Neo--- A new perspective on STM capacity

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Summary

Exploring the word length effect from the perspective of information density, the current research extended previous findings on cross-linguistic differences in STM capacity with the development of a new strategy that has the potential to double one's digit span with minimal learning and a much shorter training period. Experiments have shown promising results and responses to training differed across language groups. The underlying mechanisms are explored and discussed in relation to strategy usage, capacity estimates and optimization of language system.

Chapter I

Review on STM Capacity

1.1 The Classic

The capacity to store and manipulate information in the absence of external stimuli frees us from stimulus driven behavior and underlies our ability to learn, plan, reason and communicate. Over the recent decades extensive research has focused on understanding this vital cognitive feat and increasing its capacity. Our research explores the possibility of improving short-term memory (STM) performance based on language system from a perspective of information-modality optimization. In his seminal paper, George Miller (1956) put forward his observation that performance on short-term memory (STM) centered around 7 items. Although Miller never intended to make this a theoretical estimate of STM capacity, the notion of “Magic Number 7, plus or minus2” was readily embraced and is still applied to many standard assessments including WAIS. (Ryan & Ward 1999) It was also noted at the time that the format in which information is presented to us does not necessarily match the way with which we hold this information in immediate memory. In a process termed chunking, sets of items due to their inter-item association can be conceptually grouped into a smaller number of chunks that leads to better performance on STM tasks. An example from Miller’s study was: f-b-i-c-b-s-i-b-m-i-r-s, though intended to be 12 items as a letter span, could be grouped conceptually into four items (FBI, CBS, IBM, IRS) for United States Citizens. Miller claimed that although performance in STM can be significantly improved through increasing the information content of each chunk, the number of chunks that we can hold in our immediate memory is fixed. In other words, seven (or other estimations proposed by researchers following similar line of thought, see Cowan 2000) is still magical. Now, decades after Miller's original observation the central theme remains: What is our limit and how can we improve upon it.

In search of freedom from the severe constraints placed by limited STM capacity upon our ability to process information, undergraduate S.F. (Ericsson, Chase & Faloon 1980) gave us an impressive demonstration of the power of chunking. Over 20 months, S.F. increased his digit span from a typical 7 to 79 through extensive self-training and 230+ hours of lab testing. Two essential processes underlie his amazing memory skill (1) mnemonic associations: using his expertise in long distance running he was able to associate random numbers to items with more familiar substance relieving the burden on his STM. For example 34928931944 could be made into a combination of running time (3492 = 3 minutes 49.2 seconds - near world record time for the mile), age (893 = 89.3 - a very old person) and date (1944 = near the end of the war). (2) Organizational structure: using association alone, S.F. soon met a plateau imposed by rehearsal buffer that stores information in phonetic code. His way to proceed further was to divide each group into subgroups of three or four and to create up to a three-level hierarchy---the retrieval structure for 80 digits took the form of: 444 444-333 333- 444-333-444-5. Despite his outstanding performance on random digit span, S.F.'s performance on other STM tasks (letter span) remained normal. This led Ericsson et al. to argue that though there was seemingly no limited for increasing *memory span* through mnemonic association and a retrieval structure, it is not possible to increase *STM capacity* through extended practice.

Meanwhile, S.F. also demonstrated the weakness of chunking. Twenty months of training (230+ hours of lab testing) with prerequisite of an area of expertise beneficial to number coding (long distance running in his case), no doubt few if any followed his practice for better digit span. Considering the mechanisms of chunking this is hardly surprising: mnemonic association relies largely upon long-term memory (LTM) to make the unknown familiar. In other words it reduces the information (entropy) of incoming stimuli through association to prior experience.

(1) Depending upon the recoding scheme, an uncomfortably large database is almost always required. As for the example of running time, in theory 10000 unique associations are necessary to ensure accurate and reliable mapping from 4 digits into one time. In reality his database was probably smaller and the process was much messier: his expertise helped a great deal though in itself not sufficient, age and date were adopted to avoid the non-codable sequence (remember time is not based on decimal system). (2) The LTM approach is computationally intense and both the efforts of recoding and constructing a retrieval structure are not evenly distributed across digits. Use the same example as before, in the digit string of 3492893194**4** numbers 2 (associate running time), 3 (associate age), and **4** (associate date *and* forming supergroups) would impose a heavy computation demand in the context of a relatively fast presentation rate. That’s why S.F.’s retrieval structure was simple in principle but hard in practice; it took over one year’s practice for it to work at one

digit per second rate (even though 1 digit/sec is already much slower than normal speech rate which makes the pragmatics of the chunking approach outside a lab setting questionable).

1.2 The Alternative

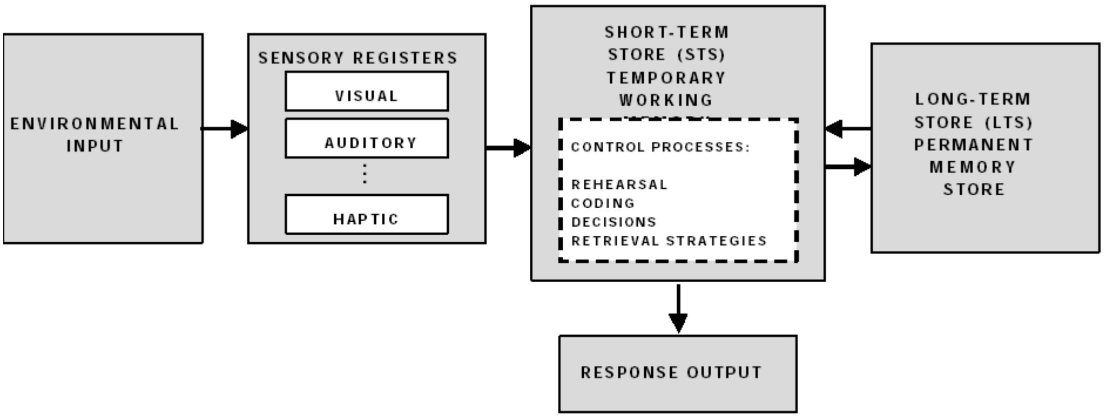


Figure 1: Atkinson-Shiffrin model of human memory

Within the general framework of human memory (Atkinson & Shaffrin 1968, Figure. 1) multiple processes involving the sensory store, short-term store and long-term store precede the actual response output in any memory task. There is no reason to assume that LTM is the only potential source of improvement. Besides chunking that relies heavily on long-term memory, mechanisms underlying the sensory registers and the short-term store itself are logical alternatives to explore. At the sensory level the modality's influence on digit span has been demonstrated in:

(1) Modality switching (Reisberg, Rappaport & O'Shaughnessy 1984). With brief training to represent digits with finger movements, participants were able to significantly increase their digit span by first holding some numbers with their digit-digit span (this term refers to number represented by finger movements) and

then switch to the more traditional phonological digit span. Adding digit-digit span typically yield an increase of 3-5 numbers at a small tradeoff from phonological span, which decreases by one on average.

