Natural scene statistics and the structure of visual signs over human history

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TWO PARTS, I and II

0. General motivation for *visual linguistics.*

I. Natural scene statistics and shapes of visual signs.

II. Combinatorial structure of letters.

PART 0

General motivation for
visual linguistics

	Laboratory	Natural production
Cognition		

	Laboratory	Natural production
Cognition	Cognitive psychology	

	Laboratory	Natural production
Cognition	Cognitive psychology	Linguistics

	Laboratory	Natural production
Cognition	Cognitive psychology	Linguistics
Vision		

	Laboratory	Natural production
Cognition	Cognitive psychology	Linguistics
Vision	Visual psychophysics	

	Laboratory	Natural production
Cognition	Cognitive psychology	Linguistics
Vision	Visual psychophysics	?

	Laboratory	Natural production
Cognition	Cognitive psychology	Linguistics
Vision	Visual psychophysics	*Visual linguistics*

Visual linguistics

Study of the relationship between the
visual system and human-produced visual signs.

Two visual linguistics research directions thus far…

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(1) Why visual signs are shaped the way they are.
- Are there any regularities in the shapes found in human-produced images?
- Why are letters and other visual symbols shaped the way they are?
- Ecological explanation/natural statistics.

Two visual linguistics research directions thus far…

(1) Why visual signs are shaped the way they are.
- Are there any regularities in the shapes found in human-produced images?
- Why are letters and other visual symbols shaped the way they are?
- Ecological explanation/natural statistics.

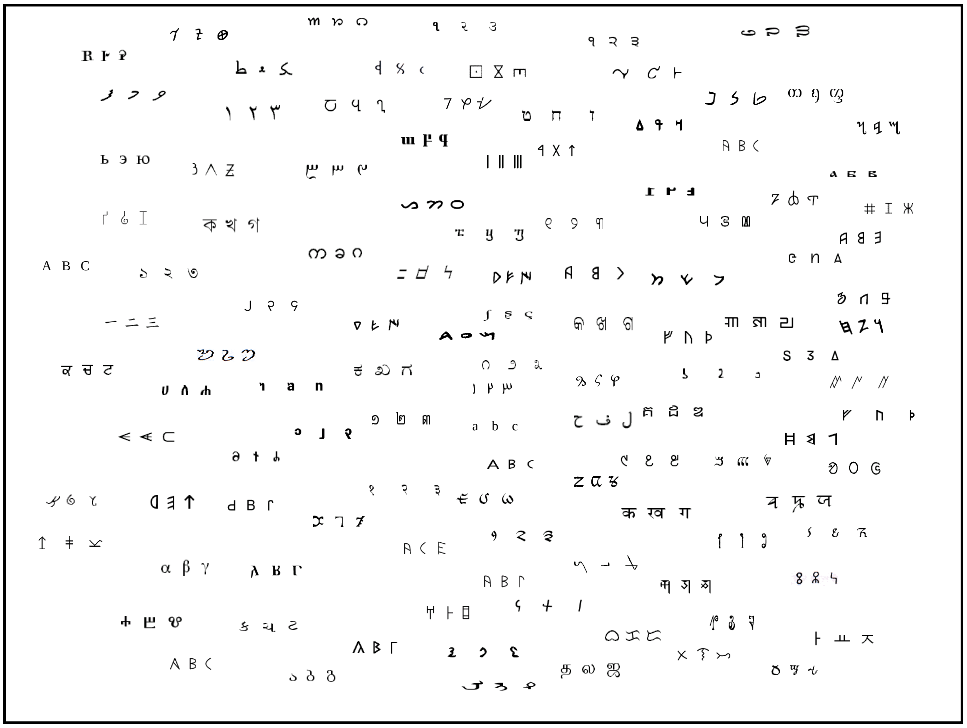
(2) The complexity and redundancy of writing systems.
- How many strokes per letter?
- How combinatorially do strokes combine into letters?
- How redundant?
- Are there laws across the hundreds of writing systems over history?
- Does the visual system prefer these settings? If so, why?

PART I

Natural scene statistics and
shapes of visual signs

PART I

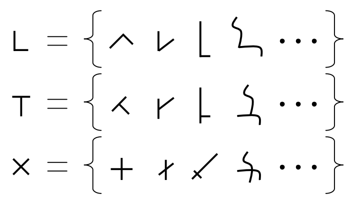
Natural scene statistics and
shapes of visual signs
…*or*…
Why visual signs are
shaped the way they are.



