact at both ends (22b), and instead the next-lowest free horizontal stroke is enlarged. If there is no free stroke, as in (22c), prominence can only apply to the entire complex, as in (22d). Bottommost strokes that cross others but are free at both ends (22e), and perhaps also those free just at the right (22f), are subject to prominence, as are strokes that are contacted at their midpoint by other strokes, as in (22g).

(22) a. 肀 (フ 一 一 丨)
b. 廿 (一 丨 丨 一)
c. 口 (丨 フ 一)

d. 串
e. 千
f. 非
g. 工

One way to put all of these observations together is to consider spatially separated strokes (and certain simple components, to be elucidated later) to be stroke groups, along with simple strokes with free ends. A stroke that ends in contact with another stroke is instead part of a stroke group that contains both strokes, unless that stroke is subject to a stroke-group-level process, like prominence, and thus a separate stroke group.

Left-edge curving also provides some information about the nature of stroke groups. According to the argument given in section 2.3, a vertical curved stroke is only possible if it is in a prosodically weak position, analogous to an unstressed syllable. I also argued that a vertical stroke in this position is more likely to be straight if it is the head of its own prosodic template, analogous to a stressed syllable. Either way, then, a potentially curvable leftmost vertical stroke should be considered a separate stroke group. Thus despite being composed of contacting strokes, each of the components in (23) should contain at least two stroke groups.

(23) 厂 尸 冂

3.2. Stroke Groups and Stroke Interactions

If stroke groups are like syllables, they should also restrict how strokes can combine, similar to the way spoken and signed syllables restrict phoneme and handshape sequences. I start my argument for this claim in section 3.2.1 with a review of previous studies on stroke interactions in the perception and production of simple line drawings, and then show how these relate to the structure of syllables in speech and signing. Combined with the previous discussion of the prosody of prominence and curving, this comparison will allow me in section 3.2.2 to interpret different kinds of basic stroke interactions in terms of different kinds of syllable-internal structure. Particularly challenging cases are surveyed in section 3.2.3.

3.2.1. Natural Stroke Interactions

A particularly insightful analysis of how perception affects written strokes is given in Changizi, Zhang, Ye, and Shimojo (2006), who counted the frequencies of all 36 possible configurations of one to three strokes in a variety of writing systems and beyond. Each of their configurations defined a class of topological equivalents, where, for example, <Z> and <[> are identical since both link three strokes at two joints. For my purposes, their key finding was that writing systems strongly favor a small subset of configurations, with only those listed in (24) approaching or exceeding a proportional frequency of .1 (taken from Figure 2, p. E118). Each configuration is illustrated with Chinese character components that contain it.

(24) a. I 一二八刂川
b. L 乚㇆𠂆㇏
c. T 丁卜亻人入
d. X 乂十
e. Z 匚凵冂乙ㄣ
f. F 匕

Changizi, Zhang, Ye, and Shimojo (ibid.) argue that the variation in configuration frequency is due to visual and not motoric processes, since the same variation is observed in trademarks, which are virtually never handwritten, but not in shorthand, where writing ease is favored over visual clarity.

Nevertheless, as noted in section 2.2, strokes are also gestural things, having not just an axis but also a direction (i.e., they are vectors), with the strong preference for the rightward and downward directions constraining what complex strokes are possible. Seeing strokes as vectors also helps explain stroke combinations as well. In particular, in Chinese character components, the T configuration is not only quite common, but is almost always written with the midpoint of one stroke (e.g., the top of the T) coinciding with the starting, not the ending, of the other stroke (e.g., the falling vertical stroke of the T).

Some Chinese character components conforming to this midpoint-start pattern are shown in (25). There are cases of a stroke ending at the midpoint of another stroke, as in (26), but most of these also conform to the midpoint-start pattern, as in (26b).

(25) 丂刀乃丌才彳夂久攵不牙手毛气牛片斤氏勿尹毋弔
(26) a. 丩厶土士彐幺夬
b. 工夕彑王歹五止日月及爿丑口田由甲

The explanation for these preferences in stroke direction and contact lies in how strokes are written, and as with the visual patterns observed by Changizi, Zhang, Ye, and Shimojo (ibid.), the motoric constraints are universal. Here the most ambitious survey is van Sommers (1984) (see also the summary in van Sommers, 1989), who reports a series of analyses and experiments on the production of simple line drawings. Regarding individual strokes, writers (and sketchers) prefer to pull the writing instrument rather than to push it, which means that right-handers, who dominate in the population, draw strokes rightward and/or downward (yielding ambiguous preferences for counterdiagonal strokes), though left-handers often draw strokes leftward and/or downward. The conventions of Chinese stroke direction, prescriptively imposed on left-handers as well, are thus not arbitrary.

The experiments reviewed in van Sommers (1984; 1989) also confirm the universality of the midpoint-start pattern of the T configuration, which has also been noted in many other studies (Goodnow and Levine, 1973; Ninio and Lieblich, 1976; Nihei, 1983; Simner, 1981; Smyth, 1989; Thomassen and Tibosch, 1991). Of course, as Smyth (1989) points out, stroke coordination also depends on hand-eye coordination, so this is not a purely motoric process.

