Language and Cognition:
Festschrift in Honor of James H-Y. Tai on His 70th Birthday.
Jung-hsing Chang (ed.)
2011, Taipei: The Crane Publishing.

Representation Efficiency and Transmission Efficiency in Sign and Speech*

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It has long been known that words in American Sign Language (ASL) have longer durations than words in English, yet due to the temporal overlap of morphemes in ASL, users of both languages are able to express propositions at the same rate. In this study we extend these findings to Taiwan Sign Language (TSL) and Mandarin, grounding the results empirically in statistical analyses of narrative productions by a large number of hearing and deaf participants (57 participants in total). We demonstrate that TSL has significantly greater representation efficiency (propositions per syllable) than Mandarin, while both languages are identical in transmission efficiency (propositions per second). Moreover, we examine how nativeness (age of first sign) and experience (years signing) affect both types of efficiency. We also reconfirm that simultaneous communication of sign and speech is less efficient than each modality produced alone. Together our results reinforce the conclusion that the ideal language of instruction for deaf children in Taiwan is TSL, not simultaneous communication or signed Chinese.

Key words: Taiwan Sign Language, Mandarin, language production, efficiency, simultaneous communication

1. Introduction

Forty years ago, Bellugi and Fischer (1972) (see also Bellugi, Fischer, and Newkirk 1979) investigated what we will call the efficiency of a sign language (American Sign Language, or ASL) and a spoken language (English). They concluded that both modalities express the same amount of information in the same amount of time, since sign language compensates for its relatively slower articulation with more compact phonological representations. These findings have had great influence on sign language research in the intervening years, but they have never been directly reconfirmed in another sign language, nor have they been quantified in any detail. In

* This paper is dedicated to our good friend Jim Tai. We hope he will enjoy our little tale, which weaves together some of his favorite things: sign language, language/cognition interactions, nativism vs. learning, and pedagogical implications of all of the above. This study could not have been conducted without his inspiration or his National Science Council grants 90-2411-H-194-025, 91-2411-H-194-030, 92-2411-H-194-007, 93-2411-H-194-001. We also thank the 57 participants (including the two who gave us permission to use their images in Figure 3), TSL consultants Mr. & Ms. Gu Yushan and Huang Biyu, assistants Wu Peilan, Li Yixian, Li Yanan, and Lin Fangyu, and comments from Jean Ann, Susan Fischer and audiences in Changsha, Hsinchu, and Chiayi, and an anonymous reviewer.

the present study we replicate and extend their results in Taiwan Sign Language, using statistical analyses of a much larger set of signers and speakers.

In the original Bellugi and Fischer (1972) study, three native bilinguals, hearing English-speaking adults who had acquired ASL from deaf parents as young children, were asked to tell the same story in sign only, speech only, or both simultaneously (what is now called simultaneous communication or simcom). For stories told in one modality only, it was found that the rate of words per second was higher for speech than for sign, since spoken words tend to be shorter than signs, yet the ratio of seconds to propositions was the same across the two modalities (propositions were counted by counting the main verbs that defined them). The main findings were replicated in a comparison between these three hearing adults and three native deaf signers. The paradox of slower sign rate with matched proposition rate was resolved by observing the high degree of morpheme overlap found in ASL, where, for example, the sign for a verb is typically articulated at the same time as its aspect marking. This morpheme overlap is much greater than in spoken English; English verb stems are completely articulated before the inflectional suffix begins. Moreover, when the native bilinguals told the story simultaneously in English and sign, the cognitive load of processing two distinct systems at the same time resulted in a drop in the spoken word rate and an increase in total pause duration, though sign rate and proposition rate were unaffected.

These early findings have since been supplemented by studies investigating the relative efficiency of sign and speech, the effects of nativeness on signing efficiency, and the pedagogical implications of these findings for the use of artificial sign systems like signed English, intended to mimic the structure of spoken language. Regarding the first point, Grosjean (1981) found that while English-speaking listeners required about 83% of a word (330 ms) to identify it, ASL-signing viewers required only about 35% of a sign (240 ms) (see also Emmorey and Corina 1990). This indicates that the high efficiency of signing involves not only morpheme overlap, but also the overlap of phonological information (coarticulation) within morphemes.

Wilbur and Nolen (1986) found that an ASL syllable, defined as a movement excursion (change of hand location; see also Wilbur 1990), was only slightly longer in duration than an English syllable (both were a little over 250 ms). They claimed that ASL signs tend to be longer than English words primarily because reduplicative movements within signs increase the number of syllables. As we will see below, we did not replicate this finding; signed syllables were still significantly longer than spoken ones, even taking reduplicative movements into account. This makes sense from an articulatory standpoint: movement excursions in speech involve much smaller distances and less massive articulators than in signing.

The notion of sign syllables as phonological units remains somewhat controversial (cf. Wilbur 1990 vs. Channon 2002). Nevertheless, as articulatory units, sign syllables provide a useful way to think about one aspect of the efficiency of a language modality. Namely, language production can be seen as an attempt to coordinate proposition generation with syllable generation. The ratio of proposition per syllable is thus a measure of the inherent efficiency of a language's representational system. We call this form of efficiency REPRESENTATION EFFICIENCY. Each syllable in a sign language can represent a bit more of each proposition than can spoken language syllables, causing signing to have higher representation efficiency than speech. This is schematized in Figure 1.

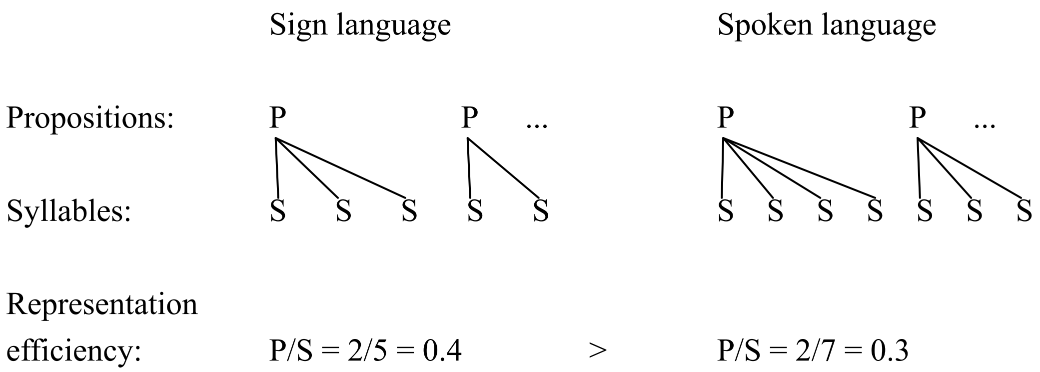


Figure 1: Representation efficiency in sign and spoken language

The relevance of nativeness and/or experience to the efficiency of sign production and reception has also been addressed in several studies (e.g. Stungis 1981; Poizner 1983; Mayberry and Fischer 1989; Meier 1991; Hildebrandt and Corina 2002). Nativeness is known to affect aspects of sign production, in particular the use of inflectional morphology (Meier 1991), which suggests that early acquisition of a sign language may improve mastery of the grammar underlying representation efficiency.