(2) Modality replacement (Hatano & Dasawa 1983, Stigler 1984). Human routinely resort to a phonological-loop based language system in STM tasks, sometimes at our own cost. It is well known among Asians that abacus calculation, which taps the visual-spatial aspect of STM, enhances one's ability to hold and manipulate numbers relative to its language-based counterparts. With practice both digit span and digits of running sum during calculation increase over time in skilled abacus users. In recent years, China witnessed a resurgence of abacus tradition in its modified form "Mental abacus training" which targets Children aged 5-7 with promising results.

1.3 The Unexplored

Before seeking external assistance from long-term memory or other sensory modalities, it is wise to examine the potential of our phonological STM first. It was found that even for visually presented letter-list recall errors tend to be acoustic in nature. This suggests that we use a phonological code in most STM tasks. (Conrad 1964) This phenomenon reflects an adaptation to extensive language usage since deaf people and children under age 5 are not influenced by phonological similarity. Later Baddeley and Hitch (1974, Baddeley 1986) proposed their famous three-component model of working memory which includes the central executive responsible for information integration as well as plan and control of behavior, and two other slave systems: the phonological (articulatory) loop which actively maintains speech based information and the visual-spatial sketchpad which sets up and maintain visual images. They also noted the effect of word length on STM, adults recall fewer long words (like “University, Bronze, Mosquito, Orchestra, Amplifier”) than shorter ones (like “Inn, Lump, Wife, Star, Golf”) that the amount of recall roughly corresponds to what adults could speak in 2 seconds and speech rate is positively correlated to memory span size. (Baddeley, Thomason & Bauchanan 1975) Their research had important implication to cross-linguistic research: Within this framework a typical digit span measuring STM would tap the phonological loop and consequently subject to word length effect. Since languages differ on the number of syllables in representing digits, one would expect speaking different languages would impact speech based STM capacity, and it turned out to be exactly the case. English/Welsh bilinguals have a larger digit span when they hold information in English rather than Welsh and this is even true for people who speak Welsh better than English. (Ellis & Hennelly 1980) (A recent reexamination of Welsh/English span difference suggests articulatory complexity at item boundaries also contribute to the phenomenon, see Murray & Jones 2002). Follow-up researches looking into other linguistic systems suggest that Chinese, in which a single syllable represents each digits, offerd the best performance on digit span. (Cheung & Kemper, 1993 Stigler, Lee & Stevenson 1986) This evidence refutes the notion “ a digit is a digit is a digit” and challenges the idea that STM is characterized by a fixed number of items (chunks).

1.4 The Insight

The cross-linguistic study also points to a new direction for improving our STM performance: If our performance reflects the biological limit on phonological loop *and* the efficiency of the language system we apply, then a logical conclusion will be to "improve the efficiency of our language in representing information" will confer further boost to STM span. However, no significant advances were made along this direction, it maybe due to the apparent ceiling some languages have reached. The smallest phonetic unit that we are able to produce and manipulate is a syllable, and as was mentioned before language such as Chinese has already reached one-to-one syllable-digit ratio with English not far behind, thus there seems to be no room for Chinese to improve language efficiency and only a relatively small potential for English as well.

However, an information-theoretical analysis suggests otherwise. All information, irrespective of the form it takes and the channel through which it is conveyed, represents levels of uncertainty in nature that could be measured in bits. An English syllable which combines 1 out of 24 consonants and 1 out of 21 vowel sounds, has the potential to represents 24*21+21=525 possible variations (V525, roughly 9 bits of information) while a decimal system digit only represents 10 possible variations (V10, little more than 3 bits of information), thus mapping a V525 symbol (a syllable in our case) to a V10 symbol (a digit) is obviously *inefficient*. In addition, some digits in

English take 2 syllables to represent, a V285625 for a V10, a huge waste of energy indeed. A major insight was gained when I realized that each subcomponent of a syllable, a consonant and a vowel, constitute a symbolic system with V>=21, which is more than sufficient for a one-to-one mapping onto a V10 system (digits). Thus with existing knowledge of their own native language and the decimal system, people could associate each digit with both a consonant and a vowel sound and learn to read digits in a new language, where every digit now reads one phoneme only. Being a consonant or vowel is dependent upon even/odd position and the whole string reads in the CVCVCVCV…manner to fit our habit of pronunciation. For the same string of digits, reading in new language would more than halve the number of syllables needed relative to reading in one's native language. In other words, this affords the potential to double STM capacity. We conducted three experiments to test the hypothesis that using Neo over one's native language will confer an increase in digit span. There are several possible approaches: (1) The bilingual approach where participants capable of using native and Neo language perform digit span in both and compare the result. (2) The cross-linguistic approach, which compares performance of participants speaking Neo to those who use their native language. (3) The S.F. approach, which uses a most devoted participant who spend huge amount of time on a specific strategy to obtain impressive results. We implemented all these approaches in the following experiments:

Chapter II

Experiments

2.1 Experiment 1

2.1.1 Methods

Participants:

The participants were 42 Native English speakers (26 women and 16 men) from Georgia Tech. All of them were undergraduates who participated the experiment to fulfill the credit requirement for their introductory psychology class.

Material:

Table 1: Neo-conversion table (English version)

b	d	g	k	L	M	n	p	s	t
1	2	3	4	5	6	7	8	9	0
ar	ay	ow	ing	or	ee	ew	an	y	oo

(11-Bar, 22-Day, 33-Go, 44-King, 55-Law, 66-Me, 77-No,88-Pan,99-Sigh,00-Too)

Participants who are native speakers were given this conversion table, (Table 1) which maps each digit in the decimal system to both a consonant and a vowel sound in English. Learning this conversion table would allow them to speak any two digit combination in one syllable, for example 85---Paul, 46---key.

Digit span: Digit span task was incorporated in a PC program written in VB. Randomly generated digits (with equal frequency) appear at the center of the screen at a 1/second rate. Participants are instructed to hold the information in STM and then report the string in the original order through keyboard input. A correct recall will increase the digit span by one and participants continue with longer string until they make a mistake. They will be offered second chance to challenge the same digit after the first mistake. Two consecutive mistakes marks the end of this test, and the best number of digits they successfully recall is defined as their digit span.

Syllable span: Syllable span task was incorporated in the same PC program written in VB. Which is identical to digit span program with the only exception that now randomly generated syllable (combination of consonant and vowel sound, randomly selected with equal frequency from the 20 possibilities listed in the conversion table) will be presented at the center of the screen and memorized for later recall.

Procedure:

At the beginning of the experiment, participants would be individually tested on their digit span and syllable span. Their performance and the strategy used in achieving the span recorded. Next they will learn the Neo conversion table (English version) and report to experimenter when they have grasped the digit-syllable conversion. Which was the first step in acquiring a new language with better efficiency in representing numbers.

It typically took participants 20-30 minutes studying Neo conversion before they moved on to computer based training of the new language, during which they would go through a series of steps of ascending difficulty: 1.Provide the corresponding consonant/vowel to randomly generated digits. 2.Provide the corresponding syllable to randomly generated digit pairs. 3. Self-paced reading digits in new language 4. Computer-paced reading of digits in new language, with increasing speed and difficulty (digits no longer appear in pairs but one by one as in standard digit span test and the participants have to keep track of consonant vowel alternation)

Participants would then be presented with opportunity of customized digit span task, when they had the options to specify the number of digits they wish to challenge, the presentation speed and the pattern of presentation (single or in pair). During this period, participants explored the best approach for them to excel in digit span task. Since the task itself did not impose requirements for specific language, they were free to choose between Neo and their native language for best performance.