The literature generally describes this interaction as one stroke being anchored on the other; I will call it midpoint anchoring. As Nihei (1983) recognizes, midpoint anchoring is distinct from what he calls fluid anchoring, also called threading (Thomassen and Tibosch, 1991) or chaining (Myers, 2019), whereby a stroke continues from where the previous left off, without lifting the writing instrument, as in complex strokes in Chinese. Like midpoint anchoring, chaining seems quite natural, appearing in the drawing habits even of very young children; the high frequency of both the T and L configurations in Changizi, Zhang, Ye, and Shimojo (2006) may thus have some motoric motivation as well.

Another type of natural interaction is what Nihei (1983) calls fixed anchoring, where two strokes begin at the same point, something that children find particularly easy to do. Given the rightward and downward stroke directions, in Chinese components the shared starting point is always at the upper left, as in (27).

(27) 厂广匚冂几又口

The high frequency of the X configuration suggests that stroke crossing should also be relatively simple, but as the above studies report, young children sometimes draw it as if it were a set of four strokes with a common starting point (i.e., using fixed anchoring). Its intermediate difficulty may arise from needing to coordinate two stroke midpoints rather than relying on a shared starting point, as in fixed anchoring, or identifying just one midpoint to use as the starting point for the other, as in midpoint anchoring.

The most difficult stroke interaction is the one Nihei (ibid.) calls ballistic, where one stroke ends at another. As with firing a projectile, here the writer/sketcher must plan the initial action in order to achieve an end goal, something that young children have particular trouble with. Its relative rarity in Chinese components, as suggested by (26) above, is thus expected (and in the next section I will argue that it is even rarer than it seems).

By way of summary, Table 1 lists various types of motoric stroke interactions with associated visual configurations and some Chinese examples.

TABLE 1. Basic stroke interactions

Interaction	Configuration	Example
None	I	二
Fixed anchoring	L	厂
Chaining	L	乚
Midpoint anchoring	T	丁
Crossing	X	乂
Ballistic	T	丄

3.2.2. *Basic Principles of Stroke Group Structure*

If stroke groups have syllable structure, their "nuclei" must be obligatory like those in spoken and signed syllables. If we adopt this hypothesis, then, we must view the smallest logically possible stroke groups, namely isolated (non-contacting) strokes, as consisting solely of a nucleus. This conclusion, consistent with the discussion in earlier sections, also links up with the observation that isolated full (non-dot) strokes tend to share axis with the nearest full stroke, as illustrated in (28): total assimilation in spoken and signed languages seems never to occur syllable-internally, only across syllables (e.g., vowel harmony).

(28) 二 刂 巜 彳 彡 巛 川

By the same reasoning, parallel strokes should represent separate syllables even if they make contact with the same stroke, as in (29). This too is consistent with the above discussion, where we saw that stroke contact of this type does not prevent curving or prominence, both diagnostics for separate stroke groups.

(29) 干 土 王 夫 牛 丌 廾 卅 井

In spoken syllables, nuclei are obligatory because they represent sonority peaks, making them a plausible candidate for the articulatory target of the entire syllable gesture. In articulatory experiments on American English speech, for instance, Browman and Goldstein (1988) found that the temporal duration remained relatively constant from the midpoint of an onset cluster to the nucleus in the same syllable, regardless of the size of the cluster. Speakers thus seem to work with a mental clock that is defined in terms of syllable-internal gestures. Nevertheless, as has often been noted (e.g., Prince and Smolensky, 2004), syllable inventories and prosodic processes both favor onsets and disfavor nucleus-initial syllables. It thus seems reasonable to suppose that when an onset is present (as it is most of the time), the timing of the nucleus depends on it rather than the other way around.

In T configurations, the onset analog would then be the stroke whose midpoint provides the starting point for the other, the analog of the nucleus. Only if the writer intends to write just one stroke is it conceptualized as a nucleus (this conceptual flip is possible because of the lack of intrinsic sonority in strokes). These analyses are sketched in (30), with O for onset and N for nucleus.

(30) a. ㇐ 丅
b. N ON (O = ㇐, N = 丨)

The proposed contrast can be made more explicit, as in Figure 2, using an autosegmental syllable model that includes moras. Here these structures are interpreted as stating that in T configurations, the location of the nucleus (μ) depends on that of the syllable as a whole (σ), which is assigned by the onset if present.

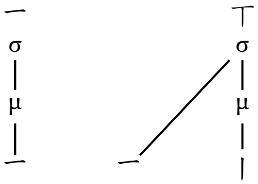


FIGURE 2. Autosegmental analyses of isolated stroke and T configuration

Since character components, as grammatical entities, are amodal, uniting motoric and visual aspects, we should not require that the sequence of strokes or stroke groups in analyses like Figure 2 must correspond with stroke order. Instead the order should be whatever makes the overall analysis the simplest. Thus even though the strokes and stroke order in the components in (31) are identical (left diagonal first), the strokes differ in interaction roles (i.e., which one provides the midpoint anchor). This allows us to express the contrast as in Figure 3, using the same strokes and abstract syllable structures, but different autosegmental links (the contrast is clearer in typefaces that mimic handwriting). As Myers (2019, Section 3.6.2) argues for numerous other reasons, stroke order should be considered part of the articulatory phonetics of character grammar, not part of character phonology per se (e.g., stroke order is surprisingly variable both within and across writers, while character form is much more stable).