Mayberry and Fischer (1989) found that the advantage in processing sign shown by deaf signers who had acquired ASL as young children was primarily localized to their greater ability at handling phonology on the fly, that is, the rapid extraction of form information. This implies a different type of efficiency, one that mediates the speed with which propositions are expressed in real physical time. We call this TRANSMISSION EFFICIENCY, quantified as the rate of propositions per second. Bellugi and Fischer (1972) quantified the same notion in terms of proposition duration (i.e. seconds per proposition), but by using the arithmetical inverse as we do here, higher values indicate greater efficiency.

As noted above, Bellugi and Fischer (1972) found that sign and speech were roughly equivalent in transmission efficiency, as schematized in Figure 2. This supports the notion that all humans, regardless of language modality, generate propositions at roughly the same rate. It is the greater representation efficiency of signing that allows this rate to be maintained despite the use of heavier articulators and larger movement excursions.

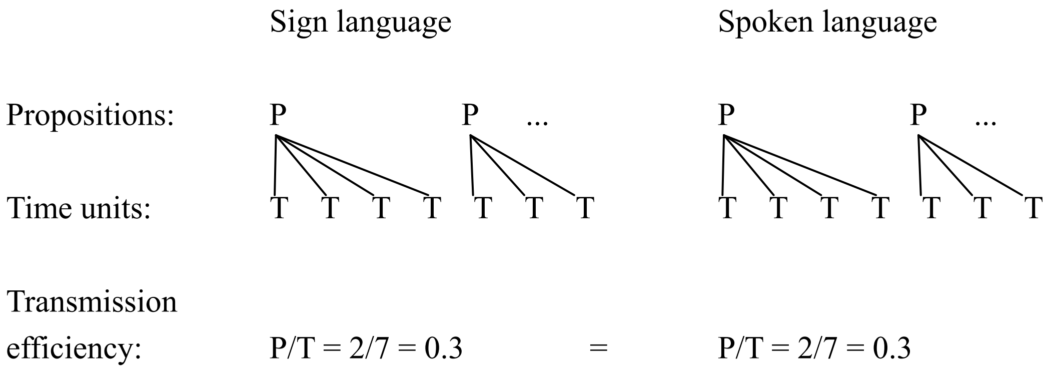


Figure 2: Transmission efficiency in sign and spoken language

The pedagogical implications of Bellugi and Fischer (1972) have also been addressed in the decades since. In particular, the attempt to sign a spoken language like English, word by word or even morpheme by morpheme, is now recognized as impossible (Supalla and McKee 2002; Wilbur 2003). Hearing parents and teachers attempting to do so end up producing imperfect output that is missing important grammatical information (Marmor and Petitto 1979; Wodlinger-Cohen 1991; cf. Mayer and Lowenbraun 1990). Moreover, deaf children who are presented with signed English tend to modify it, in particular by overlapping the morphemes, to make it more suitable to a manual-visual modality (Supalla 1991). For similar reasons, simultaneous communication (simcom) has come under considerable fire in recent decades for causing signing to become ungrammatical or unintelligible (Wilbur and Petersen 1998; Akamatsu, and Stewart 1998; cf. Emmorey, Borinstein, Thompson, and Gollan 2008, for discussion of cross-modality code switching, which is a quite different phenomenon). Moreover, since English doesn't allow morpheme overlap, sign transmission efficiency is notably lower in signed English, and often in simultaneous communication as well. The consequences for education are clear: deaf children should be taught in their native language, not a signed version of a spoken language, and without accompanying speech (see, e.g. Wilbur 2000 for the benefits to deaf children in American of using ASL to teach English and English literacy).

Despite the body of work that has built on Bellugi and Fischer (1972), the original study tested only six participants, namely three deaf monolingual ASL signers and three hearing ASL-English bilinguals, all of whom were native signers (most signers, deaf or hearing, do not begin to acquire sign at birth; see review in Marschark, Lang and Albertini 2002). The study also involved primarily qualitative analyses: representation efficiency was not quantified at all and transmission efficiency rates were not analyzed for statistical significance. Finally, the study focused exclusively on English and ASL.

The purpose of the present study was to test the conclusions advanced in Bellugi and Fischer (1972) by extending their basic methodology to a larger data set, taken from a different sign language / spoken language combination. Our study looked at Mandarin Chinese and Taiwan Sign Language (TSL), the natural sign language of the deaf in Taiwan (Smith and Ting 1979, 1984; Tai and Tsay 2009), historically unrelated to ASL. Mandarin differs from English in several ways that might be expected to affect its efficiency. Some properties might seem to increase the duration between main verbs, and thus the measurement of proposition rate: Mandarin is syllable-timed rather than stress-timed (Grabe and Low 2002), it uses syllabic (sometimes stressed) grammatical morphemes rather than subsyllabic inflectional affixes (e.g. past tense is marked in English by subsyllabic *-ed* while completive aspect is marked in Mandarin by syllabic 了 *le*), and it prefers compounds over monosyllabic morphemes (e.g. compare English *wasp* with Mandarin 黃蜂 *huángfēng*, literally "yellow bee"). Other properties of Mandarin might seem to decrease the duration between main verbs, in particular the rarity of words longer than two syllables. TSL shares typological features common to all sign languages, including morphological and phonological overlap, and a preference for signs formed with at most one movement excursion, unless the sign involves reduplication of movements or is a sequential compound (Tsay and Myers 2009).

Confirming the greater degree of representation efficiency of TSL compared with Mandarin, and establishing that both languages have equivalent transmission efficiency, would have important pedagogical implications. Educators of the deaf in Taiwan sometimes believe that signed Chinese is a more appropriate vehicle of education than TSL, giving it the misleading name of 文法手語 *wénfǎ shǒuyǔ* "grammar-based sign language," as opposed to 自然手語 *zìrán shǒuyǔ* "natural sign language" (TSL). As noted above, the evidence from decades of research in the United States points in exactly the opposite direction, with deaf children benefiting more from being taught in a natural sign language. Recently this evidence has been backed up in Taiwan by Liu (2004), who demonstrated experimentally that deaf children understood less of a story when it was presented in signed Chinese than when the same story was presented in TSL (see also Liu and Tseng 2007).