At the end of experiment participants would perform the digit span again and report the strategy they adopt to achieve it. For those whose performance involved using Neo, they were asked to take another digit span task using their native language only. Thus for every participant we filed DSE (digit span end, using native language only). For the group who spoke Neo in their final performance, we file DSNeo (digit span Neo). Strategy uses in both languages are filed as EP (end pattern) and NP (neo pattern) respectively. Also a second syllable span was carried out to obtain SSE (syllable span end). 21 English participants ended up in experimental group and the remaining 21 (consists of 16 participants who were exposed to Neo but for a number of reasons choose not to use for best performance and another 5 who were not exposed to Neo, there is no baseline between these two groups).

Thus at the end of experiment we have the following factors for each participant on file: Native language (English/Chinese), Digit span original (DSO) and strategy (OP), Digit span end (DSE) and Strategy (EP), Syllable span original (SSO) and syllable span end (SSE) and for those who use Neo for digit span, Digit span Neo (DSNeo) and strategy (NP). From which we were able to derive many other important statistics including percentage of improvement and contribution of Neo.

2.1.2 Results:

Digit span: The original digit span for English speaker participated in the study was 7.45 with a standard deviation of 1.09. (Figure 2) Over the session extensive exposure to digit span test conferred small but significant increase to their digit span performance in English (Digit span M=8.29, SD=1.12. mean increase=0.83), t=4.80, P<. 001. There was no difference between the experiment and control group in their original digit span (experimental group M =7.48, SD=1.28, control group M=7.43, SD=.87), F (1,40)=. 02, P=. 889. Nor in their end digit span in English (experimental group M= 8.14, SD 1.11, control group M=8.43, SD 1.03), F (1,40)=.75, P=. 392. However, the best performance of experimental group (M =11.62, SD=2.06) was significantly better than that of control group (M=8.47, SD=1.08) F (1,40)=38.35, P<. 001, indicating Neo did boost digit span over native language. The pattern held when we compared within experimental group their digit span performance in both neo and native languages, the mean difference is 3.48, t=13.65 P<. 001.

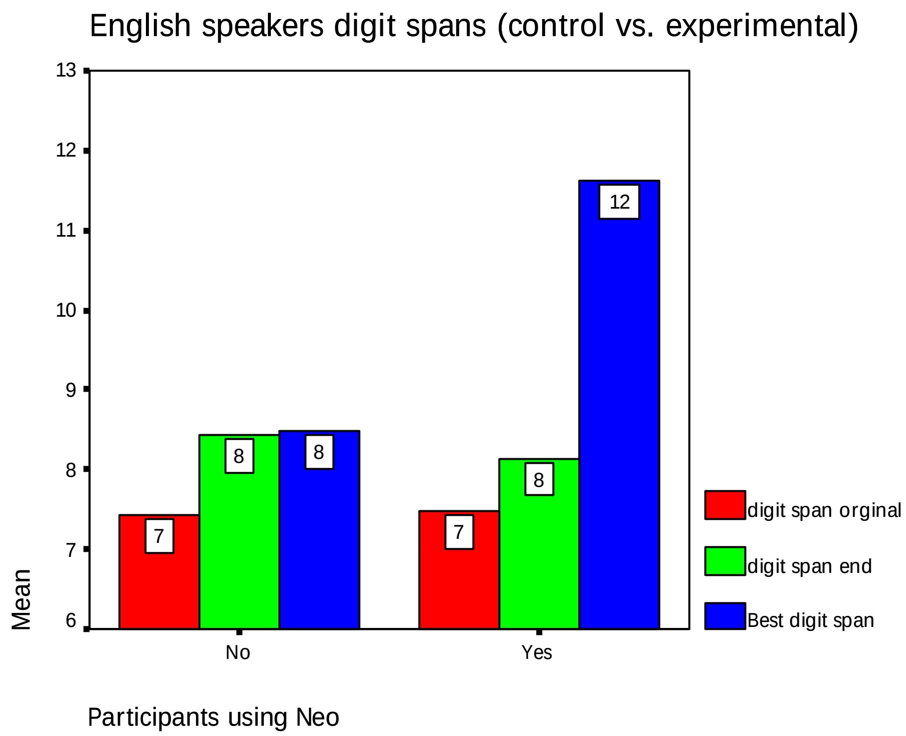


Figure 2: Performance on digit span of English speakers. Red-digit span measured at the beginning of the experiment. Green-digit span measured at the end of the experiment in English. Blue-best digit performance, for experiment group it is performance at the end of the experiment using Neo.

Syllable span: English speakers began the experiment with a syllable span of 4.45 on average (M=4.45, SD= .73). There is no significant difference between experimental group (M=4.62, SD= .67) and control group (M=4.29, SD= .78) on this measure. However, over the experiment session the syllable span of the experimental group increased to an average of 5.38 (SD= .74) and was significantly larger than that of the control group (M=4.43, SD= .60) at the end of the experiment, $F(1,40)=21.05$,

$P<.001$.

In sum (1) the results confirm the previous finding that digit span of English speakers centered around 7 with a standard deviation of 1. (Miller 1956) (2) Hour-long exposure to digits training confers slight but significant increase to digit span, which should be take into consideration when we judge the efficacy of any memory strategy applied. (3) For those 21 participants who were capable of using the strategy, Neo language conferred a significant boost to digit span performance independent of the exposure effect. In other words, the Neo strategy worked well. (4) The syllable span of English speakers started similar between experiment and control groups but became significantly different at the end of the experiment session.

2.2 Experiment 2

2.2.1 Methods

Participants:

The participants were 18 Chinese speakers (11 women and 7 men). 16 of them live in the States and were students/staff from Georgia Tech, Emory University, Georgia State University and Penn State University. Among them 12 were graduate students, one undergraduate and three postdoctoral fellows. Two other participants were recruited from China through e-mail correspondence. They either volunteered or participated in the experiment for payment.

Material:

Table 2: Neo-conversion table (Chinese version)

d	t	l	n	g	K	h	zh	ch	s
1	2	3	4	5	6	7	8	9	0
a	uo	e	u	Ai	An	ao	ang	eng	ong

Participants whose native language is Chinese were given this conversion table (Table 2) which maps each digit in the decimal system to both a consonant (shengmu) and a vowel (yunmu) sound in Pinyin system (Chinese phonetic symbol system). Learning this conversion table would allow them to speak any two digits combination in one syllable, for example 77-hao, 67-kao.

Digit & Syllable span: Digit and syllable span tasks are identical to that of experiment one with the only exception that consonants and vowels used in generating the syllables will be randomly selected from the 20 possibilities listed in the Chinese version of the conversion table.

Procedure:

Identical to that of experiment one. Chinese participants underwent digit/syllable span, Neo conversion table, computer-based training of Neo language, customized training and final retesting of digit/syllable span in the order specified. The entire session lasted about 2 hours. 8 Chinese participants ended up in experimental group while the remaining 10 in control group.