(31) a. 人
b. 入

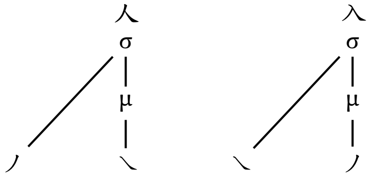


FIGURE 3. Autosegmental analyses of contrasting diagonal T configurations

The autosegmental framework allows us to express other types of stroke interactions as well. In contrast to the T configuration, the X configuration involves two strokes that share a single location. Conceptually, in producing a cross as in (32a), the writer is trying to place two strokes, with distinct axis features, in the same place. This situation may be codified as in (32b), as a single syllable with a short nucleus (N rather than NN), or more explicitly as in Figure 4, with the two strokes linked to a single mora.

(32) a. 十
b. N

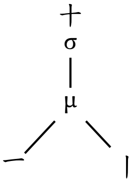


FIGURE 4. Autosegmental analysis of X configuration (crossed strokes)

Since parallel strokes can only appear in separate syllables, in more complex stroke combinations each T and X configuration must form a separate syllable as well, with the syllabic affiliations of the shared stroke(s) indicated through autosegmental association lines. The components in (33a), then, have the syllable structures represented linearly in (33b) (with syllable boundaries marked "."), and autosegmentally in Figure 5. The cross-syllable association lines are dotted to indicate that they do not actually intersect with the others; each syllable is meant to be lying in its own plane.

(33) a. 丌 廾 千 井
b. ON.ON N.N ON.N N.N.N.N

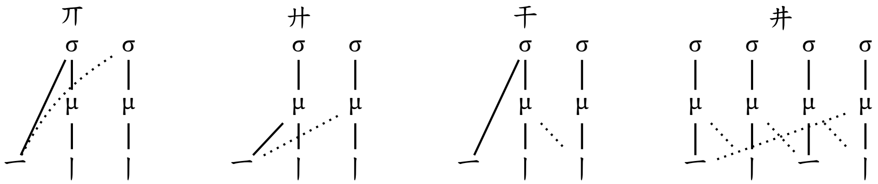


FIGURE 5. Autosegmental analyses of combinations of T and X configurations

One nice consequence of the analysis so far is that by treating the midpoint-anchored stroke in T configurations and crossed strokes in X configurations as nuclei (linked to moras), it puts them in the same class as isolated strokes. As we saw in section 2.3, strokes that are free at their endpoint (i.e., crossed or midpoint-anchored strokes) are subject to prominence and curving, just like isolated strokes. If prominence is an analog of stress and curving an analog of vowel reduction, it makes sense that both would be consistently realizable on the analog of the nucleus.

While midpoint anchoring involves a stroke-on-stroke dependency and crossing involves a symmetrical inter-stroke relationship, strokes sharing a fixed anchor refer to a point that is external to both. It is thus possible to see such strokes as sharing a single empty onset slot (for empty onsets in spoken language, see Marlett and Stemberger, 1983). This would make both strokes themselves into nuclei, as sketched in (34) and Figure 6, with the empty set symbol representing the featureless onset.

(34) a. 厂
b. ON.ON

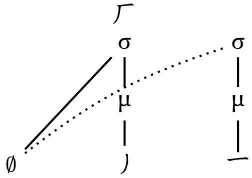


FIGURE 6. Autosegmental analysis of fixed anchoring

Even though the horizontal stroke in (34) starts from the vertical stroke, the latter is not itself an onset, but the nucleus (linked to a mora) in a separate syllable. This is why it may be curved (i.e., undergo a prosodic process akin to vowel reduction). A stroke undergoing left edge curving may also be crossed, as in (35), because crossing strokes are also moraic.

(35) a. 廾卅
b. 力九尹

However, if curved strokes are nuclei, they should be incapable of serving as the onset for midpoint anchoring, since onsets are linked directly to the syllable node and have no mora. Yet as the examples in (36) suggest, T configurations do sprout from curved strokes in a small number of components.

(36) 片月

Perhaps in such rare cases, the leftmost stroke is both the nucleus of one syllable and the onset for another, a situation that can indeed arise in spoken languages (see, e.g., Dell and Elmedlaoui, 1988). This would result in the linear analysis for two of the strokes in (37a) given in (37b), with the autosegmental structure as in Figure 7. Since curving itself is partly lexicalized (see section 2.3), perhaps this unusual syllable structure is as well.

(37) a. 片 (丿 ㇀ portion)
b. N.ON...

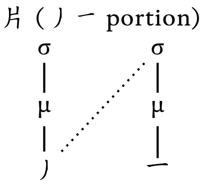


FIGURE 7. Autosegmental analysis of curved stroke offering midpoint anchoring

The next stroke interaction to consider is the chaining of simple strokes to form a complex stroke, as in (38) (these are all of the complex strokes that are also considered to be components by Chuang and Teng, 2009). Since complex strokes are still single strokes, they should be analyzed as comprising a single stroke group. The simplest analysis would thus be to treat all simple segments within a complex stroke as part of the nucleus, that is, as a separate mora.