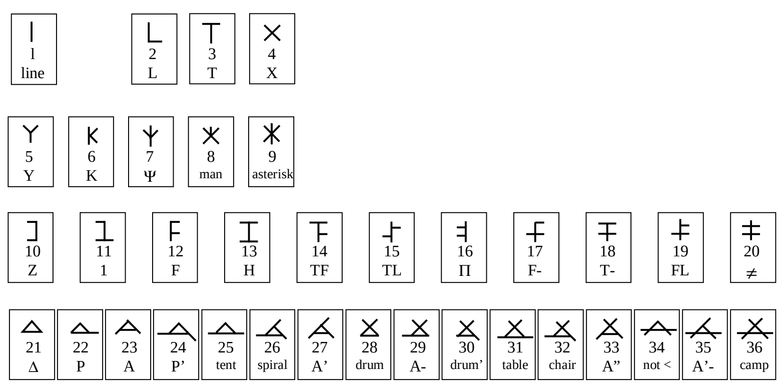
My ecological hypothesis

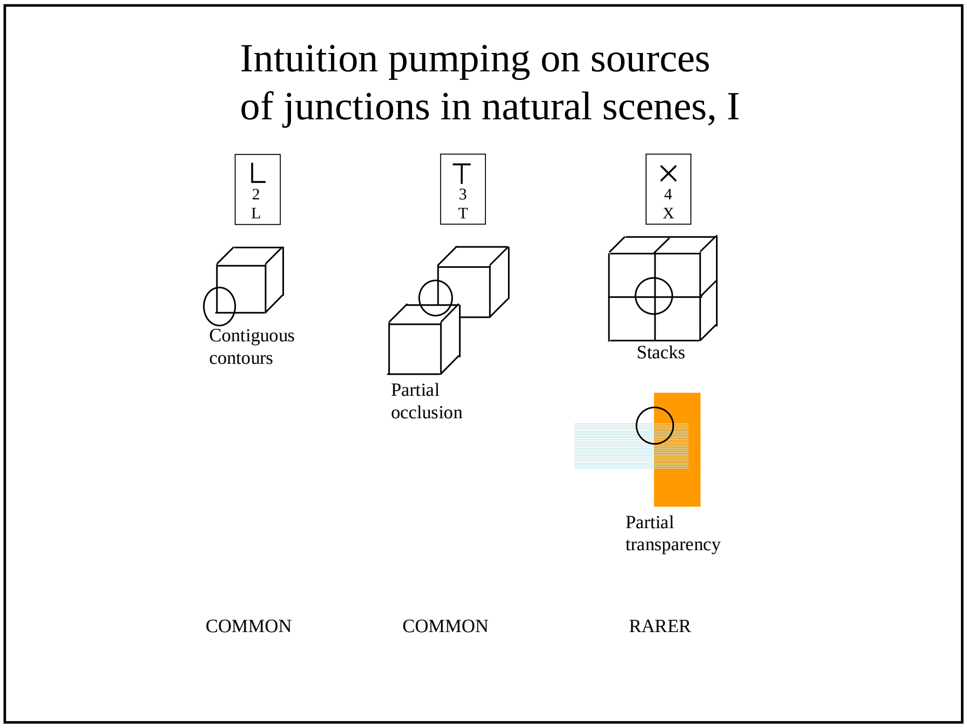
The configurations of strokes found in writing systems are selected to match the configurations of contours found in natural scenes, because that is what the visual system is good at processing.

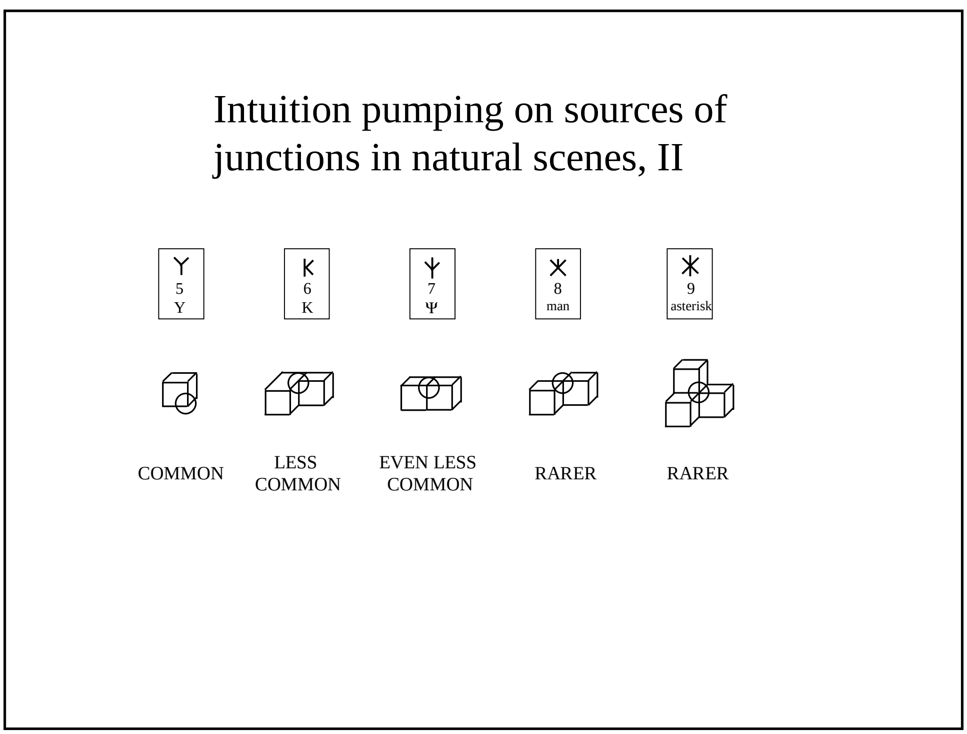
What I mean by “shape”: *configurations*



All the possible configuration types

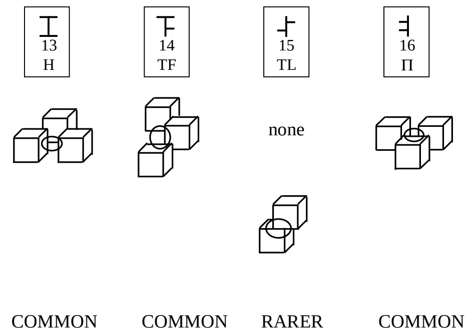



Intuition pumping on sources of junctions in natural scenes, I
2
L
3
T
4
X
Contiguous contours
Partial occlusion
Stacks
Partial transparency
COMMON
COMMON
RARER


Intuition pumping on sources of junctions in natural scenes, II
5
Y
6
K
7
Ψ
8
man
9
asterisk
COMMON
LESS COMMON
EVEN LESS COMMON
RARER
RARER

Intuition pumping on sources of junctions in natural scenes, III

Occlusion interpetation:



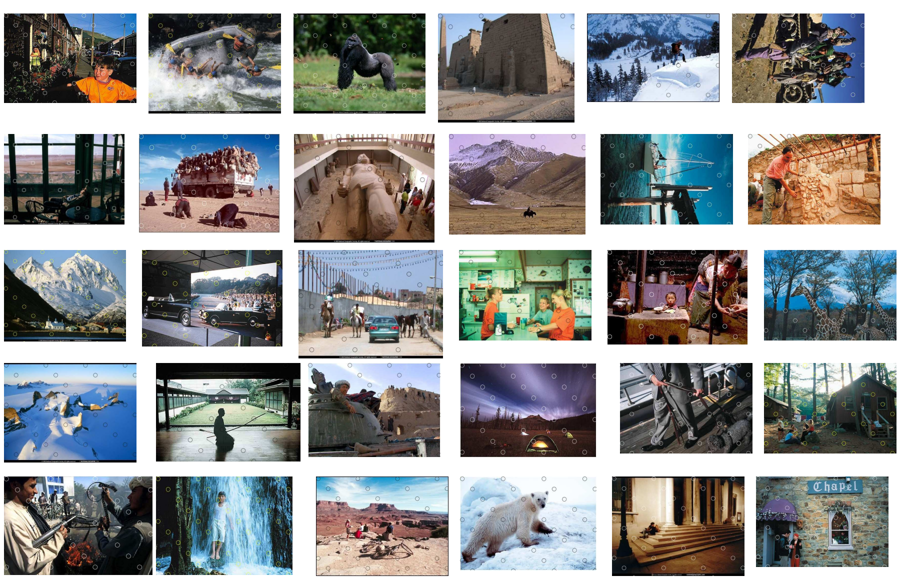
ECOLOGICAL PREDICTION

(a) Natural scene measurements

(b) Semi-a-priori predictions

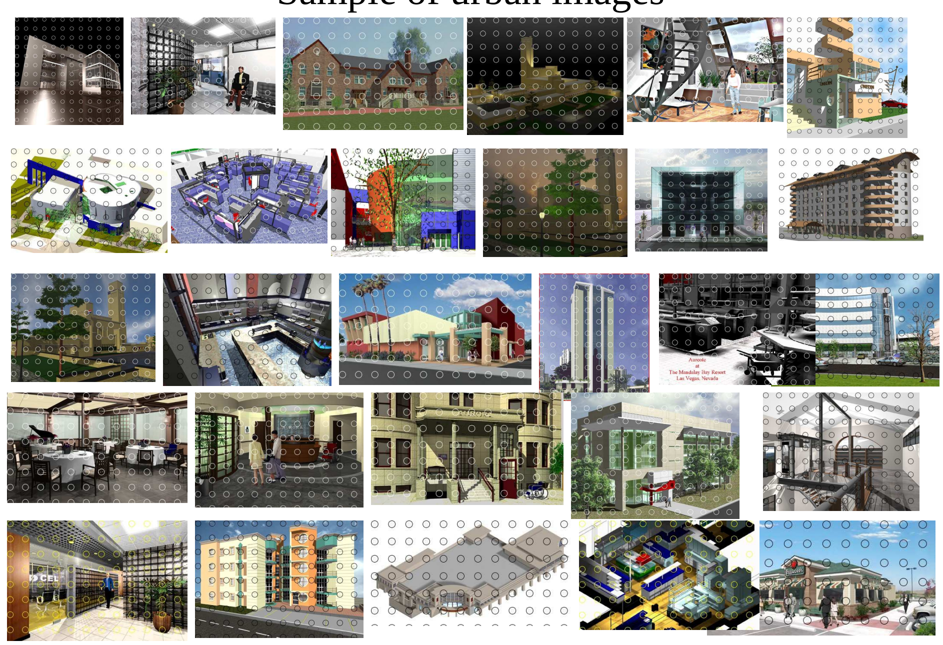
(a) Predictions from natural scene measurements

Sample of rural images

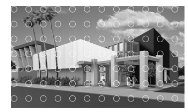


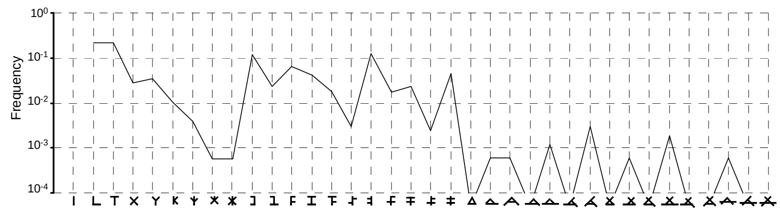
Configuration spectrum
for *rural* images

Sample of urban images

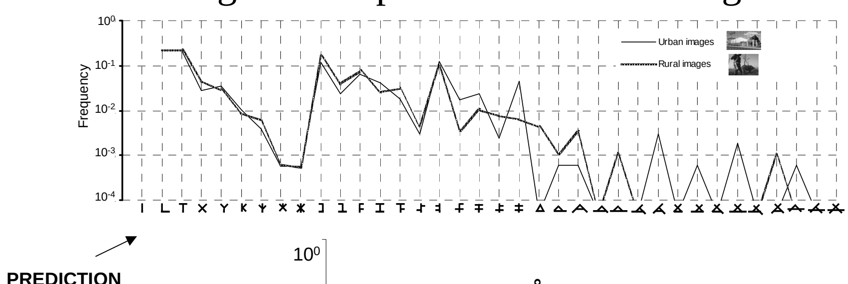


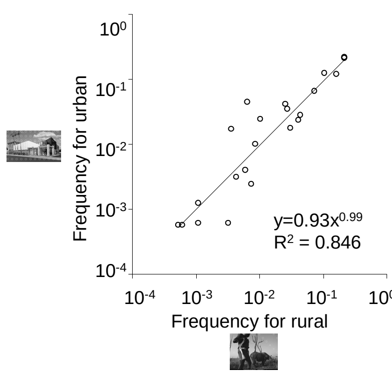
Configuration spectrum for *urban* images