2.2.2 Results:

Digit span: A similar pattern was observed in Chinese participants. (Fig. 3) The original digit span for Chinese speaker participated in the study was 9.33 with a standard deviation of 1.08. Over the session extensive exposure to digit span test conferred small but significant increase to their digit span performance in Chinese (Digit span M=9.89, SD=1.08. mean increase=0.56), t=2.56, P<. 05. There was no difference between the experiment and control group in their original digit span (experimental group M =9.63, SD=1.06, control group M=9.10, SD= 1.10), F (1,16)=1.04, P=. 332. Nor in their end digit span in Chinese (experimental group M= 9.88, SD .99, control group M=9.90, SD 1.19), F (1,16)= 002, P=. 963. However, the best performance of experimental group (M =12.5, SD=1.30) was significantly better than that of control group (M=10.2, SD=1.31) F (1,16)=13.63, P<. 01, indicating Neo also boosted digit span performance over Chinese. The pattern held when we compared within experimental group their digit span performance in both neo and Chinese, the mean difference is 2.88, t=5.58 P<. 001.

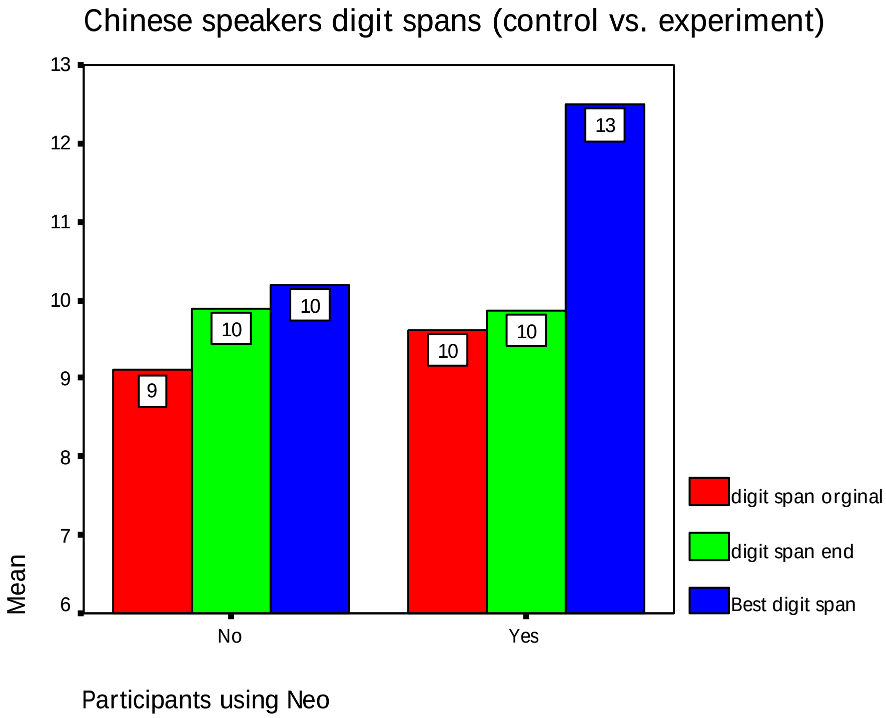


Figure 3: Performance on digit span of Chinese speakers. Red-digit span measured at the beginning of the experiment. Green-digit span measured at the end of the experiment in English. Blue-best digit performance, for experiment group it is performance at the end of the experiment in Neo.

Syllable span: Chinese speakers began the experiment with a syllable span of 5.22 on average (M=5.22, SD= 1.06). Unlike English speakers, there is significant difference between experimental group (M=5.75, SD= 1.03) and control group (M=4.8, SD= .91) on original syllable span. However, this difference disappeared over the experiment session, the end syllable span of the control group increased to an average of 5.70 (SD= 1.16) and was no longer statistically different from that of the experiment group (M=5.75, SD= .46), F (1,16)= .13, P=. 91.

In sum, (1) the results confirm the previous finding that digit span of Chinese speakers centered around 9 with a standard deviation of 1. (Cheung & Kemper 1993) (2) Similar to experiment one with English speakers, hour-long exposure to digits training confer slight but significant increase to digit span, which should be take into consideration when we judge the efficacy of any memory strategy applied. (3) For those 8 Chinese participants who were capable of using the strategy, Neo language conferred a significant boost to digit span performance independent of the exposure effect. (4) Unlike the English group, syllable span of Chinese speakers in experiment and control groups started significantly different but the difference was gone at the end of the experiment session.

2.2.3 English-Chinese comparison:

Response to strategy: We pooled the results from two groups and subjected them to a 2 (neo vs. native language) * 2 (English vs. Chinese) ANOVA. The dependent variable was improvement measured in percentage, taking into account the difference in baseline. (Percentage increase makes better sense here than absolute span increase since increasing digit span from 4 to 8 is a different story comparing to increase from 8 to 12) Both a significant Neo effect (F (1,56)=28.73, P<. 001) and speech effect (F (1,56)=6.05, P<. 05) were observed, as well as a Neo*speech interaction, F(1,56)=4.80, P<.05. (Fig. 4)

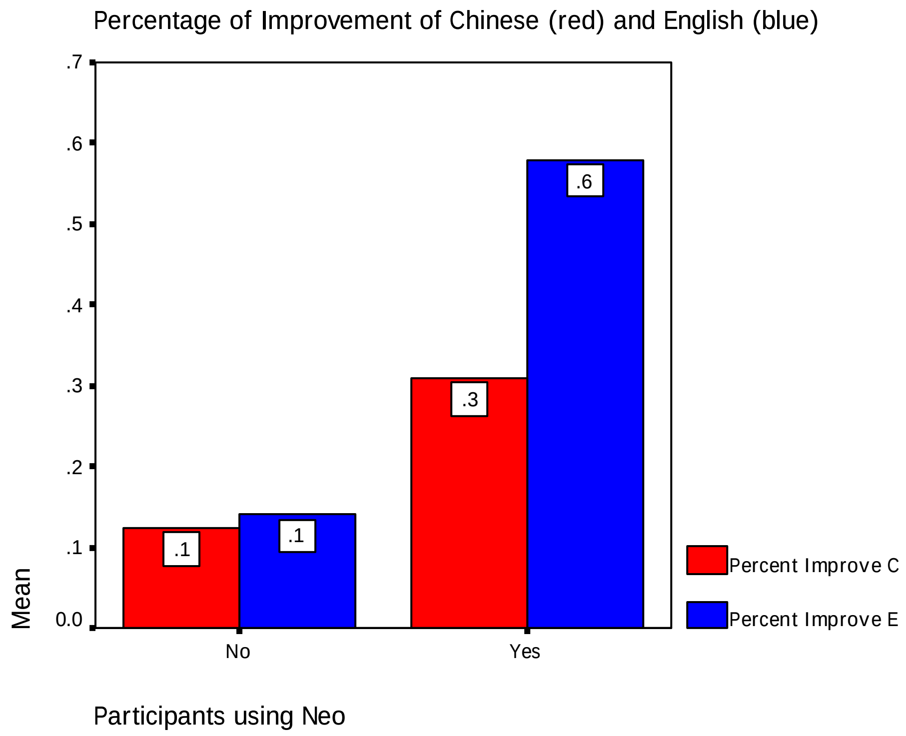


Figure 4: Comparison of experimental and control group on improvement. Red-percentage improvement among Chinese participants. Blue- percentage improvement among English participants.