(38) a. ㇄ ㇆ 匚 ㇇ ㇏
b. 乙 ㇉ ㇈

This analysis is illustrated linearly in (39) and autosegmentally in Figure 8. Note that by giving each stroke segment its own mora, we capture the observation that complex strokes tend to take up more space than the I, T, and X configurations, all of which are analyzed as monomoraic.

(39) a. 

b. NNN

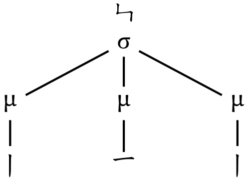


FIGURE 8. Autosegmental analysis of a complex stroke

Although trimoraic syllables like that posited above are rare in spoken languages, they are not impossible, and such complex strokes tend to be disfavored in Chinese character components as well; Chuang and Teng (2009) report lower type frequencies for the components in (38b) as compared with those in (38a).

The last stroke interaction to analyze is the ballistic interaction, where one stroke ends at another. Recall that this interaction is hard for children to learn and relatively rare in character components. If the ease and high frequency of fixed and midpoint anchoring relate to onsets being unmarked in syllables, the markedness of the ballistic interaction suggests that it may relate to the most marked syllable component, the coda, which is as disfavored in languages as the onset is favored (e.g., Prince and Smolensky, 2004). Crucially, the source of the markedness seems similar as well: like ballistic strokes, timing the coda properly requires planning ahead. For example, Browman and Goldstein (1988) found that while American English speakers coordinated the nucleus with the onset cluster as a whole, each of the individual coda consonants were coordinated separately with each other.

Not all end stroke contact is coda-like, however. Since the bottom-most stroke in (40a) undergoes prominence, it must be a separate stroke group, and thus cannot form the coda for the other strokes, even though there is a ballistic interaction. A similar conclusion applies in (41), given the larger size of the right-edge stroke. Such contact is thus posited to involve cross-syllabic coordination (like cross-syllabic assimilation in stroke axis), rather than syllable-internal structure. As promised earlier in section 3.2.1, then, what seem to be ballistic interactions in character components are often merely closely concatenated but separate stroke groups.

(40) a. 

b. ON.N

(41) a. 丩

b. NN.N

By contrast, as noted in section 3.1, the bottommost stroke in (42a) remains short because it is not free on its endpoint. Here, then, we have a plausible candidate for a coda analog, resulting in the syllable-final structure indicated in (42b), with a long nucleus (the complex stroke) plus coda.

(42) a. 口 (丨 ㇕ 一)

b. …NNC (㇕ 一)

A spot of bother is presented by the first stroke in this component. Even though the left edge stroke shares a fixed anchor with the complex stroke, a situation that we analyzed above as disyllabic sharing of a single empty onset, examples like that in (43) remind us that this entire complex can be subject to prominence, and thus must comprise a syllable as a whole. This forces us to treat the left edge vertical stroke as an onset, resulting in the analysis in (44), or in autosegmental terms in Figure 9. Perhaps this is justified because the left edge stroke is also unusual in another way: its endpoint defines the starting point of another stroke, but since they are not produced in sequence, these two strokes are not chained.

(43) 串

(44) a. 口

b. ONNC

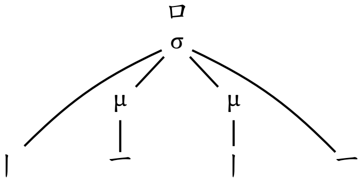


FIGURE 9. Autosegmental analysis of ballistic stroke in a box-shaped stroke group

Note that in Figure 9 I have linked the coda directly to the syllable node. This differs from the more common autosegmental representation for closed syllables (as in Figure 1 above), where the coda is linked to a mora (e.g., Hayes, 1989). Nevertheless, direct linking of the coda to the syllable node has also been argued for in spoken phonology (e.g., Tranel, 1991). While this representation implies that the nucleus and coda do not form a constituent (the rime), syllables need not have rimes; sign languages have syllables (Sandler, 2008; Sandler and Lillo-Martin, 2006) but I am unaware of any argument that they have rimes, and even some spoken languages provide at best only weak evidence for them (Berg and Koops, 2010).

Moreover, directly linking the coda to the syllable is needed here to avoid ambiguities in interpretation. We have already decided that each of the simple segments in a complex stroke links to its own mora, so giving the coda a mora here would falsely imply a three-segment complex stroke. Alternatively, letting it share the mora with a nuclear stroke would falsely imply crossed strokes. This analytical situation ultimately arises from the lack of intrinsic stroke sonority, which forces the moraic structure itself to do all of the work.

The non-moraic coda hypothesis does have some advantages, however. One is that it helps capture the fact that the ballistic stroke not only ends at another stroke, but also starts at another, namely the leftmost stroke that we analyze as the onset. By linking both the onset and coda to the same node (σ) we imply that they share a location as well. Indeed, as we saw earlier in section 3.2.1, ballistic strokes often start at a leftmost vertical stroke; further examples are given in (45).

(45) 尸 日 目 月

Another advantage is that the non-moraic coda keeps the stroke group small, as with the I, T, and X configurations, in contrast to the the polymoraic representations posited for the larger complex strokes. This point is illustrated by the compact components in (46).