Signed Chinese is, if anything, even more ill-suited to the sign modality than signed English because Taiwanese educators generally also adopt the traditional assumption that the basic unit of spoken Mandarin is the same as in written Chinese, namely the character (representing a single monosyllabic morpheme). In actual fact, most Mandarin words are compounds (Zhou and Marslen-Wilson 1995), and even for spoken Mandarin, the high degree of homophony makes it highly unlikely that even listeners (let alone viewers of sign) can access words morpheme by morpheme (Packard 1999). Signed Chinese complicates the problem still further by attempting to make each monosyllabic character sign iconically related to the written character (Ann 1998). This overloads the combinatorial possibilities permitted by manual articulation, resulting in even more homophony, including the use of puns that only make sense to their hearing inventors (e.g. using the sign for "flower" for both 花 *huā* "flower" and 華 *huá* "Chinese").

An example of a lexical difference between TSL and signed Chinese is shown in Figure 3. Mandarin morphology and phonology conspire to favor polysyllabic words (Duanmu 2007), but natural sign languages like ASL and TSL favor monosyllabic words (Wilbur 1990). Thus by artificially requiring the signed Chinese form to adhere to Mandarin structure, it ends up much longer than the TSL form, hence much more inefficient.

TSL

逃 "escape"

Signed Chinese

逃 "escape" 出 "out" 出 "out" + 去 "go"

(from Mandarin 逃出去 *táochūqù* "escape")

Figure 3: Taiwan Sign Language vs. signed Chinese forms of ESCAPE

It has also been demonstrated that producing Mandarin and sign simultaneously is just as problematic as English/sign simcom. In a study of Chinese/sign simcom produced by deaf educators in Taiwan, Hsing (2003) found that an average of only 81% of the information present in the speech was preserved in the sign, and up to 43% of the sign productions were ungrammatical. Moreover, the faster the speech, the more signs were dropped, suggesting that an acceptable level of information content could only be preserved by sacrificing transmission efficiency. This implies that lectures would have to be significantly longer in order for simcom to convey the same amount of information as Mandarin or TSL alone.

Aside from looking at a new pair of languages, our study also attempted to address some of the methodological limitations of Bellugi and Fischer (1972). In particular, we included almost ten times as many participants, with both monolinguals and bilinguals and both deaf and hearing signers, who varied widely both in age at which they began to sign and in years of experience with signing. This not only gave us a sample more representative of the actual signing population in Taiwan, but statistically it allowed us to separate out modality, simultaneous communication, deafness, age of acquisition, and experience as effects on both representation efficiency (quantified as propositions per syllable) and transmission efficiency (quantified as propositions per second).

Nevertheless, we must admit at the outset that our study shares an important limitation with that of Bellugi and Fischer (1972), in that we followed them in identifying propositions solely in terms of main verbs (i.e. predicate-defining lexical items). Since we neglected all of the other signs produced by our participants (except in how they affected the number of syllables or proposition durations), we did not consider how non-nativeness or simultaneity of signing with speaking affected the production of these other signs, thereby affecting grammaticality or intelligibility. We also neglected all nonmanual cues, which are known to provide important information about morphological, syntactic and prosodic structure (Liddell 1980; Nespor and Sandler 1999; Su 2008, 2010; Su and Tai 2008; Tai and Su, to appear).

Thus we cannot assume that the signing produced during simultaneous communication was complete and grammatical TSL. In fact, we know that it often was not. Table 1 shows part of the transcript from a simcom session produced by a hearing non-native bilingual, where it is clear that several words in the spoken Mandarin have no correspondent in the signing. The cognitive challenge of simcom is also suggested by the many temporal misalignments between speech and sign, and perhaps also by the atypical syntax of the spoken sentence 他們常常跟著牠說話、聊天 *tāmen chángcháng gēnzhe tā shuōhuà, liáotiān* "They often talked, chatted accompanying it." The dropped words were rarely main verbs, however, so proposition rate, operationalized as main verb rate, was unaffected.

Table 1: Example of simultaneous communication in Mandarin and sign

Spoken:	有	個	小	男孩		他	和		
	exist	class.	small	boy		he	and		
Signed:	有			男	孩子	和			
	exist			male	child	and			
Spoken:	他	的	小	狗狗		養	了		
	he	poss.	small	doggy		raise	asp.		
Signed:	和				狗	養			
	and				dog	raise			
Spoken:	一		隻	小	青蛙	把	牠	養	在
	one		class.	small	frog	obj.	it	raise	loc.
Signed:	一	瓶子			青蛙	瓶子			
	one	bottle {false start}			frog	bottle {continues ...			
Spoken:	瓶子	裡面	他們	常常	跟著		牠	說話	聊天
	bottle	inside	they	often	accompanying		it	talk	chat
Signed:		裡面						說話	說話
	...}	inside						talk	talk
								{right hand}	{left hand}

Strikingly, however, despite this limitation in the sensitivity of our quantitative measures, we will see that our data still strongly support the notions that signing has greater representation efficiency than speech and that signing and speech have identical transmission efficiency.

2. Experiment

Fifty-seven Taiwanese participants, both deaf and hearing, varying both in age of first exposure to sign and in years of experience with sign, were recorded telling the same story in sign, speech, or simultaneously. Three of the hearing participants were children of deaf adults and native bilinguals of TSL and Mandarin, allowing us to replicate exactly Bellugi and Fischer (1972), who studied three hearing native bilinguals of ASL and English. However, by defining representation efficiency and transmission efficiency quantitatively, and conducting further statistical analyses comparing all thirty-one hearing participants with all twenty-six deaf participants, we were able to test their claims with greater rigor.

2.1 Methods

2.1.1 Participants

Twenty-six deaf adults, ranging in age from 23 to 61, were recruited from central/south Taiwan (Changhwa, Chiayi, Tainan, and Kaohsiung). All were judged as fluent TSL signers by our TSL consultants. The deaf participants included four native TSL signers who were first exposed to TSL by deaf signers by the second year of life. Twenty-one of the remaining deaf participants were first exposed to TSL later (at ages 7 to 23), and one 23-year-old deaf participant never acquired TSL, preferring to use spoken Mandarin (with the help of a hearing aid) and signed Chinese.

Thirty-one hearing adult signers, ranging in age from 17 to 61, were recruited from Chiayi, Taipei, Tainan, and Kaohsiung. Three were native signers of TSL, and thus were Mandarin-TSL bilinguals. The remaining twenty-eight did not learn sign until aged 15 to 55. Hearing participants varied widely in their reasons for learning to sign, including having deaf relatives, working with the deaf as social workers or teachers, or being associated with the deaf community in more informal ways. All were considered to be fluent signers by our TSL consultants, though as noted above, our dependent measures for efficiency do not take grammaticality or completeness into account.

2.1.2 Materials

Rather than allowing the participants to choose their own narratives, as Bellugi and Fischer (1972) did, we restricted our participants to a specific story, namely the so-called "frog story" expressed in a wordless picture book (Mayer 1969), which has become a standard tool in research on narrative production (e.g. Berman and Slobin 1994). The story involves a boy and his dog searching for an escaped frog through different settings, and thus retelling the story requires reference to a variety of agents, objects, locations, motions, and mental states. The story is quite simple and clearly aimed at children, and so is likely to elicit more of a child-directed register, including perhaps the avoidance of complex modifiers and a slower overall production rate; these properties may be expected to lower the proposition rate compared with the narratives told by Bellugi and Fischer's participants, regardless of any language differences. Moreover, our task involved picture description, so it was both less taxing on the memory and less spontaneous than the free storytelling task of the earlier study.