The main effect of speech confirms previous finding on cross-linguistic difference. (Cheung & Kemper 1993) and the main effect of Neo demonstrated the efficacy of the new strategy. The Neo* Speech interaction showing English speakers benefit more from using Neo relative to Chinese speakers is an intriguing phenomenon and may result from two possible mechanisms: (1) English speakers have better native syllable-neo syllable tradeoff ratio than Chinese speakers, thus English speakers suffer less penalty to span in native language for each Neo span gained. (2) English speakers were capable of representing more digits in Neo than Chinese speakers. (3) It is also possible that English speakers benefit from combined effects of both.

The tradeoff between English and Neo language is analogous to what has been observed in Reisberg's digit-digit span study (1984) where a combination of finger span and traditional span increased their finger span at a cost to their traditional span. In our case, increase in Neo span was always accompanied by a decrease in span in native language. An example would be a participant began experiment with 8 digits in English and ended up with a digit span of 11, which consists of 4 syllables in Neo (accounting for 8 digits) and 3 digits in English. The tradeoff is calculated as (8-3)/4=1.25, in theory as long as this number is smaller than 2 the tradeoff is worthwhile. Another derived statistics is the contribution of Neo to final performance. For this participant it would be calculated as 4*2/11=. 73. Analysis has shown that English and Chinese has similar tradeoff ratio (English mean=1.19 vs. Chinese mean=1.10 t=. 574 P=. 57) but significantly different number of Neo syllables they applied (English mean=4.47 vs. Chinese mean=3.0 t=4.89, P<. 001) as well as in the contribution of Neo to the final performance (English mean=77.8% Chinese mean=48.1%), t=4.63 P<. 001. (Fig. 5) The results indicated that though English speaker were as efficient as Chinese speakers in Neo-native syllable tradeoff, they were much better at adopting the Neo language than Chinese speakers, which contributed to their greater improvement within the 2 hours period. It remains to be explored whether Chinese speakers could reach the same efficacy with longer period of training.

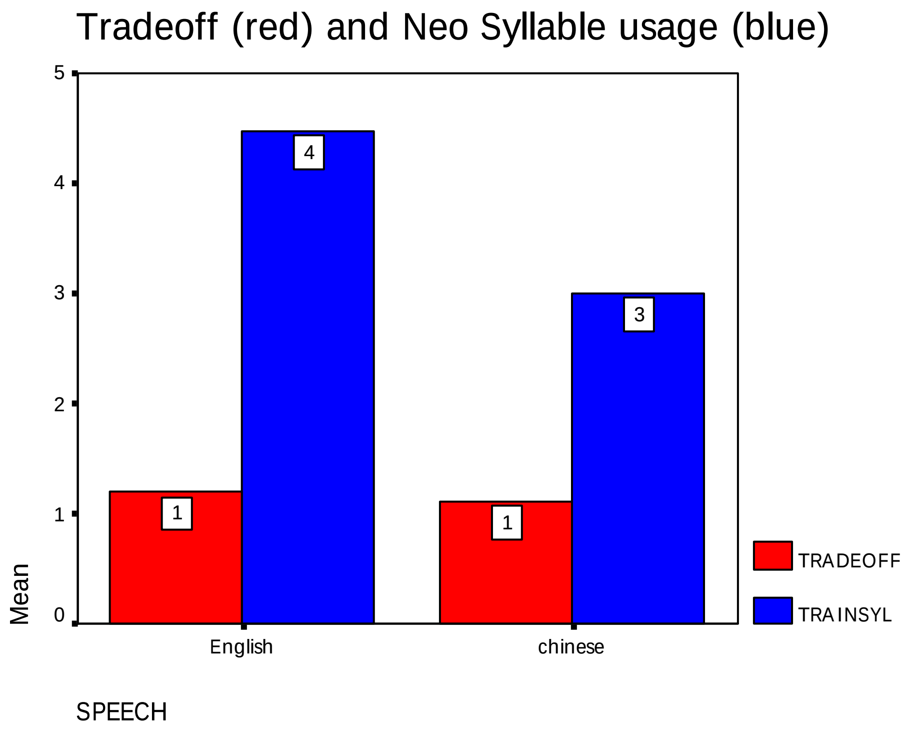


Figure 5: Comparison of English and Chinese speakers on tradeoff ratio (red) and number of Neo syllables adopted in best performance (blue).

Syllable estimation: We set out to test the syllable span of all 60 participants with the hope of obtaining a good estimate of syllable span from which we may derive an information span. There was no reason to assume one's syllable span is going to change over the period of 2 hours experimental session, however the finding is likely to be confounded by differences in educational system of China and the United States. In China every school year children receive the same extensive phonetic training in the form of Pinyin system while American children do not experience such uniformity of training: some underwent the whole-word reading approach and skipped much of the phonetic training while those who did receive phonetic training vary on the amount and the symbols they stick to. (As I realized with dismay through the experiment, a large percentage of undergraduates in the States have problem with international phonetic symbol and the situation is not much better with the Webster phonetic symbol system.) Thus two-syllable span test were given at the beginning and the end of experiment to check on this issue.

As shown in Figure 6A and Fig 6B, the original syllable span (SSO) for Chinese speakers had a mean of 5.22 with SD of 1.06 whereas English SSO mean=4.45 SD=.74. The syllable span end (SSE) showed an average .50 increases for Chinese speakers and a similar .45 increase for English speakers. I interviewed every participant whose SSE is different from SSO for possible reasons of change and the invariably the response I got was “feel more comfortable with syllables” rather than explicit strategy change characterizing change in digit span performance. I assume SSE would be a better indicator of syllable span once the familiarity effect are somewhat controlled for. When we analyze the influence of native language and Neo use on change in syllable span (SSE-SSO) over the experimental session with ANOVA, neither native language nor Neo have a main effect on syllable change, but a significant Neo*speech interaction, $F(1, 56)=8.53$, $P<.01$. My speculation is that English speakers under the training condition benefited from the 2 hours exposure to syllable conversion to compensate for their lack of familiarity to phonetic system while Chinese speakers with extensive training on Pinyin reached a ceiling effect and makes little, if any improvement. The story with the control group is just the reverse, Chinese speakers who did not perform very well on SSO took the opportunity to revive their memory with Pinyin system and improve their SSE performance to extent indistinguishable from that of experimental group while English speakers who became control largely due to their problem with phonetic system invested less on syllable conversion and showed little improvement on SSE. It also suggest that the population mean of syllable span of this age group is probably around 5.7 and a few more hours phonetic training is likely to consolidate performance that is indistinguishable across language groups.