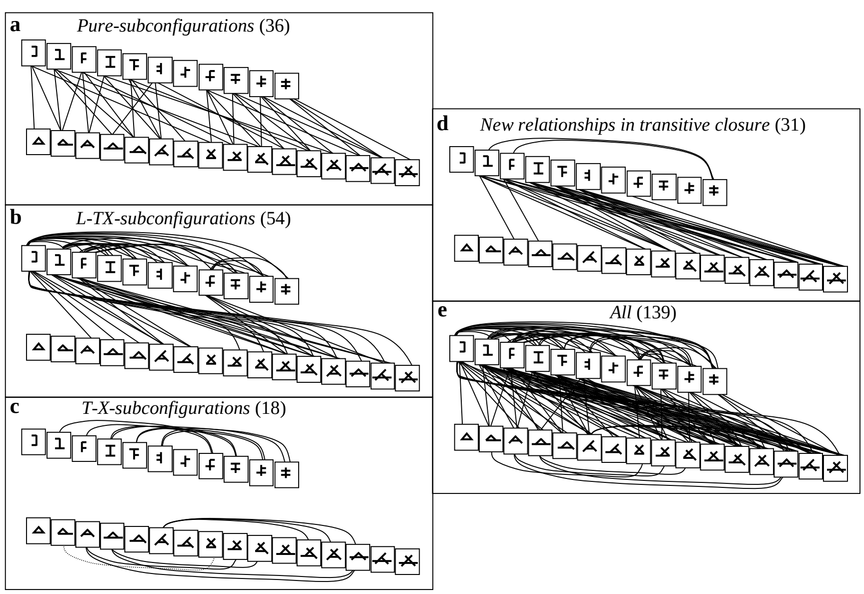


Configuration spectra for natural images





(b) Predictions from a semi-a-priori analysis



(40% of the 351 potential)

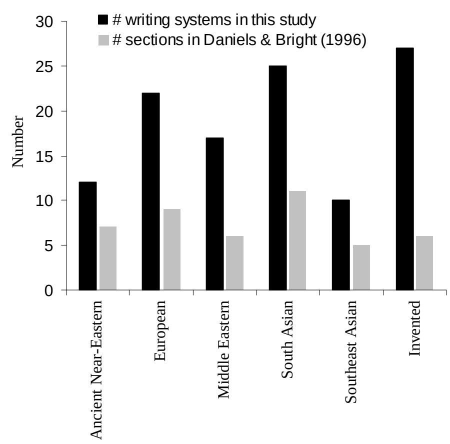
DATA

(1) Characters from 115 non-logographic writing systems.

(2) Thousands of Chinese (logographic) characters (Manser et al., *Pocket Oxford Chinese Dictionary*, 2003)

(3) Thousands of non-linguistic symbols (Dreyfuss, *Symbol Sourcebook*, 1972)

The non-logographic writing systems…

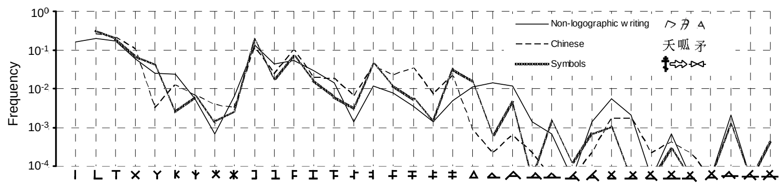


The non-logographic writing systems…

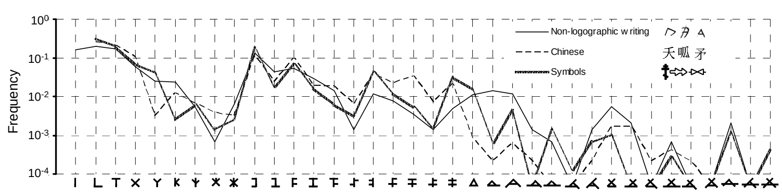
	Name, and sample characters	Kind of system	Date	Phylogeny	avg char length L	number of stroke types B	number of characters C	total # edges δ
1	Ahom	abugida	1250	Brahmi -->	2.40	26	40	68
2	Albanian (Elbasan)	alphabet	1750	Invented: unknown	2.60	32	53	82
3	Ancient Berber (Vertical)	abjad	-150	Punic -->	2.68	12	25	23
4	Arabic	abjad	512	Aramaic --> Nabataean -->	2.63	19	35	36
5	Arabic	numeral	512	Aramaic --> Nabataean Aramaic -->	2.00	10	10	13
6	Aramaic	abjad	-900	Phoenician -->	2.68	11	22	25
7	Armenian (Eastern)	alphabet	405	Invented: Mesrop-Mashtots	2.21	24	39	42
8	Asomtavruli	alphabet	430	Greek -->	2.42	25	38	52
9	Avestan	alphabet	250	Aramaic --> Psalter and Old Pahlavi -->	2.42	35	53	77
10	Bassa	alphabet	unknown	Invented: unknown	2.37	24	30	38
11	Batak (Kara Batak)	abugida	1350	Brahmi --> Pallava --> Old Kawi -->	2.15	13	33	33
12	Bengali	abugida	1050	Brahmi --> Devanagari -->	3.91	29	45	113
13	Bengali	numeral	1050	Brahmi --> Devanagari -->	1.80	14	10	15
14	Brahmi	abugida	-450	Aramaic -->	2.14	24	43	51
15	Buhid (Mangyan)	abugida	1350	Brahmi --> Pallava --> Old Kawi -->	3.78	5	18	12
16	Burmese	abugida	1150	Brahmi --> Mon -->	2.51	29	41	85
17	Burmese	numeral	1150	Brahmi --> Mon -->	1.40	10	10	6
18	Carrier (Dene)	syllabary (rotating)	1885	Invented: Father Adrien-Gabriel Morice	3.20	61	180	68
19	Celtiberian	alphabet (syllabic)	-550	Punic --> Iberian -->	3.29	9	28	36
20	Cherokee	syllabary	1819	Invented: George Guess	2.35	51	85	102
21	Chinese	numeral	-1150	unknown	3.00	6	10	13
22	Cypriot	syllabary	-800	Linear B -->	3.84	19	55	68
23	Cyrillic (Abkhaz)	alphabet	950	Greek --> Old Church Slavonic -->	3.69	19	62	42
24	Dehong	abugida	1050	Brahmi --> Sinhala -->	3.39	13	33	40
25	Dehong	numeral	1050	Brahmi --> Sinhala -->	1.90	11	10	12
26	Deseret	alphabet	1850	Invented: George D. Watt	1.68	27	38	34
27	Devanagari	abugida	1050	Brahmi -->	3.27	30	45	83
28	Devanagari	numeral	1050	Brahmi -->	1.40	13	10	8
29	Dives Akuru	abugida	1200	Brahmi --> Sinhala -->	3.77	21	23	31
30	Enochian	alphabet	1580	Invented: Dr. John Dee and Sir Edward Kelly	2.52	19	21	37
31	Ethiopic (Ge'ez)	abugida	350	Southern Linear --> Sabaean/Minean -->	2.63	20	40	41
32	Etruscan (archaic)	alphabet	-750	Greek -->	2.91	11	23	25
33	Faliscan	alphabet	-650	Greek --> Etruscan -->	2.52	15	21	32
34	Fraser	alphabet	1915	Invented: James Ostram Fraser	2.37	17	41	36
35	Glagolitic	alphabet	860	Greek -->	4.51	22	41	95
36	Gothic (Wulfila)	alphabet	350	Greek -->	2.32	17	25	37
37	Greek α β γ	alphabet	-750	Phoenician -->	1.71	21	24	24
38	Gujarati	abugida	1592	Brahmi --> Devanagari -->	2.21	32	42	63
39	Gujarati	numeral	1592	Brahmi --> Devanagari -->	1.50	13	10	10
40	Gurmukhi	abugida	1550	Brahmi -->	3.20	31	46	93
41	Gurmukhi	numeral	1550	Brahmi -->	1.90	12	10	11
42	Hanuno'o (Mangyan)	abugida	1350	Brahmi --> Pallava --> Old Kawi -->	3.13	13	16	34
43	Hebrew	abjad	-125	Aramaic -->	2.55	18	33	30
44	Hindu-Arabic 1 2 3	numeral	700	Brahmi -->	1.60	9	10	9
45	Hungarian Runes	alphabet	1000	Aramaic --> Sogdian --> Turkic -->	3.08	12	40	34
46	Hungarian Runes	numeral	1000	Aramaic --> Sogdian --> Turkic -->	2.50	4	6	12