2.1.3 Procedure

Participants produced the story in three different ways: signed, spoken, or both simultaneously. Twenty-four of the deaf participants, including the four native signers, told the story only in sign; two, who had hearing aids, also told the story in spoken Mandarin. Seven of the hearing participants, including two of the native signers, told the story once in sign and once in Mandarin. The remaining twenty-six hearing participants, including one of the three native signers, told the story in all three ways. For those telling the story more than once, the order was arbitrarily distributed across participants.

Participants were first given time to become familiar with the storybook pictures, scanned so that each successive picture spread could be displayed on a computer screen with the press of a button. When participants felt ready, they began to describe the story, pausing occasionally to press the button to bring up the next picture. Each narrative was recorded on digital video for transcription and analysis.

Note that unlike Bellugi and Fischer (1972), the number and duration of pauses in our study could not be taken as an index of cognitive load, since they were affected primarily by interacting with the pictures (studying their content and turning from one picture to the next). Therefore we did not include pause duration in our dependent measures.

2.1.4 Data preparation

Narrative durations were measured using video editing software, with narratives ranging in length from 1 m 40 s to 12 m 23 s. The time participants spent hesitating or pressing the button to display the pictures was removed, leaving total durations ranging from 1 m 0 s to 9 m 17 s. All duration-based analyses used only these pause-free measures.

Durations of narratives produced in Mandarin (with or without simultaneously signing) ranged from 1 m 22 s to 7 m 2 s. Mandarin narratives were transcribed into Chinese characters and segmented into words (not necessarily monosyllabic). The number of Mandarin words ranged from 179 to 1,158, and the number of Chinese characters, hence Mandarin syllables, ranged from 241 to 1,577. Propositions were counted by counting main verbs or adjectival predicates (e.g. 青蛙不見了 *qīngwā bújiàn le* "the frog is missing"). The number of propositions ranged from 25 to 146 per narration.

Durations of narratives produced in sign (whether by deaf or hearing participants, and with or without simultaneously speaking) ranged from 1 m 0 s to 9 m 17 s. The number of signs in narratives ranged from 58 to 595. Syllables were defined as movement excursions (changes in hand location), with stationary signs counted as monosyllabic if they contained local movement (e.g. finger wiggling). The number of syllables defined in this way ranged from 58 to 595 across narratives. Propositions were counted the same way as for Mandarin, by counting main verbs or adjectival predicates. The number of propositions ranged from 18 to 175.

2.2 Results and discussion

As basic checks on previous claims in the literature, we first analyzed the word production rates and syllable durations for speech and sign produced separately. Then we examined how modality affected representation efficiency and transmission efficiency. We also examined how sign efficiency was affected by nativeness (i.e. age of first sign) and experience (i.e. years of signing), as modulated by being deaf versus hearing. Finally we analyzed how simultaneous communication affected the influence of these factors on efficiency in sign and speech.

2.2.1 Words per second

Bellugi and Fischer (1972) found that native English-ASL bilinguals produced English words roughly twice as fast as ASL signs. The results from our three native hearing Mandarin-TSL bilinguals (A, B, C), speaking and signing in separate recordings, were similar to those of their study, as shown in Table 2. Our word rates were somewhat lower than for their study, but this may be due to our using a children's picture book to elicit the narratives.

Table 2: Word per second rates for native hearing Mandarin-TSL bilinguals

Participant	Speech	Sign
A	2.76	2.68
B	2.81	1.24
C	3.12	1.74

To determine if the difference in word rates across modalities held for deaf signers vs. hearing speakers more generally, we compared the word rates of the 29 narratives spoken by hearing Mandarin speakers (without simultaneously signing) with those signed by the 26 deaf TSL signers. Since word rate may also be affected by age (perhaps involving a general slowing of word access and motor movements for older participants), we included both modality and age in a linear regression analysis, along with their interaction (as with all of the other regression analyses in this study, the categorical variable of modality was coded numerically, here with sign = 1 and speech = -1). This analysis showed an effect of modality (coefficient $B = -0.85$, $t(51) = -3.93$, $p < .001$): similar to what was found with the bilinguals, word rate in speech (2.91 words per second) was much higher than in sign (1.55 words per second). Age showed no significant effect, nor was there any interaction between the two factors.

2.2.2 Syllable duration

As noted earlier, Wilbur and Nolen (1986) found that ASL syllables, defined as movement excursions, tended to be only slightly longer than syllables in English. Calculating syllable duration by dividing the total number of syllables in narratives by duration in seconds, we did not find a similar match between syllables in TSL and Mandarin. As Table 3 shows, for our three hearing native hearing TSL-Mandarin bilinguals producing narratives separately in speech and in sign, syllable durations (in milliseconds) for Mandarin were quite close to those reported for English (around 250 ms), but for sign they were much longer than those reported for ASL by Wilbur and Nolen (1986).

Table 3: Syllable durations for native hearing Mandarin-TSL bilinguals (msec).

Participant	Speech	Sign
A	243	345
B	253	641
C	214	500

Similar results were found in a comparison of signing by the deaf participants and speech by the hearing participants (in narratives produced without simultaneously signing), again using a linear regression analysis including both modality and age. Signed syllables were significant longer (553 ms) than spoken syllables (244 ms) ($B = 0.21$, $t(51) = 3.19$, $p < .01$). Age showed no main effect, nor did it interact with modality.

The discrepancy between these results and those of Wilbur and Nolen (1986) may be partly explained by the nature of our materials, which involved a large number of motion verbs (as the frog made its escape and the boy and dog followed) in a story aimed at children. Thus arm movements tended to be lengthened, both to represent actual movements in the story and to exaggerate the prosody, as is appropriate for child-directed speech. Nevertheless, our results are consistent with the more general claim of Wilbur and Nolen (1986) that signed syllable duration depends on discourse context; some of the contexts they tested, including elicitation tasks, produced sign syllable durations (up to 361 ms) close to the range of those we found. In any event, we should not be surprised that it takes longer to move heavy articulators large distances in sign than to move light articulators short distances in speech. It is this physical difference that motivates the greater representation efficiency of sign, a measure we turn to next.

2.2.3 Representation efficiency

We now turn to results bearing on the central interests of this study, beginning with representation efficiency. Bellugi and Fischer (1972) provided no quantitative analyses of representation efficiency, but in their qualitative descriptions, they emphasized the great degree over morpheme overlap in ASL. In both sign and speech, we quantified representation efficiency as the number of propositions per syllable. If TSL behaves like ASL, then, we expect it to have a higher representation efficiency score than Mandarin.