(46) a. 日 目
b. ONNCC ONNCCC

The analysis also merges naturally with the one given above for curved strokes that act as midpoint anchors. As shown in the autosegmental representation of (47) given in Figure 10, it is straightforward to indicate that this stroke performs double duty as nucleus of one syllable and onset for another.

(47) a. 月
b. N.ONNCC

The autosegmental analysis of stroke sharing introduced in (33) and Figure 5 also allows us to treat the two box-shaped structures in (48) as separate stroke groups, necessary to explain how only the lower one is subject to prominence; see Figure 11.

(48) a. 㠯 (as in 官)
b. ONNC.ONNC

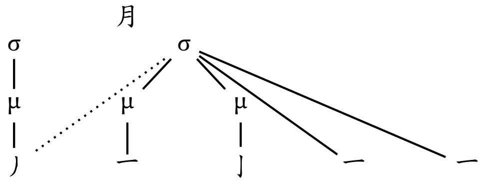


FIGURE 10. Autosegmental analysis of a ballistic stroke starting from a curved stroke

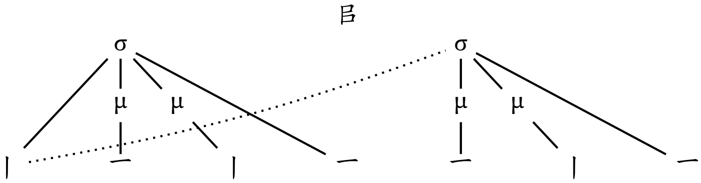


FIGURE 11. Autosegmental analysis of onset stroke shared by two box-shaped stroke groups

The coda analysis also seems appropriate for box-like structures containing a ballistic stroke but missing one or more sides. For example, the top portion of the component in (49a) seems analyzable as indicated by the underlined portion of (49b), where the onset is the curved vertical stroke at the left, the nucleus is the horizontal stroke starting from it (completing the T configuration), and the coda is the short vertical stroke at the upper right that makes endpoint contact.

(49) a. 片
b. N.$\underline{\text{ONC}}$.ONN

Ballistic strokes may appear in onsetless syllables as well, however. The cases in (50) can be analyzed in terms of cross-syllable contact between two nuclei rather than a coda (as in (40) and (41) above). Namely, in (50a) and (50b) the contacted stroke is prominent (lengthened) and reduced (curved), respectively, both hallmarks of independent stroke groups.

(50) a. 爿 止
b. 非

The cases in (51), however, do not show clear signs of the contacted stroke being in a separate syllable. For example, the character in (51c) contains two Chuang and Teng (2009) components, where that on the left (which lacks a Unicode entry) has two ballistic strokes ending at a vertical stroke and that on the right has one ballistic stroke running leftward and downward into the vertical segment of a complex stroke. In none of these cases is there clear prominence or curving in the stroke providing endpoint contact.

(51) a. 彐臼
b. 雪 (bottom component)
c. 北

In such cases, linking the coda strokes to the syllable node does not imply that it starts at the onset, simply because there is no onset, as indicated in (52) and Figure 12.

(52) a. 北 (left component)
b. NCC

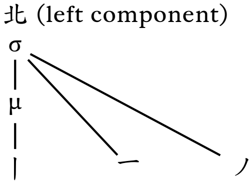


FIGURE 12. Autosegmental analysis of ballistic strokes without starting point contact

It should be clear by now that our neat inventory of basic stroke interactions cannot hope to cover all of the attested interactions that arise as the number and complexity of strokes increases. Changizi, Zhang, Ye, and Shimojo (2006) managed to restrict the scope of their investigation to just 36 visual configurations by imposing a maximum of three strokes, and then restricted it further by considering topology rather than geometry. By contrast, the Chuang and Teng (2009) inventory has 441 geometrically distinct Chinese character components containing up to 17 strokes.

Unsurprisingly, then, from now on the analytical problems and attempted technical fixes come fast and furious, so before continuing I offer the reader a last peaceful moment in the form of Table 2, which summarizes the proposed syllable structures for various types of simple stroke interactions.

TABLE 2. Basic stroke interactions

Interaction	Example	Syllable structure
None	二	N.N
Fixed anchoring	厂	ON.ON
Chaining	乚	NN
Midpoint anchoring	丁	ON
Crossing	乂	N
Ballistic to prominent/curved stroke	丄	N.N
Ballistic to non-prominent/curved stroke	口	...NC

3.2.3. *More Complex Stroke Interactions*

Space (fortunately) precludes a complete analysis for each and every character component, and the complex ways in which strokes can interact (unfortunately) precludes a particularly coherent overview. Thus I will merely illustrate a few cases, from what seems to me to be the least to the most problematic.

I start with crossed complex strokes, as in (53). At first it seems it may be hard to specify the precise location of the crossing, but as seen in Figure 13, we can easily code the two complex strokes via bimoraic syllables and the crossing via association lines linking the appropriate simple strokes to a single mora.

(53) a. 乜
b. NN.NN

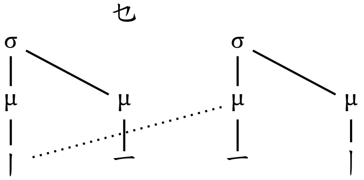


FIGURE 13. Autosegmental analysis of crossed complex strokes

A slightly trickier situation arises in (54), where a complex stroke not only crosses another stroke, but also shares its starting point. Consistent with the analyses in section 3.2.3, the two strokes must thus also share an empty onset slot, as in Figure 14.