	Name	Kind of system	Date	Phylogeny	avg char length L	number of stroke types B	number of characters C	total # edges δ
47	Iberian (northern)	alphabet (syllabic)	-1000	Punic -->	3.46	11	26	27
48	Iberian (southern)	alphabet (syllabic)	-1000	Punic -->	3.14	11	22	30
49	International phonetic	alphabet	1847	Invented: Isaac Pitman and Henry Ellis	2.42	47	170	119
50	Kannada	abugida	550	Brahmi -->	2.79	34	47	92
51	Kannada	numeral	550	Brahmi -->	1.00	10	10	0
52	Kharoshthi	abugida	-450	Aramaic -->	1.72	30	39	44
53	Kharoshthi	numeral	-450	Aramaic -->	1.88	7	8	11
54	Khmer	abugida	611	Brahmi --> Pallava -->	7.49	33	68	70
55	Khmer	numeral	611	Brahmi --> Pallava -->	3.70	14	10	30
56	Korean (Hangeul)	alphabet	1446	Invented: King Seycong	2.83	8	24	19
57	Kpelle	syllabary	1930	Invented: Chief Gbili	3.07	74	88	198
58	Latin, ancient	alphabet	-650	Greek --> Etruscan -->	2.67	10	21	25
59	Latin, modern a b c	alphabet	1600	Greek --> Etruscan --> ancient Latin -->	2.08	14	26	33
60	Latin, modern all-caps A B C	alphabet	1600	Greek --> Etruscan --> ancient Latin -->	2.50	17	26	41
61	Lepcha (Rong)	abugida	1720	Brahmi --> Devanagari --> Tibetan -->	2.68	44	77	95
62	Lepcha (Rong)	numeral	1720	Brahmi --> Devanagari --> Tibetan -->	2.60	15	10	27
63	Limbu	abugida	1730	Brahmi --> Devanagari --> Tibetan --> Lepcha -->	2.51	34	37	72
64	Linear B	syllabary	-1550	Linear A -->	5.03	34	73	148
65	Marsiliana	alphabet	-650	Greek -->	2.88	15	26	33
66	Meroitic (non-hieroglyphic)	abugida	-250	Ancient Egyptian -->	3.46	19	23	55
67	Messapic	alphabet	-550	Greek -->	2.87	14	23	34
68	Middle Adriatic (South Picene)	alphabet	-650	Greek --> Etruscan -->	2.70	13	23	32
69	Middle Persian (Pahlavi)	abjad	200	Aramaic -->	2.00	16	22	25
70	Mkhedruli	alphabet	1200	Greek --> Asomtavruli --> Nushka-khucuri -->	2.21	38	38	73
71	Mongolian	alphabet	1150	Aramaic --> Sogdian -->	3.29	28	35	77
72	Mongolian	numeral	1150	Aramaic --> Sogdian -->	1.60	11	10	9
73	Nabataean	abjad	50	Aramaic -->	1.77	18	22	24
74	Ndjuka'	syllabary	1910	Invented: Afaka Atumisi	2.35	36	52	78
75	New Tai Lue	numeral	1950	Invented: unknown	2.23	12	10	12
76	N'Ko	alphabet	1949	Invented: Soulemayne Kante	2.14	20	22	28
77	N'Ko	numeral	1949	Invented: Soulemayne Kante	2.60	6	10	9
78	North Picene	alphabet	-650	Greek --> Etruscan -->	2.67	13	18	27
79	Nuskha-khucuri	alphabet	850	Greek --> Asomtavruli -->	3.58	16	38	31
80	Old Church Slavonic	alphabet	850	Greek -->	3.33	27	42	70
81	Old Permic (Abur)	alphabet	1390	Invented: St. Stephen of Perm	3.11	29	38	71
82	Oriya	abugida	1051	Brahmi --> Kalinga -->	2.89	34	44	101
83	Oriya	numeral	1051	Brahmi --> Kalinga -->	1.50	15	10	10
84	Oscan	alphabet	-650	Greek --> Etruscan -->	2.71	14	21	28
85	Pahawh Hmong	alphabet (unusual)	1959	Invented: Shong Lue Yang	3.30	42	86	95
86	Pahawh Hmong	numeral	1959	Invented: Shong Lue Yang	2.50	15	10	30
87	Parthian	abjad	100	Aramaic -->	2.59	14	22	25
88	Pashto	abjad	600	Aramaic --> Nabataean --> Arabic -->	2.73	20	40	47
89	'Phags-pa	abugida	1269	Brahmi --> Devanagari --> Tibetan -->	4.53	21	40	56
90	Phoenician	abjad	-1250	Northern Linear (Canaanite) -->	2.86	13	22	34
91	Pollard Miao	alphabet (unusual)	1905	Invented: Samuel Pollard	2.11	22	47	32
92	Psalter	abjad	100	Aramaic -->	2.00	19	21	28
93	Redjang (Kaganga)	abugida	1350	Brahmi --> Pallava --> Old Kawi -->	3.00	10	36	16
94	Runic (Danish Futhark)	alphabet	800	unknown	2.63	10	16	21
95	Runic (Elder Futhark)	alphabet	50	unknown	3.13	6	24	16
96	Sabaean/Minean	abjad	-500	Southern Linear --> Sabaean/Minean -->	3.55	12	29	28
97	Samaritan	abjad	-50	Aramaic --> Old Hebrew ??? -->	4.32	24	22	72
98	Santali (Ol Cemet')	alphabet	1920	Invented: Pandit Raghunath Murmu	3.33	29	30	80
99	Santali (Ol Cemet')	numeral	1920	Invented: Pandit Raghunath Murmu	1.40	11	10	7
100	Sil'oti Nagri	abugida	1300	Invented: Saint Shahjalal	3.33	28	34	69
101	Somali (Osmanya)	alphabet	1922	Invented: Cismaan Kenadiid	1.90	29	30	38
102	Somali (Osmanya)	numeral	1922	Invented: Cismaan Kenadiid	1.50	15	10	10
103	Sorang Sompeng	alphabet	1936	Invented: Mangei Gomango	2.29	34	24	58
104	Sorang Sompeng	numeral	1936	Invented: Mangei Gomango	1.40	12	10	8
105	South Arabian	abjad	-600	Southern Linear -->	3.29	13	28	36
106	Soyombo	abugida	1686	Invented: Bogdo Zanabazar	3.63	27	35	88
107	Syriac	abjad	400	Aramaic -->	2.27	25	22	50
108	Tagalog	abugida	900	Brahmi --> Pallava --> Old Kawi -->	1.93	17	16	23
109	Tagbanwa	abugida	900	Brahmi --> Pallava --> Old Kawi -->	2.23	19	15	26
110	Tamil	abugida	-300	Brahmi -->	2.74	29	34	62
111	Thaana	abugida	1550	Invented: Unknown	2.09	23	35	42
112	Theban	alphabet	100	Invented: Unknown	3.83	28	24	69
113	Tifinagh	abjad	-100	Punic --> Ancient Berber -->	2.88	13	25	23
114	Umbrian	alphabet	-350	Greek --> Etruscan -->	2.48	16	21	30
115	Varang Kshiti	alphabet	1900	Invented: Lako Bodra	2.86	17	21	26