This is exactly what we found. Table 4 shows the proposition per syllable rates for the three native Mandarin-TSL bilinguals (each modality produced separately). The ratio of the speech rate to sign rate is approximately one-half, indicating a great degree of overlapping information in TSL as compared with Mandarin.

Table 4. Proposition per syllable rates for native hearing Mandarin-TSL bilinguals

Participant	Speech	Sign
A	0.11	0.18
B	0.12	0.24
C	0.11	0.21

The same pattern emerged in a regression analysis on signing by the deaf participants and speech by the hearing participants, looking at the effects of modality and age on proposition per syllable rates. An initial analysis including the interaction term showed only marginal effects (i.e. $.05 < p < .1$) for both factors and their interaction. Since the interaction was not significant, we reran the regression without it. This revealed an effect of modality ($B = 0.07$, $t(52) = 14.11$, $p < .0001$): the proposition per syllable rate for signing (0.27) was significantly greater than that for speaking (0.12) (see Figure 4). Age again had no significant effect.

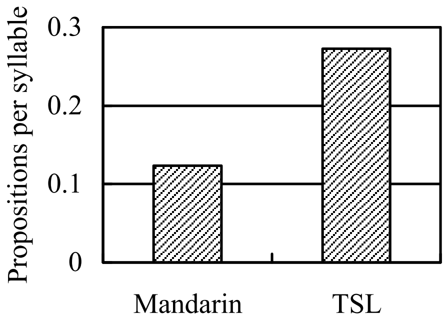


Figure 4: The mean representation efficiency of spoken Mandarin (hearing) and TSL (deaf)

2.2.4 Transmission efficiency

Bellugi and Fischer (1972) quantified transmission efficiency in terms of the duration of propositions (seconds per proposition), but we used the inverse (propositions per second) so that higher values represent greater efficiency. If TSL and Mandarin behave like ASL and English, we expect to find no difference in their transmission efficiency, despite their significant differences in representation efficiency.

We first looked at the proposition per second rates for our three native hearing Mandarin-TSL bilinguals (each modality used separately). As can be seen in Table 5, the ratio of transmission efficiency in speech to signing averages around 1, suggesting that the transmission efficiency of the two modalities is identical. Consistent with the evidence mentioned earlier that our participants presented their narrations more slowly than Bellugi and Fischer's, our proposition per second rates are somewhat lower than theirs (our mean value is 0.45, compared with their mean of 0.78, based on the inverse of their second per proposition rates).

Table 5: Proposition per second rates for native hearing Mandarin-TSL bilinguals.

Participant	Speech	Sign
A	0.44	0.51
B	0.47	0.37
C	0.52	0.41

Similarly, no difference in transmission efficiency emerged when we compared deaf signers and hearing speakers in a regression analysis using modality and age as independent variables, whether or not the interaction was included (all *p*s > .1). As illustrated in Figure 5, transmission efficiency was 0.517 for Mandarin and 0.524 for TSL. The fact that no effect emerged even in this larger sample suggests that the two modalities truly are equally efficient in the transmission of information.

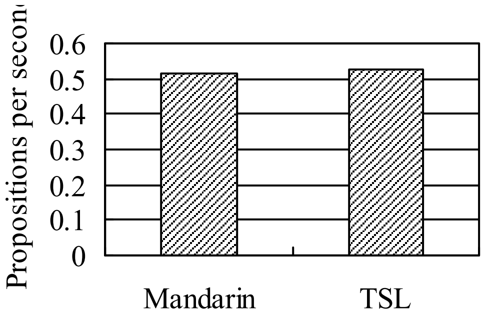


Figure 5: The mean transmission efficiency of spoken Mandarin (hearing) and TSL (deaf)

2.2.5 Effects of age of acquisition and experience on signing efficiency

Our use of a larger and more varied sample of participants made it possible to address an issue merely assumed by Bellugi and Fischer (1972), namely the effect of nativeness on the representation efficiency and/or transmission efficiency of signing. For these analyses, we looked at all 55 signed narratives (produced without simultaneously speaking), whether produced by deaf or hearing participants. We quantified degree of nativeness as age of acquisition, i.e. the age at which the participant first began signing. To distinguish nativeness from years of experience with signing (i.e. age at test minus age of acquisition), we included this as a separate independent variable. Since the age of the participants at the time of testing (17-61 years, *SD* 10.31 years) did not vary as much as their age of acquisition (0-55 years, *SD* 13.34 years) or years of experience (0-60 years, *SD* 14.28), the age of acquisition and experience variables were inversely correlated ($r = -.72$, $t(53) = -7.63$, $p < .001$). This raises the risk of collinearity: if independent variables are overly correlated, it is impossible to distinguish their separate contributions to variation of the dependent variable. Fortunately, the correlation here implies the relatively small variance inflation factor (VIF) of 2.10, far below the threshold of 10 considered to indicate serious collinearity (Montgomery, Peck, and Vining 2001). Similarly, the associated condition number $\kappa = 8.14$ also indicates only a relatively low degree of collinearity (Baayen 2008). Thus our analysis should be capable of separating out the effects of age of first exposure to sign from the effects of experience using sign.

It is possible that the experience of being deaf would also affect sign efficiency, most likely by increasing the motivation to represent and transmit signed information efficiently, and deafness may also modulate the roles of the other factors. Thus we also included the categorical variable of deafness (deaf = 1 vs. hearing = -1).

We then ran a multiple regression predicting sign representation efficiency (propositions per syllable), crossing all three of the above independent variables (age of acquisition × years of experience × deafness). The only significant result was an interaction between age of acquisition and years of experience ($B = 1.3\times10^{-4}$, $t(47) = 2.33$, $p < .05$). Figure 6 visualizes this interaction a so-called lattice plot (Baayen 2008) showing a series of six scatterplots running from the lower left to the upper right. Each scatterplot shows the correlation between years of signing experience (x axis) and propositions per syllable (y axis) for participants who acquired sign in a different age range (represented by shading in the bar above the scatterplot). As we move rightward in the lower row from the scatterplot for the earliest-acquiring participants, then again left to right across the upper row, the data come from participants who acquired sign at ever older ages (note that the dark shading on the heading bars shifts).