(54) a. 又
b. ON.ONN

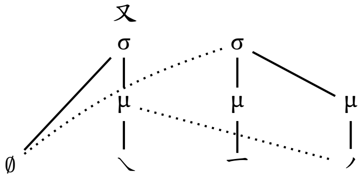


FIGURE 14. Autosegmental analysis of crossing strokes sharing a starting point

In section 3.2.3 we saw that left edge curved strokes, hypothesized to be syllable nuclei, can nevertheless provide the starting point in midpoint anchoring, forcing us to treat them as onsets as well. A similar ambiguity in syllable position arises with complex strokes. Even though each segment in a complex stroke is moraic, it is still possible for a segment to offer midpoint anchoring, as in (55) (the third example contains two Chuang and Teng, 2009, components because the relevant component has no Unicode entry). Autosegmentally this can be handled by doubly linking the segment that serves both as anchor and as part of the complex nucleus, as in Figure 15.

(55) a. 刀 乃 与
b. NN.ON NNNN.ON (N.)NNN.ON

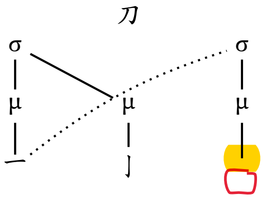


FIGURE 15. Autosegmental analysis of midpoint anchoring from a complex stroke

As we already saw in the previous section, some of the greatest challenges come from the analysis of ballistic strokes, since while by definition they end at another stroke, they typically also start from another stroke, making their position within the stroke group analytically ambiguous. As illustrated in (56), the starting point may even be the first segment of a complex stroke.

(56) a. 皿 (丨 ㇆ 丨 丨 ㇐)
b. 罒 (丨 ㇆ 丨 丨 ㇐)

Conveniently, the prominence of the bottom stroke in (56a) shows that it is a separate stroke group. We have also already just seen that midpoint anchoring from one segment of a complex stroke can be analyzed as an onset-nucleus structure (here repeated twice, one per internal stroke). All of these considerations lead to the linear analysis in (57) and autosegmental representation in Figure 16. Aside from the highly counterintuitive idea that such a small component could really contain so many stroke groups, there is no technical problem yet.

(57) a. 
b. ON.ONN.ON.ON.N

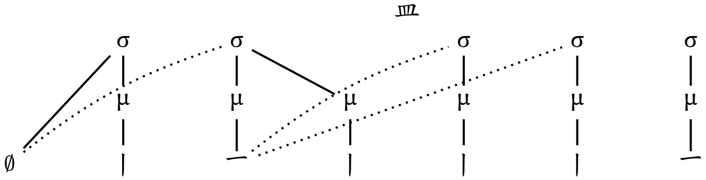


FIGURE 16. Autosegmental analysis of midpoint anchoring from a complex stroke

The component in (56b), however, appears to be a single box-shaped stroke group. We are thus obliged to somehow represent the anchoring of the two internal strokes from the top right complex stroke while still recognizing them as ballistically ending at the bottommost stroke within the same syllable. While it is trivial to give it the same linear analysis as we did for its rotated counterpart, as in (58), the autosegmental representation in Figure 17 seems to falsely imply that two of the coda strokes start at the left stroke (since they all directly link to the syllable node), whereas actually only one of them does (namely the stroke forming the box bottom). Perhaps we could stipulate that if onsets and codas are identical stroke types they cannot be interpreted as linked together; stroke contact requires a difference in axis. Even so, this analysis has the additional counterintuitive effect of giving this component a totally different structure from the virtually identical component in (57).

(58) a. 罒 目
b. ONNCCC ONNCCC

A particularly striking example of the challenges posed by my analysis of ballistic strokes as coda-like is the component in (59a), which contains two horizontal ballistic strokes linking two vertical ones (plus a fifth forming the bottom of the box). The T configuration at the top is readily analyzed as ON, but simply concatenating all five ballistic strokes as codas, as in (59b), fails to indicate which stroke links with which. Nevertheless, given that the lower box seems prominent as a whole, the

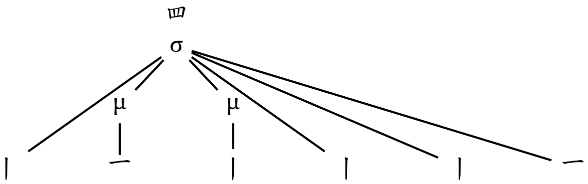


FIGURE 17. Autosegmental analysis of ballistic stroke in a box-shaped stroke group

treatment here of it as a single stroke group does at least capture that prosodic observation. Moreover, the oddity of this type of situation is correlated with its rarity in the Chuang and Teng (2009) inventory.

(59) a. 面
b. ON.ONNCCCCC

The component family in (60) raises further problems (those in (60e-f) are not in the Chuang and Teng, 2009, component inventory but are included for completeness).