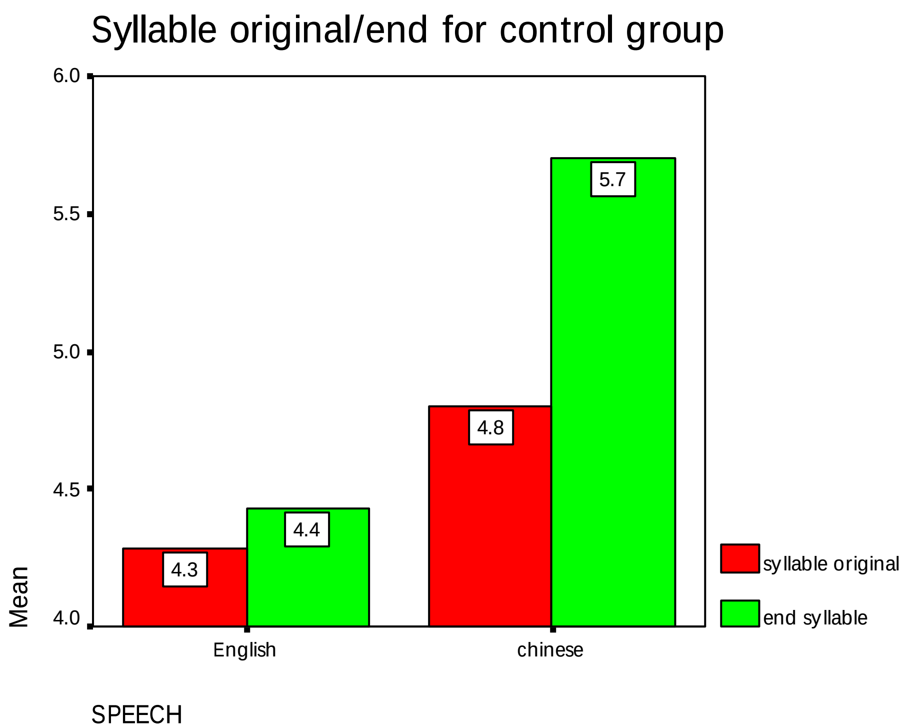


Figure 6A: Comparison of syllable span between Chinese and English speakers (control group). Red: syllable span at the beginning of the experiment. Green: syllable span at the end of the experiment.

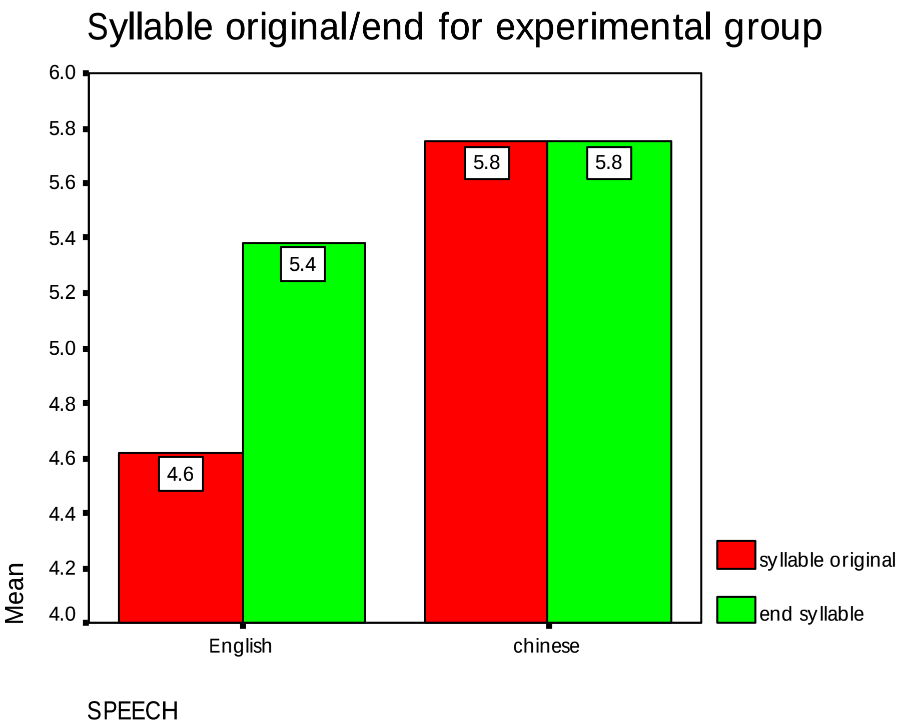


Figure 6B: Comparison of syllable span between Chinese and English speakers (experimental group). Red: syllable span at the beginning of the experiment. Green: syllable span at the end of the experiment.

2.3 Experiment 3

2.3.1 Methods

Participants:

Two very devoted participants from Experiment 2, one Chinese male at Georgia Tech and one Chinese female at Penn Sate University, agreed to invest 10 hours instead of 2 hours on this training program.

Material:

The computer program used in experiment three is identical to that used in experiment 2. For the 8 one hour training session after the first session, participants practiced with printed copy of random digits tables. Each table consists of 40*47 randomly generated digits with the help of free online program at www.graphpad.com/quickcalcs/**random**N1.cfm .

Procedure

The first session of the experiment was identical to experiment 2. After the initial 2-hour experimental session participants would spend another 8 hours in the form of 8 one-hour training sessions over the period of a week. During each practice session participants practiced with either the customized training computer program or printed random digit table. At the end of each session standard digit span tests were administered to keep record of change in performance.

2.3.2 Results:

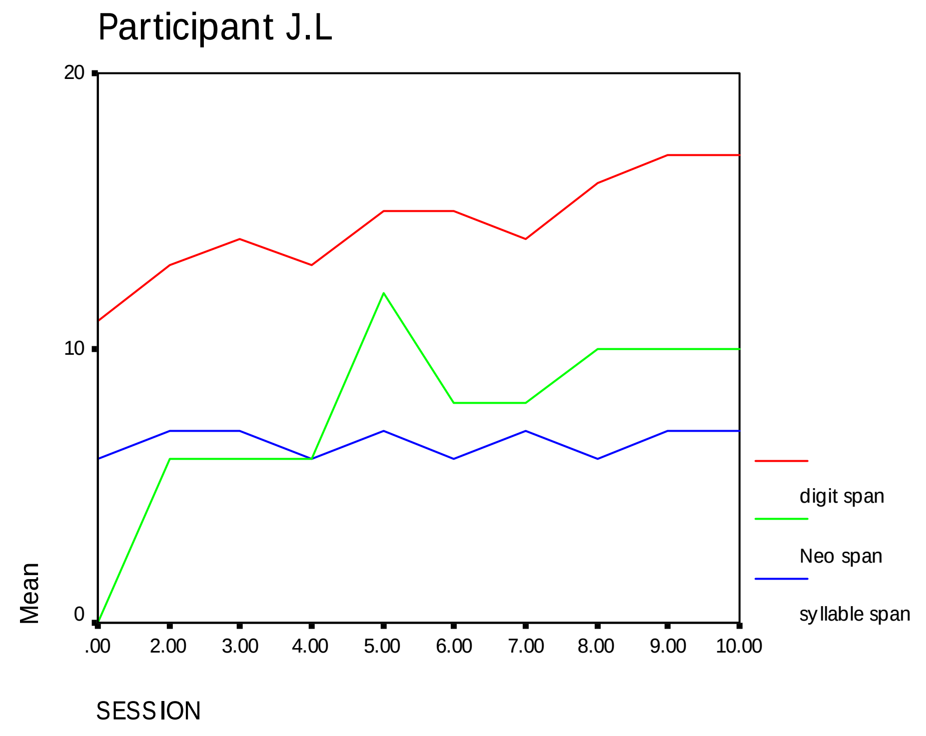
As shown in Figure 7A and 7B: The male participant (J.L) began with a digit span of 11. At the end of the experimental session he achieved a digit span of 13 in the form of 3 neo syllable plus 7 digits in Chinese (13=3s+7), at the end of 10-hour training he reached a digit span of 17 in the form of (5s+7). The female participant (K.C.) also began with a digit span 11. At the end of experimental session her digit span remained 11 as she prefer to use native language for digit span at the time (thus she was included in the control group then). Over the remaining training session her ability to use neo syllable system improved considerably and she ended up with a digit span of 18 in the form of (6s/6). The syllable span of both participants remained same over the session, fluctuating between 6 and 7 averaging 6.5 and 6.3 respectively.