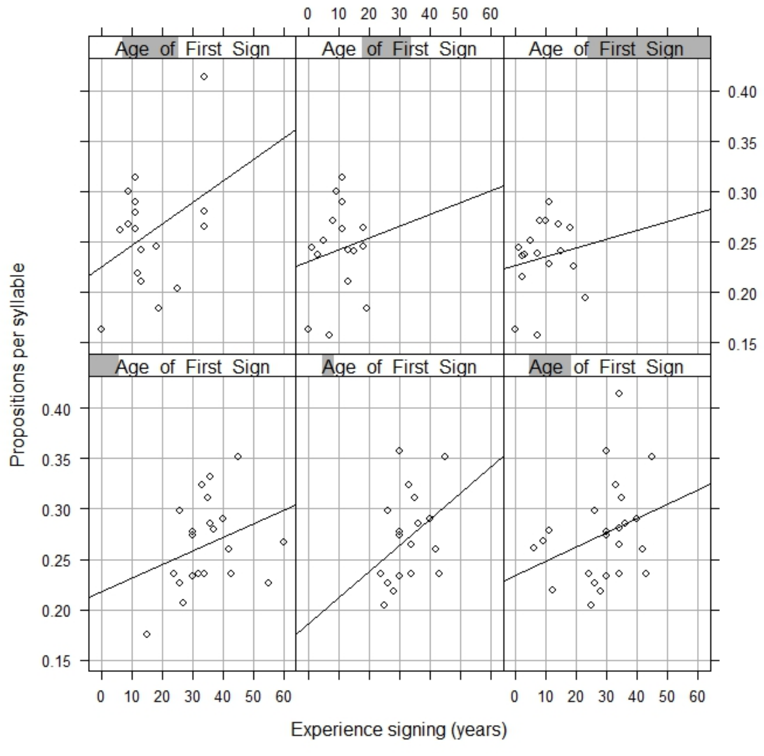
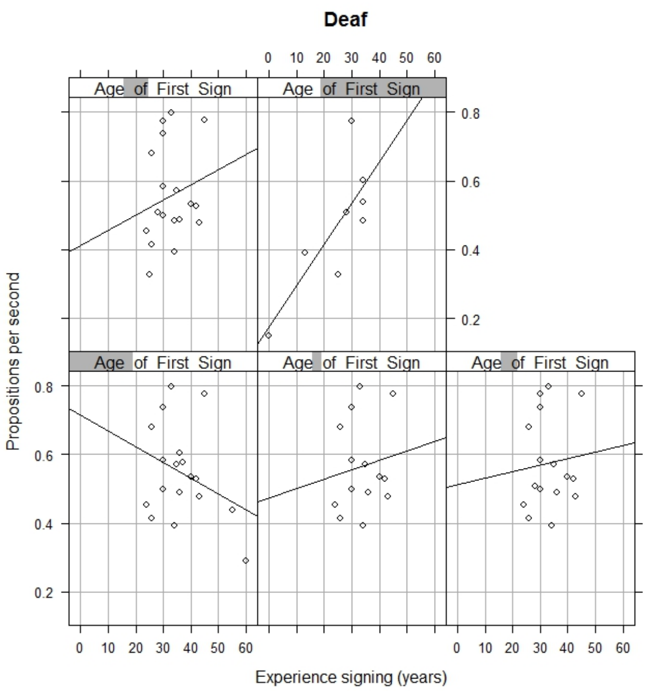


Figure 6: The interaction between age of first sign and signing experience in their effects on representation efficiency in signing

For the first four age ranges of first sign exposure (particularly in the second scatterplot in the bottom row, showing participants who acquired sign around the age of seven), the data seem to show a relatively strong positive correlation between signing experience and propositions per syllable, but in the last two scatterplots at the upper right (for participants who acquired sign from around the age of 20) the correlation is weaker (i.e. the trend lines are more horizontal). This suggests that the younger someone begins to sign, the more their representational efficiency will be improved by subsequent experience.

However, this effect was associated with a rather small coefficient, and neither of the component factors in this interaction, nor deafness, showed significant effects by themselves (*p*s > .1); all three remained nonsignificant in a model without any interactions. The evidence that representation efficiency is affected by anything other than modality is thus quite weak. Moreover, since we did not analyze the grammaticality or intelligibility of the narratives, we cannot conclude that nativeness and experience (and deafness) are truly irrelevant to these crucial aspects of sign representation.

We then performed a regression model using the same independent variables, but with sign transmission efficiency (propositions per second) as dependent variable. In sharp contrast to the previous analysis, transmission efficiency showed quite a complex pattern of effects, illustrated in the two lattice plots in Figure 7. These show the relationships among deafness, age of acquisition, and signing experience (there are fewer scatterplots in the upper lattice plot because there were fewer deaf than hearing participants).



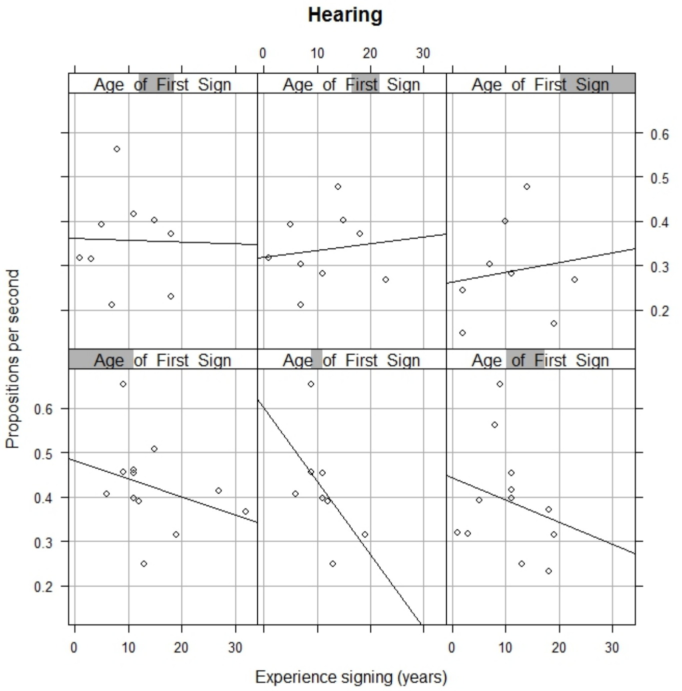


Figure 7: The interactions among deafness, age of first sign, and signing experience in their effects on transmission efficiency in signing

Age of acquisition had a significant effect (B = -0.02, $t(47) = -3.88$, $p < .001$): the older that sign was acquired, the lower the transmission efficiency. Years of experience also had a significant effect (B = -0.007, $t(47) = -2.39$, $p < .05$); six out of the eleven scatterplots in the figure show a rising slope, suggesting that experience tended to improve transmission (though interactions with the other variables make the sign of this coefficient negative). These two variables also showed a significant interaction with each other (B = 0.0005, t(47) = 3.49, $p < .01$), but the interaction seems to go the opposite way from that seen with representation efficiency: for both deaf and hearing participants, those who acquired sign later (the top row of scatterplots in each lattice plot) tended to show stronger positive effects of experience on transmission efficiency than those who acquired sign early (the bottom row of scatterplots in each lattice plot). That is, later learners benefited more from experience, perhaps because early learners were already near maximum transmission efficiency.