(60) a. 田
b. 由
c. 甲
d. 申
e. 甴
f. 曱

The box seems to form a single stroke group because in (60b-c) it is the target of bottommost prominence, with the extended stroke as a separate stroke group. That makes the internal horizontal stroke part of the same stroke group as the box, and thus a coda, as in earlier analyses. The problem is that this stroke is also crossed, which means it is moraic, but codas cannot be moraic (or else the autosegmental representations become ambiguous, as discussed earlier).

One way to respond to this challenge is to start with the supposition that the box-shaped stroke group is actually that in (61a), as analyzed in (61b), whereas the central vertical stroke is a separate stroke group in all cases, including in (60a). The crossing problem can then be dealt with by treating crossing here as a mere accident of the central vertical stroke's starting and ending points, rather than being something represented phonologically. This seems counterintuitive given the high salience of the cross, but if the coiners of (60e-f) were able to decompose it, doing so is not impossible.

(61) a. 日
b. ONNCC

This now merely leaves us with the challenge of representing the vertical stroke's position within the formal straightjacket I have set myself. Across the components in (60), the starting point of this stroke is variously above the box, at the top of the box, or at the central horizontal stroke, which can be represented respectively as an onsetless syllable, as a syllable with the onset in the first segment of a complex stroke (as in (55) and Figure 15 above), and as a syllable with the onset at the box's first coda stroke. The ending point of the vertical stroke is variously at the central horizontal stroke, at the bottom of the box, or below the box, which can be represented respectively as sharing a coda with the box's first coda stroke, as sharing a coda with the box's final coda stroke, or as being a codaless open syllable. None of these possibilities raises any fatal problems, as sketched in (62) and (63), with subscripts to indicate the cross-syllable autosegmental linking. Figure 18 spells out the idea for one component.

(62) a. 田 甲 甲
b. $ON_1NCC_2.O_1NC_2$ $ON_1NCC.O_1N$ $ONNC_1C.O_1N$
(63) a. 申 由 由
b. $ONNCC.N$ $ONNCC_1.NC_1$ $ONNC_1C.NC_1$

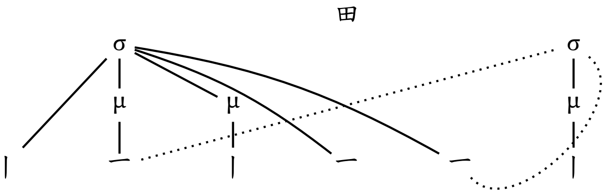


FIGURE 18. Autosegmental analysis of ballistic stroke in a box-shaped stroke group

Another challenging component family is that in (64). In the first component, the lower complex stroke shares its start with the ballistic stroke, which can be expressed via a shared autosegmental link between the first stroke group's coda and the second stroke group's onset, as indicated by the coindexing; note that neither onset nor coda is moraic, so there is no risk of misinterpreting the shared link as stroke crossing. In the second component, a single onset is shared between the upper and lower complex strokes. In the third component, neither complex stroke has an onset; the ballistic stroke does, but the representational scheme does not allow me to represent it unambiguously so I leave it out, as I did with the crossed strokes in the previous component family. While hardly an ideal solution, at least all of these representations show the lower complex stroke as forming a separate stroke group, allowing it to be subject to bottommost prominence.

(64) a. 己 巳 已
b. $\mathrm{NNC_1.O_1NN}$ $\mathrm{O_1NNC.O_1NN}$ NNC.NN

I end my survey with an analysis of the most complex component in the Chuang and Teng (2009) inventory, that in (65a). Figure 19 indicates schematically which component parts correspond to which of the stroke groups listed in (65b).

(65) a. 龜
b. ONN.NNC.NNC.NNC.ONNCC.ONC.N.ONN

FIGURE 19. Sketch of a stroke group analysis of the most complex component

While no utterly fatal problems have arisen in this survey, we have needed a plethora of special devices (if not special pleading), some of which have yielded counterintuitive results. More importantly, I have yet to provide any argument that any of this matters to actual readers or writers. Collecting proper psycholinguistic data will have to await the proverbial future research, but in the next section I do examine one possible psychological implication of the stroke-group-as-syllable analysis.

3.3. Stroke Groups and Menzerath's Law

A demonstration that stroke groups, as I have identified them, conform to the Menzerath-Altmann law would be consistent with the claim that they influenced the evolution of characters into their modern forms. The modeling work here is based on syllabic analyses for all 441 components of Chuang and Teng (ibid.)[2]. The analyses are based on component forms as they appear in Chuang and Teng's regular (handwriting

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[2] The data are available at `https://osf.io/nbhcm/`.

style) typeface. A variety of analytical decisions are scattered throughout, and I am not entirely sure if I have applied all of my principles completely consistently, but hopefully this merely added noise and not bias.

If stroke groups have some validity, we expect that within character components, there should be an inverse power relationship between mean stroke group complexity and the number of stroke groups. To test this, I operationalized stroke group complexity as the number of O, N, C segments in the linear syllabic analyses, where N represents a mora and O and C represent simple strokes without a mora. Autosegmental lines are not counted.

Following Prün (1994), Figure 20 shows the nonlinear best-fit for the simplified Menzarath equation in (66a), with the model parameters and other statistical values shown in (66b).