The results from these two devoted participants have several important implications: (1) As partial response to the question raised at the end of experiment 2, it suggests that given further training, Chinese speakers were also able to grasp and benefit from Neo in a similar pattern as English speakers. Within ten hours' period, their final performances were approaching the theoretical max and dominated by use of Neo. Over reliance on the old system may inhibit acquisition of the Neo system, (like in the case of K.C. who didn't use Neo until the 6th session and was put into control group in experiment 2) but does not seem to reduce the efficacy of the Neo system once it is well learnt. (K.C. ended up with digit span of 18 at the end of the experiment, set the highest digit span record in our study.)

(2) It lends support to the notion that syllable span remained relatively stable over time and the cross-linguistic difference as well as the experiment-control difference between starting and end syllable span observed in first two experiments were probably, as previously discussed, artifacts from educational background and phonetics exposure. Consequently, it supports estimation of STM in terms of information capacity as a reliable alternative to traditional item based estimate.

(3) Comparing to previous studies reaching comparable performance of digit span

over 16. The Neo strategy proved to be a much more efficient alternative. S.F reached a digit span of 18 at the end of the third month of his self-training (Ericsson et al. 1980) and skilled abacus operated took years to reach similar level. (Stigler 1984). While in our case, 10 hours training over the period of a week with minimal learning proved sufficient, making Neo a practical choice for people interested in better STM performance.



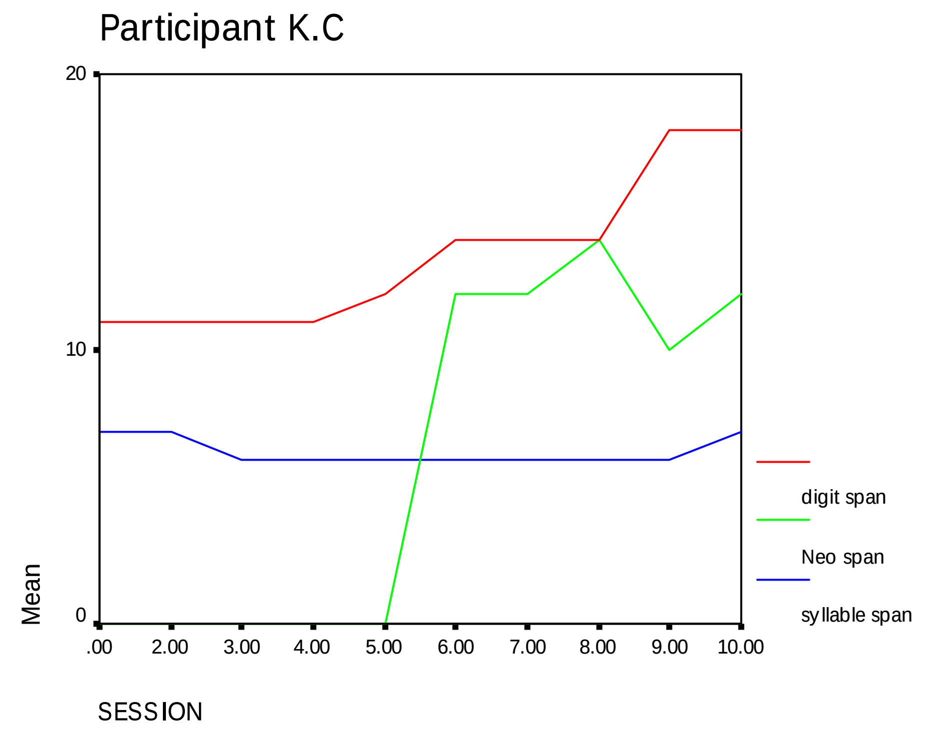


Figure 7: Change in span performance over time for J.L & K.C.

Chapter III

Discussion

3.1 Discussion on results:

Several conclusions can be drawn from the current study

Break the limit: It is possible to break the one syllable-one item limit and represent information with a much more efficient language system. When targeting a limited set of symbols like the decimal system, such a new language is not difficult to acquire and very moderate efficiency of which is sufficient to significantly boost short-term memory performance.

Cross-linguistic difference:

Several differences across language groups have been observed.

(1.) The original digit span difference follows the prediction of word length effect and has been demonstrated previously by a number of researchers, our study provides further support on that.

(2.) The faster and larger benefit from Neo language among English speakers relative to Chinese speakers raises an interesting point. Sometimes learning does not only involve formation of new associations but inhibition of old habit as well. Chinese speakers, whose numerical system are more efficient language-wise to start with, tends to have greater difficulty in adapting to the new system despite their additional edge of better training with Pinyin system and the obvious advantage of Neo over

Chinese in representing numbers.

(3.) The syllable difference likely results from difference in educational background, and unlike the digit span difference from coding efficiency, syllable difference tends to even out with more practice. The estimate is around 5.7 syllables for people of college age, which is much less than my original estimation from digit span which put syllable span around 10, suggesting other process may also be involved in our everyday manipulation of numbers. Still 5.7 syllables combined with V525 per syllable for English speakers; yields approximately 53 bits of information capacity for the phonological loop. This is much larger than typical estimate of STM capacity. (For decimal digit span task, 53 bits translated into a span of 21 digits, excluding all other strategies like switching, rehearsal, association, retrieval structure etc.)

Better predictor: In our example, one's original digit span has no predictive value at all in terms of whether one will grasp the conversion within two hours and benefit from Neo ($r=.037$, $P<.78$), while one's syllable span does make good predictions. ($r=.354$, $P<.01$) This is at odds with previous findings that STM performance (measured in digit span) predicts success in language acquisition. (Ardila, 2003) This phenomenon is likely specific to our study, but it worth a cautionary note that typical measure of STM does not necessarily make good prediction of performance on similar STM tasks, especially when it involves modification/inhibition of original algorithms. It is also interesting to note the predictive value of syllable span in our example suggests proficiency with phonemes helps acquisition of the Neo language, which resonant with finding from developmental study on children suggesting that phonological awareness being an important predictor in learning to read. (Booth, Perfetti & MacWhinney 1999)

3.2 General Discussion

Strategy behind every task: The current study touched upon some aspects of strategy use that merits a discussion dedicated to this topic. The word “strategy” should not be associated with anything fancy like a trick to outsmart others. It is better defined as a detailed specification of actions towards a goal, interchangeable with the word “algorithm” for our purpose. Several subtopics of interest include