Although deafness by itself had no significant main effect ($p > .3$), there was a significant interaction between deafness and the age of first sign (B = -0.01, $t(47) =$ -2.23, $p < .05$). To see this in Figure 7, note that the vertical position of the data points in the lattice plot for the deaf participants remains roughly between 0.2 and 0.8 propositions per second, regardless of age of acquisition, whereas in the lattice plot for the hearing participants, the range of data points gradually shifts downward, from a range around 0.2 to 0.7 propositions per second for those who acquired sign at the youngest ages, down to a range around 0.1 to 0.5 propositions per second for those who acquired sign at the oldest ages. This means that age of first exposure to sign had a stronger effect on hearing signers than on deaf signers: early exposure benefited hearing signers in their sign transmission efficiency, but deaf signers all had high sign transmission efficiency regardless of when they began signing.

There was also a three-way interaction among all three variables ($B = 3.38\times10^{-4}$, $t(47) = 2.26$, $p < .05$). Deaf participants seemed to benefit more from experience if they had acquired sign late (compare the steep upward slopes of the trend lines in the top row of the lattice plot for deaf participants with the flatter or even downward sloping lines in the bottom row of this lattice plot). By contrast, hearing participants seemed to show no benefit from experience if they acquired sign late (see the flat slopes of the trend lines in the upper row of the lattice plot for hearing participants) and an apparent detriment from experience if they acquired sign early. This last observation seems paradoxical until we remember that for the hearing participants, most of their experience is with speech rather than sign. Thus the downward sloping lines seem to suggest that there was some language attrition (see Seliger and Vago 1991, for more on this phenomenon in spoken language).

A possible interpretation of the pattern of differences between the deaf and hearing participants is that the former had a stronger motivation to sign efficiently, given that it is their primary communicative modality. This motivation then enabled them to overcome the usual negative effects of late acquisition on mastering the phonology and phonetics of a language. Deaf participants who acquired sign late benefited greatly from subsequent experience because they were, in a sense, making up for lost time, under strong motivational pressures. These observations are entirely consistent with the literature on the learning of second (spoken) languages, the mastery of which also depends to a great extent on the degree of motivation (e.g. Crookes and Schmidt 1991).

A more general observation concerning all of the above findings is that sign transmission efficiency is affected much more strongly by age of acquisition and experience than is sign representation efficiency. It seems that it is much easier for signers to understand how propositions are encoded into signed syllables than it is to actually implement this encoding process in real time. This process is so difficult that it can only be mastered if signers begin implementing it at an early age, or are motivated so strongly by the need to communicate that they practice the skill to a sufficient degree of proficiency. The finding that early age (nativeness) benefits transmission efficiency is consistent with the earlier finding by Mayberry and Fischer (1989) that the efficiency of real-time phonological processing is a key bottleneck in the processing of sign, though our results suggest that strongly motivated practice may also help.

2.2.6 Effects of simultaneous communication on signing and speaking

Bellugi and Fischer (1972) noted that simultaneous communication seemed to increase cognitive load, as indicated by an increase in the duration of pauses. Our extraction of pauses meant that we could not study cognitive load using the same measure, but we were able to look for effects of simultaneity on representation efficiency and transmission efficiency, in both signing and speech. We expected that cognitive load would primarily be expressed in lowered transmission efficiency, for one or both modalities. Representation efficiency should not be affected, since this reflects long-term knowledge of linguistic structure rather than the implementation of this knowledge in real time.

Only one of our three native Mandarin-TSL bilinguals (labeled C in Tables 2 through 5) produced the story with modalities both separate (spoken Mandarin only or signed TSL only) and simultaneous. As can be seen in Table 6, this participant showed virtually no effect of simultaneity on representation efficiency (0.11 vs. 0.10 for speech and 0.21 vs. 0.20 for sign), but there were drops in transmission efficiency for both speech (from 0.52 to 0.39) and sign (from 0.41 to 0.35). These patterns are consistent with our expectations.

Table 6: Proposition per syllable and per second rates for a native Mandarin-TSL bilingual (separately signing or speaking vs. simultaneous communication)

	Efficiency	Speech	Sign
Separate	Representation	0.11	0.21
	Transmission	0.52	0.41
Simultaneous	Representation	0.10	0.20
	Transmission	0.39	0.35

To examine whether this participant was typical, we analyzed the results from the 26 hearing participants who produced the story all three ways: spoken Mandarin only, signed TSL only, or both simultaneously. Again using proposition per syllable and per second rates as measures of representation efficiency and transmission efficiency, respectively, we ran a generalized form of linear regression called linear mixed-effects modeling (Baayen 2008), which allowed us to include age of acquisition and years of experience as between-group factors, and modality (sign = 1 vs. speech = -1) and simultaneity of modalities (simultaneous = 1 vs. separate = -1) as within-group factors.

Significance was computed with the pvals.fnc function of the languageR package (Baayen 2008) in R (R Development Core Team 2010); this function uses resampling rather than the *t* distribution to estimate *p* values.

As with the native bilingual, the analysis of representational efficiency showed no effect of simultaneity: for simultaneous communication, the proposition per syllable rate, averaged across speech and sign, was 0.181, virtually identical to the average rate of 0.183 for speech and sign produced separately ($p > .7$). Simultaneity also failed to show any interaction with the other factors (*p*s > .9). Instead, representational efficiency was affected by modality, with signing showing a proposition per syllable rate of 0.24 versus 0.12 for speech ($B = 0.09$, $p < .001$), and by years since first sign, which hurt efficiency ($B = -0.002$, $p < .05$), perhaps because most of the experience of these hearing participants in later life was not with sign but with speech, which has lower representational efficiency. Modality also interacted with signing experience ($B = -0.002$, $p < .05$), such that sign representation efficiency was hurt by years of experience (again, mainly with speech) whereas experience had no effect on speech representation efficiency (since these hearing participants had presumably mastered it at a very early age). Modality also interacted with the age of sign acquisition ($B = -0.0001$, $p < .05$), such that the earlier sign was acquired, the more representationally efficient the signing and less representationally efficient the speech. In other words, age of acquisition affected mastery of representational efficiency for the earlier-acquired modality. However, the three-way interaction among all of these variables ($B = 4.61\times10^{-5}$, $p < .05$) showed that experience hurt early sign learners more than late sign learners, but only for signing: as hearing adults, the structure of the spoken modality always seemed to be the better mastered.

These complexities are similar to the interaction patterns we discussed earlier, but should not overshadow the main finding here, namely a lack of any effect of simultaneous communication on representational efficiency. Of course the usual caveat holds here, since we know from non-quantitative observations like those illustrated in Table 1 that simcom can have detrimental effects on the grammaticality and intelligibility of signing.

The analysis of transmission efficiency (propositions per second) showed a quite different pattern. Although the effect of simultaneity again failed to reach statistical significance, it came much closer than for representation efficiency ($B = -0.042$, $p = .18$): as with the native bilingual, the mean proposition per second rate, averaged across the speech and sign of multiple hearing participants, was lower with simultaneous communication (0.35) than with separate productions (0.43) (see Figure 8).