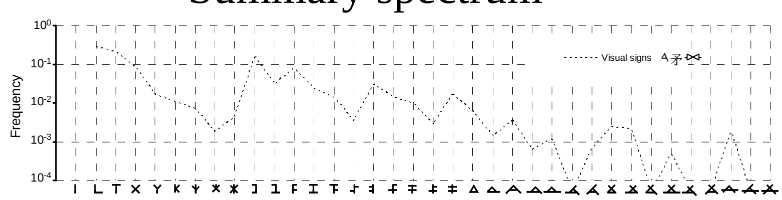
Visual sign spectra



Visual sign spectra

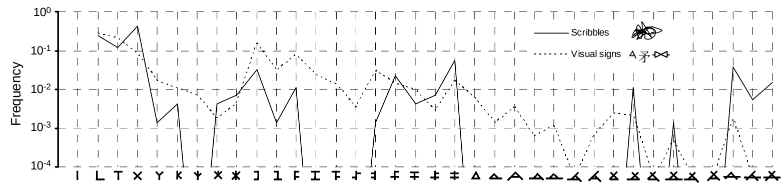


Summary spectrum

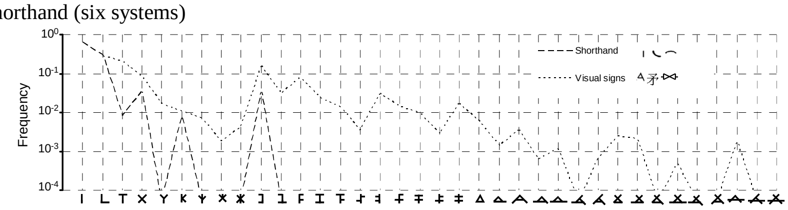


Not a tautology

Scribbles by children



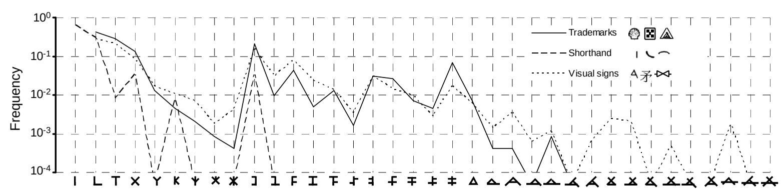
Shorthand (six systems)



Also, “random strokes” and tilings.