(1) Tradeoff: There are no innately good or bad strategies as strategies not only differ in their potential outcome but in other aspects like prerequisite, learning time (difficulty to grasp) and complexity (difficulty in implementation). For digit span, holding all the digits in one string in native language may get you the smallest span, but it is also the easiest to implement and requires no learning. Its robustness makes it a good choice in noisy, distracting or anxiety provoking environment. Another strategy, holding digits in two groups, on and off the center of attention yields better result, requires no learning, but harder to implement especially for people of old or very young age as well as under less than optimal environmental conditions. The list goes on until we reach the other extreme of the spectrum, like the example of S.F. an algorithms yielding very high potential also has the most demanding prerequisite, takes years of training for proper implementation. The best suit for a population should strike a balance in between. (Table 3)

Table 3: Comparison between strategies on efficacy (Higher ranking indicating better potential) and complexity (Higher ranking indicating easier acquisition)

Strategy (Algorithm)	Whole-string	Mid-cut	Neo	Mnemonic Association	Hierarchical Structure
Efficacy Ranking	E	D	B	B	A
Complexity Ranking	A	A-	B-	D	E

(2) Estimation: When all of the algorithms involved are specified *and* proper implementation guaranteed, good estimate of performance can be obtained and I would argue, are only obtainable under these conditions. The implication is, once the proper implementation of algorithms is achieved, there is no point keep practicing as practice targets mastery of algorithms instead of modifying the algorithms themselves. In our study, people who perform digit span with the whole-string approach are very unlikely to make improvement if they stick to the same approach at the end of the experiment since whole string is an easily implemented algorithm and practice on mastering it was simply wasted. People who invested time on other slightly more complicated strategy like mid-cut gained moderate improvement and soon reached plateau as they master the strategy and fixate on the maximum span allowed by the algorithm. The Neo strategy has an estimated performance of 20 digits when mastered so it is understandable that even when people left the lab with an impressive span of 15, I would still predict with certainty that they haven't reached mastery of the algorithm and should continue to make progress until they reach plateau around 20. Data from two devoted participants making continuous increase confirming a gradual progression towards Neo mastery.

(3) Overlap: Actions within an algorithm may have different underlying mechanisms. Strategies that fall into the same category exclude each other while those from different categories facilitated one another. Associating digits to running time or historical date may both be good practice, but the same string can either be coded as running time or date but not both. Thus it confers little benefit for one already with a large data set to acquire another unless for special reasons or as prerequisite for other strategies. (In S.F.'s case, date was not adopted until several months into the training to deal with non-codable sequences). The same can be said about organizational structure, whether the simplest mid-cut or the most complicated 3 level hierarchy, people are better off sticking to one structure only. However, a combination of association and retrieval structure from two categories proved most successful in S.F.'s case. Taking all these into consideration, Neo language would be a welcome addition to our armory in battle against our own limit. It strikes a good balance between tradeoffs (it took one session to obtain a digit span of 12 and one week to achieve digit span of 18, roughly 1/7 the time for S.F. to reach the same result). It is a phoneme based system and thus is free from the heavy database or speed constrain characterize previous approaches. It also has wide application to other language-based tasks including calculation. And since its mechanism falls in a category rarely explored before, it would in theory work in conjunction rather than exclusion with other known strategies suggesting that if we were ever met another S.F. willing to invest (in Ericsson's own words) "*only* a few hundred hours of practice" then the human record of digit span will be 160 instead of 80.

Benefit from a new language:

From the perspective on information receiver:

Being the receiver of information means the environmental input is pre-determined, and the best we can make out of the situation is to code the input in an efficient way. The motto is "An item is *not* an item is *not* an item." Thinking of STM as a fixed number of items and chunking as the only way out is misleading, deeper under the surface is optimization of our phonological loop in representing information. I have discussed the advantages of Neo language approach in terms of speed, easy acquisition and good compatibility with other approaches, it is also important to understand these discussions are not limited to decimal system (digit span), but STM performance on any symbolic system with moderate dimensions (almost all STM tasks fits this criterion). This will include, but not limited to STM on shape, color, music notes, direction, location… or people, fruits, tool, animal when the sets are better defined. All one needs to do is to create a 24*21 table (in the case of English speakers), map the symbols from systems of interest to phonemes and complete one's own version of the Neo language, which will ensure more than twice the efficiency of phonological loop in representing the same information independent of other strategies.

From the perspective of information provider:

The key to better efficiency in information communication is the information provider, who determines the format of environmental input. Here the motto is "A bit is a bit is a bit." There has been an ongoing debate in China as whether the nation should replace the current logographic language system with alphabetical systems like what Koreans have done. The current study provides at least part of the answer: A system with a large number of symbols is no doubt harder to acquire and is prone to dialect confusion as there are not enough syllables to ensure one-to-one mapping. (The problem is partially solved by introduction of tonal system) However, a larger symbol set also means that each symbol codes for greater amount of information and in combination with a tight one syllable to one symbol mapping barely saved by the tones, results in better STM capacity and consequently better calculation and faster communication. As previous discussed, STM information span for English speakers has been estimated to be around 53 bits. (Even this 53 bits derived from syllable span is likely to be a very conservative estimation of our potential since it does not take into consideration of possibilities of learning new phonemes or adding phonetic features like tones and stress which are as good as phoneme information-wise and can be processed in parallel in phonological loop). It is the choice of information provider, either to present the information in very inefficient binary system or much more efficient Neo system and as the result of which, the same individual who has the same background knowledge and same biological constraint on phonological loop may either demonstrate a STM of 7 bits or 53 bits. The far-reaching implication of this concerns the optimization of our own language, in other words, make everyone a better information provider instead of train a few to be better information receiver. The importance of which cannot be overemphasized as language underlies most aspects of our cognition. Take the decimal system as an example; we use it on a daily basis in representing quantity, telling the price, calculating the outcome as well as less arithmetical uses like time, date, phone number, credit account and SSN. For those in the profession of accounting, clerk or certain customer services, dealing with numbers accounts for a significant portion of their life and the inefficiency of our language wasted a good portion of their our lives for no good reason. Beyond saving time and energy, a more efficient system also makes the impossible possible. Consider the example shown in Figure 8, mental arithmetic of 62*32 is within the reach of most of us since holding the intermediate results of 6 digits (124 and 186) is only moderately challenging, while multiplying 1862 by 4732 is beyond most of us since holding the intermediate 17 digits *in English* is simply too much. However, the information content of 17 digits is around 53 bits and in theory should be within our capacity if proper language system is adopted. This is exactly the case, with the Neo system that represents intermediate results of 17 digits in only 9 syllables, one could succeed (though awkwardly) in such arithmetic adventure.

62	1862	
*32	* 4732	
124 (6)	3724 (17)	lao.tu (9)
186	5586	gai.zhan
1984	13034	1long.lu
	7448	hu.nang
	8810984	

Figure 8: Comparison of two language systems in calculation.

To conclude, though it is premature to recommend overhaul of current language systems towards better efficiency due to concerns of cost-effectiveness, culture identities etc. It seems very reasonable to recommend a modification of our vocabulary on the numerical system, which is so frequently and widely used and so inefficient in representing information. As this study has demonstrated, acquisition and effective use of the Neo language of decimal system can happen within 10 hours even though it involves inhibition of a previously overlearnt system and this small effort should benefit our STM capacity permanently. It is often the case that man seeks external help without realizing that we are the ones who limit our own potential, at least let’s this not be the case with STM capacity.

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