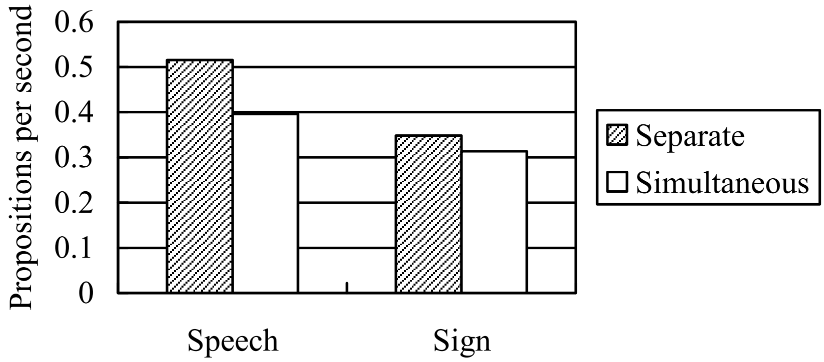


Figure 8: The effect of simultaneous communication on mean transmission efficiency in hearing participants

Again as with the native bilingual, simultaneous communication did not hurt one modality more than the other in transmission efficiency (no interaction: $p > .9$). However, there was a marginally significant effect of modality, with the transmission efficiency for signing of 0.33 propositions per second being lower than the 0.45 propositions per second rate for speaking ($B = -.057$, $p = .06$). Unsurprisingly, then, the hearing participants (most of whom were not native signers) were generally more efficient at producing speech than sign. Moreover, even though transmission efficiency was again affected both by age of first sign ($B = -0.005$, $p < .01$) and by signing experience ($B = -0.006$, $p < .05$), there was no interaction of these factors with anything else (*p*s > .2). This suggests that the hearing participants simply had insufficiently strong motivation to master sign transmission efficiency to the level of the deaf signers analyzed above, regardless of how early the hearing participants acquired sign or how much sign experience they had.

Nevertheless, the drop in transmission efficiency shows that communication did suffer in simcom. Thus even without quantifying the number of morphemes dropped in signing, as we saw in Table 1, we have confirmed the consensus view that simcom is not an appropriate method for communication between hearing and deaf interlocutors.

3. Conclusions

Overall, then, the key findings of Bellugi and Fischer (1972) hold up, even with more detailed analyses of a pair of languages quite different from those that they studied, and with a larger sampling and greater variety of participants. TSL represents information more efficiently than Mandarin due to overlap of information, which, when used by sufficiently proficient signers, allows the transmission of information to be equally efficient in the two languages, just as in ASL and English. The matching in transmission efficiency is quite striking, suggesting that the human language production system sends propositions to be encoded at roughly the same rate regardless of language or modality.

We also confirmed the usefulness of the notion of (articulatory) syllables as a unit of comparison, allowing the quantification of representation efficiency. While the syllable durations we measured for TSL were longer than those measured by Wilbur and Nolen (1986) for ASL, the difference may have been due to our discourse context mimicking child-directed speech, which encouraged slower production and exaggerated intonation (expressed in sign with longer movement excursions).

Our inclusion of age of acquisition and years of experience as continuous variables in the regression analyses also allowed us to confirm the importance of nativeness in the efficiency of signing, primarily for transmission efficiency: the younger a participant was first exposed to sign, the higher the proposition per second rate, regardless of years of experience. By contrast, even hearing late learners of sign were able to match the proposition per syllable rate typical of fluent deaf signers (though whether they did this as grammatically and intelligibility is another question). At least for the measures we used, the effects of age of acquisition were thus primarily a matter of temporal performance (per second rates), not of structural competence (per syllable rates). That is, native signers were more efficient in the mechanics of converting propositions into strings of syllables in real time, consistent with the observations of Mayberry and Fischer (1989). Nevertheless, given sufficient motivation to master signing, as is the case for the deaf participants, even late learners can benefit greatly from experience.

The pedagogical implications of Bellugi and Fischer (1972) were also confirmed and strengthened by this study. The amount that a student can learn from lectures over a school year depends at least partly on the transmission efficiency of the language used by the teacher. We have confirmed that this rate is identical for TSL and spoken Mandarin, when produced separately. Our results suggest that it doesn't matter so much if the teacher is a native signer or not, though deaf signers seem to be better motivated to master the challenges of real-time transmission efficiency. Deaf children in Taiwan thus have the potential of learning at the same rate as their hearing friends taught in Mandarin, but only if they are taught in TSL. This includes their rate of learning Mandarin itself; studies in the United States have demonstrated that deaf children are readily able to learn English if it is taught via ASL (e.g. Wilbur 2000). By contrast, given the much lower representation efficiency of speech relative to sign, artificial sign systems that convert spoken morpheme sequences into manual gestures will necessarily have lower transmission efficiency, thus lengthening the time needed to teach the same material. We have also confirmed that simultaneous communication reduces transmission efficiency as well. If our observed drop from 0.43 to 0.35 propositions per second is typical of Mandarin/sign simcom, this implies that in a ten-month school year, deaf children taught using simcom could only complete around 80% of the curriculum, resulting in a loss of two months of instruction every year. These quantitative observations are consistent with the detrimental effects on grammaticality and intelligibility that we noted in our transcripts for simcom, as well as in more systematic studies of English/sign simcom (Wilbur and Petersen 1998) and Mandarin/sign simcom (Hsing 2003).

The evidence therefore strongly suggests that equitable instruction for deaf and hearing children is possible only if classes in deaf schools in Taiwan are taught exclusively in TSL, not in signed Chinese and not simultaneously in sign and spoken Chinese.

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手語與口語的表徵效率與傳輸效率

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過去的研究早已發現美國手語單詞的時長比英語單詞長；但由於手語是視覺－手勢管道的語言，在表達手語單詞時，詞素可以同時呈現，因此手語和口語在同樣的時間內所能表達命題訊息量並無差異。本文進一步將上述結果延伸至台灣手語和漢語的比較。我們收集了合計 57 人的聾人的手語及聽人的漢語、手語及口手語並用之故事語料，以統計方法進行分析，提供實證結果。我們發現台灣手語的表徵效率（即每音節的命題量）遠大於漢語；然而兩者在傳輸效率上並無差異，即兩者每秒鐘有相同的命題數。我們也檢視了學習手語的年齡及使用手語的經驗對表徵效率及傳輸效率的影響。另外，我們也發現同時使用口語和手語說故事時，其效率往往不如單獨使用手語或漢語。綜合上述的研究結果，我們認為，相較於口語或口手語，使用台灣自然手語教育聾生效率最佳。

關鍵詞：台灣自然手語、漢語、語言產生、效率、口手語共時溝通