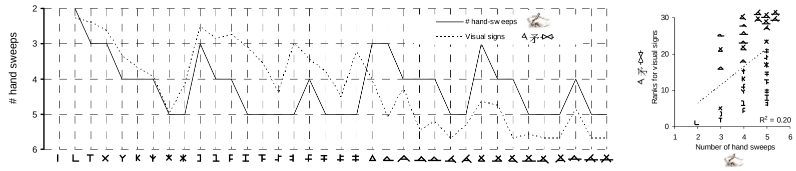
Visual versus motor, I

Trademarks versus shorthand

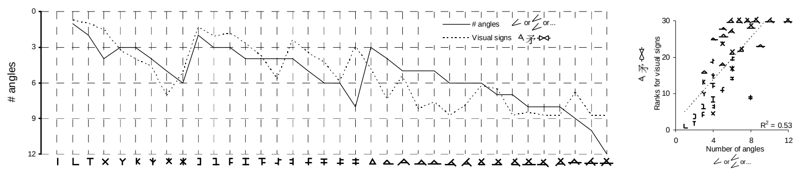


Visual versus motor, II

Minimum # hand-sweeps

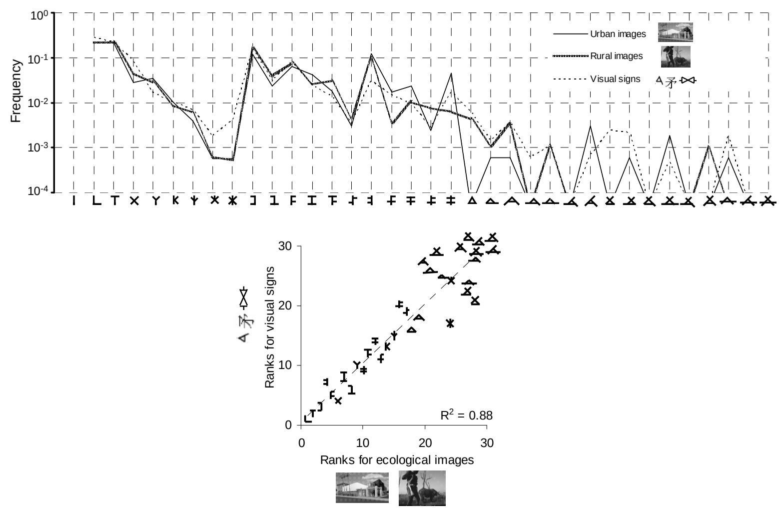


angles in stimulus (stimulus complexity)

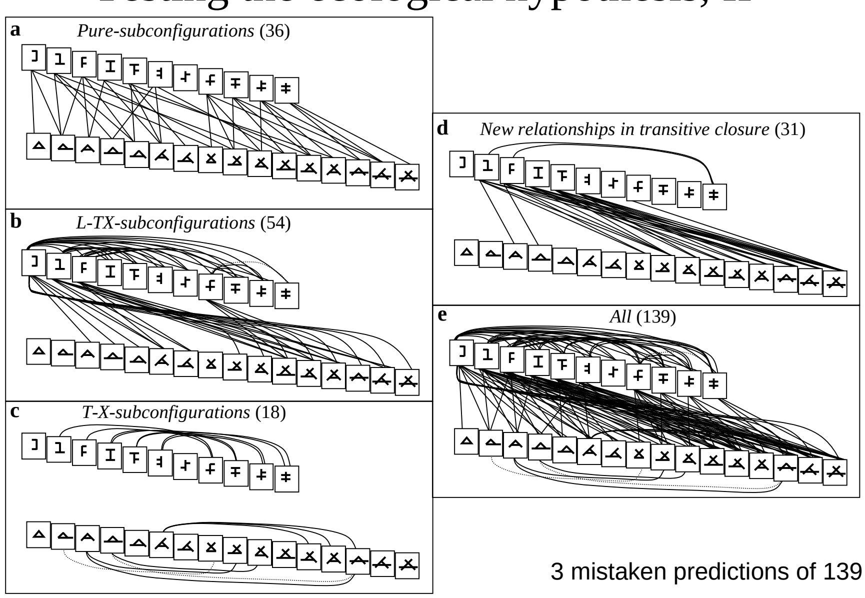


“Visual” wins

Testing the ecological hypothesis, I



Testing the ecological hypothesis, II



3 mistaken predictions of 139

Conclusion to Part I:

• There are regularities in the kinds of structures/shapes found in visual signs over human history.

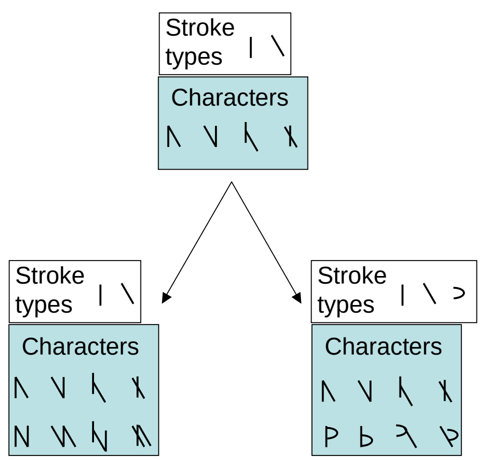
• They appear to not be driven primarily by motor optimization. (trademarks, hand-sweeps, cursive and shorthand)

• Estimates of the ecological frequency of configuration types accords well with the frequencies across visual signs, suggesting that visual sign structures have been selected to match the contour-combinations found in natural scenes, because that is what the human visual system is good at processing.

PART II

Combinatorial structure of letters

How do writing
systems get larger?

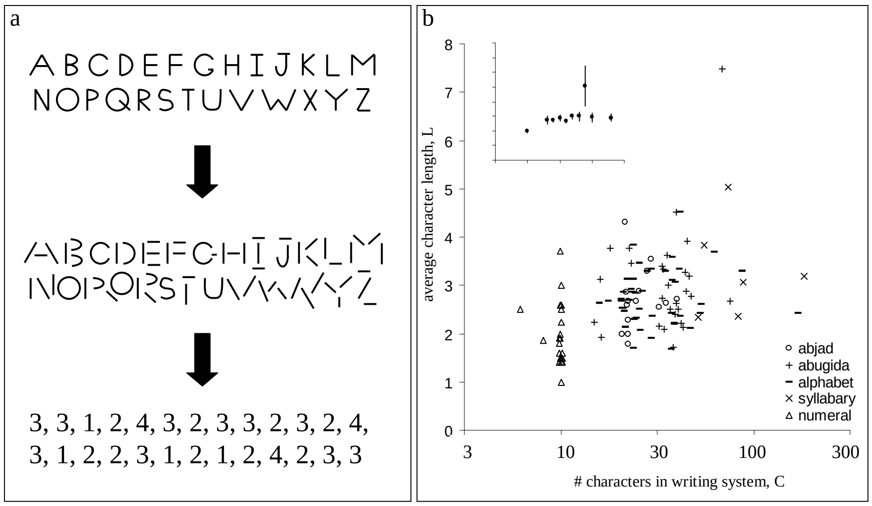


Universal type approach

length L increases [~ log C]
stroke types B invariant.