(66) a. $y = ax^b, b < 0$
b. $a = 2.44, b = -0.19, p_b < .0001, R^2 = .82$

The coefficients are of the expected signs (positive a, negative b) and statistically significant; here I highlight p_b, the p value for b, which confirms that this is an inverse power function (against the null hypothesis $b = 0$). However, the data points are much more scattered than in other applications of Menzerath's law to Chinese script. Again following Prün (ibid., p. 149), I quantified model fit using the coefficient of determination R^2 (Prün labels it D). As shown in (66b), this value is relatively high but still far below the R^2 =.99 reported by Prün (ibid.) for component complexity in characters.

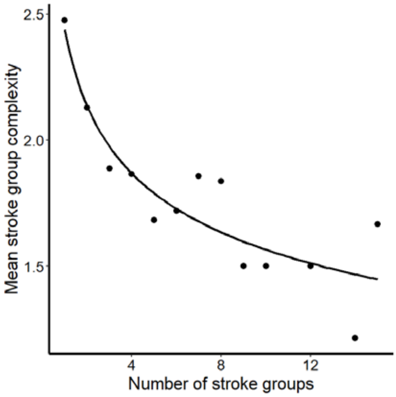

FIGURE 20. Mean stroke group complexity as a function of the number of stroke groups

While the less than perfect fit may relate to inconsistencies in how stroke groups were identified, could the fact that there is any fit at all be dismissed as confounding with other factors known to obey Menzerath's law? In particular, Bohn (1998) demonstrated an inverse power relationship between mean stroke complexity and stroke number within character components. In my analyses, isolated and crossed simple strokes are the simplest possible stroke groups (N), whereas complex strokes are necessarily more complex (NN...). Thus it could be that Figure 20 merely recapitulates Bohn's analysis in an obscured form.

The ideal way to rule this out would be to build a model that also includes stroke number and stroke complexity as interacting factors, but statistical interaction is only well defined for (generalized) linear models, not the nonlinear model that I used to fit the power law. However, it is still possible (as well as conceptually simpler and less assumption-prone) to build separate nonlinear models for multiple subsets of the data, in each of which stroke number and complexity are held constant. If Menzerath's law still applies in each of the subsets, this cannot be ascribed to stroke number or complexity.

This I did for eight subsets of components with two to five strokes, where the mean stroke complexity (as defined by Bohn, 1998, where hooks add complexity) was either 1 or higher than 1 (ranging from 1.2 to 3); outside these ranges the subsets were too small, falling below ten data points per subset. These subsets still cover the majority of the total data (over 65%). As can be seen in Table 3, all of the subsets are consistent with an inverse power law, though not all are statistically significant or show very strong model fits.

TABLE 3. Menzerath's law across subsets of character components

	Mean stroke complexity = 1 Stroke number				Mean stroke complexity > 1 Stroke number			
	2	3	4	5	2	3	4	5
a	1.64	2.84	3.88	2.51	3.00	3.76	5.06	6.06
b	−0.57	−0.97	−1.02	−0.44	−0.56	−0.84	−0.84	−0.86
p_b	0.013	<0.0001	<0.0001	0.23	0.0001	<0.0001	<0.0001	<0.0001
R^2	0.30	0.49	0.59	0.14	0.27	0.41	0.72	0.76

The results thus add some (weak) support for the claim that stroke groups may be psychologically real, or at least were while characters were evolving.

4. Conclusions

There is no doubt that Chinese character components and strokes are psychologically real levels of structure. It is also relatively easy to see components as analogous to morphemes and strokes as analogous to phonological segments. The evidence for an intermediate syllable-like level, the stroke group, is nowhere near as strong, but this initial exploration has nevertheless uncovered some interesting patterns. Compared with the list of syllable properties in (19) above, the stroke group scorecard in (67) suggests that there may indeed be some genuine similarities with syllables, as marked in italics.

(67) a. In a stroke group, there is no analog to intrinsic sonority.
b. There is as yet no evidence that stroke groups are perceptually salient.
c. *Stroke groups are targeted by analogs to foot-level processes like stress.*
d. *Articulatory gestures are more closely coordinated within than across stroke groups.*
e. *Stroke groups may have analogs to obligatory nuclei, favored onsets, and disfavored codas.*
f. *Stroke groups compete for space in character components (Menzerath's law).*

Future research can take many possible directions. The most fundamental question is whether the syllable analogy is really needed to preserve whatever is genuine in the stroke group hypothesis. After all, even in sign language phonology there have been arguments that what most linguists consider to be syllables may actually be more analogous to complex segments (Channon, 2003). Another issue is how to extend the present analysis to the many writing systems that, unlike Chinese script, have strongly curved strokes, including circles, semicircles, and loops; among these are systems historically derived from Chinese, like Japanese hiragana. Previous analyses of Roman letters have considered curved strokes (e.g., Watt, 1980; Primus, 2004), and van Sommers (1984) includes a chapter-length discussion of the production of curvilinear forms. Still, circle-like strokes do complicate matters, particularly since they allow two strokes to contact each other in more than one place, a possibility we did not have to worry about when analyzing Chinese script. In my opinion, however, most urgently needed is the collection of psycholinguistic evidence that writers and readers actually do learn or process characters in terms of stroke groups.

Regardless of how research progresses, I hope this preliminary study has at least revealed the rich and challenging nature of a still under-explored aspect of writing systems: the precise formulation of stroke interactions.

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