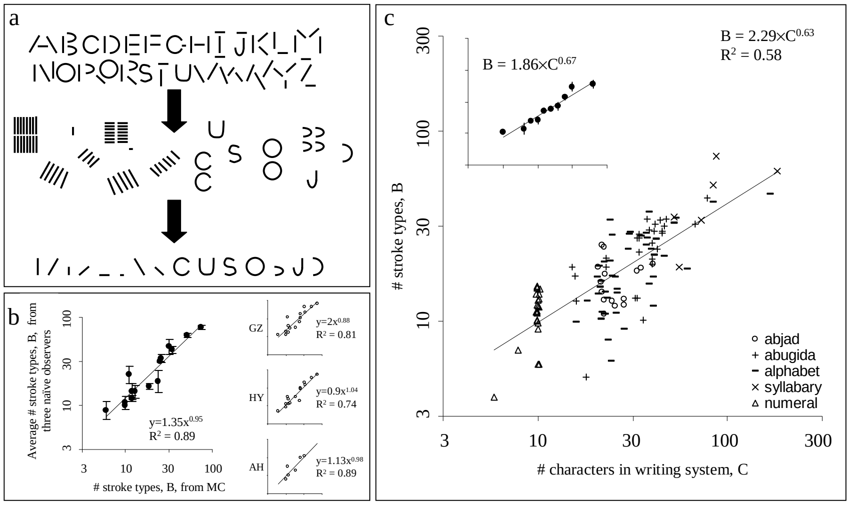
Invariant-length approach

length L invariant.
$C \sim B^d$, where $d \leq L$, so
B increases $\sim C^{1/d}$



Writing systems appear, then, to follow the invariant-length approach.

Recall that this implies that the number of stroke types must increase…



stroke types does indeed increase, as expected from the invariant-length.

But from the stroke-type plot, we can *also* infer how combinatorial characters are.

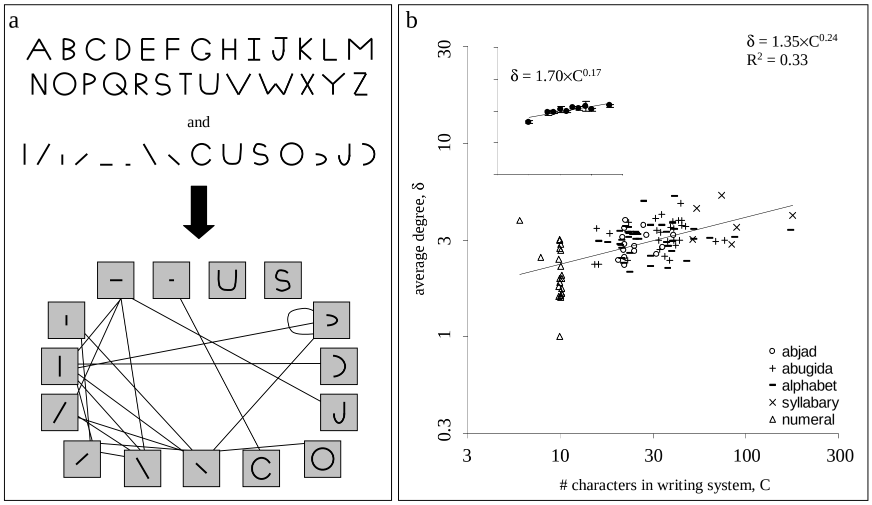
Length L= 3 strokes per character, so the *maximum* number of degrees of freedom relating stroke types and characters is 3.
I.e., $C \sim B^3$.

But the *actual* relationship between them from the plot is…
$C = 0.268 \times B^{1.587}$. The combinatorial degree, $d = 1.587 \approx 1.5$.

Redundancy $R \equiv 1 - d/L \approx 50\%$.

There is another way to estimate combinatorial degree and redundancy…

If combinatorial, then stroke types in larger writing systems must interact with a greater number of *other* stroke types.



Average degree per node does, indeed, increase.
Namely approximately as $\delta \sim C^v$, where $v \approx 0.24$.

$C \sim B\delta^{L-1} \sim BC^{v(L-1)}$.

$\Downarrow$

$C \sim B^{1/[1-v(L-1)]}$.

So, we can compute combinatorial degree $d = 1/[1-v(L-1)]$.
For $v \approx 0.24$, $d \approx 1.5$.

Redundancy $R \equiv 1 - d/L \approx 50\%$, as before.

Summary of Part II:

- Writing systems increase in size via the invariant-length approach, not the universal-stroke-type approach. [*Suggests some upper limit to visual processing. (?)*]

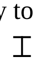
- The average number of strokes per character is ≈ 3. [*Why? Subitizing limit?*]

- The number of stroke types increases, with combinatorial degree exponent of ≈ 1.5. (Via two distinct kinds of estimate.) Therefore, only half of the possible degrees of freedom are utilized, and thus redundancy ≈ 50%. [*Presumably useful for discriminability.*]

Summary of ALL

- Visual signs have been selected to be shaped like the ecology.

- Letters in writing systems have been selected to have approximately 50% redundancy.

- Visual linguistics—the study of human visual signs—may be a promising approach to discovering fundamental principles governing vision. (E.g., there is more likely to be mechanisms in the visual system for processing  than  .)

- Future directions include:
  - Human judgments of stimulus complexity.
  - Camouflage and animal visual signalling.