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Task Difficulty and Neural Efficiency Hypothesis of Intelligence: Differences of Semantic-Syntactic Error Detection between Gifted and Non-Gifted Children

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Gifted children are precocious in verbal abilities. While the neural efficiency hypothesis of intelligence has supporting evidence across cultures, electrophysiological responses associated with intelligence varied in children with different intellectual levels on various tasks. To test the hypothesis by components of the event-related field (ERF) on gifted children, we used a semantic-and-syntactic error detection task to study sentence processing in language comprehension. Three types of determiner-particle final sentences were presented visually to subjects in this magnetoencephalography (MEG) experiment: the congruent (a correct particle with a detection task), incongruent (an incorrect particle with a detection task), and filler (a correct particle followed by a word recall task) conditions.

To detect different waveforms within and between the gifted group (GT) (N = 19) and non-gifted group (NG) (N = 15), the permutation t tests (iteration: 1000; p = .05; two tailed) were adopted to compare the ERF of the two groups. For the within group comparison, the NG group showed stronger amplitudes only around 600 ms, while the GT group had early components closed to 400 ms and the late time-window around 600ms. For the incongruent-subtract-filler comparison, a significant ERF difference was found between the two groups at a late time window around 650 ms in the right occipital channel. The topography revealed stronger current in the occipito-temporal region for the GT group during this time-window. In contrast, no statistically significant difference was found by comparing incongruent-subtract-congruent (IC) and congruent-subtract-filler (CF) conditions.

Interestingly, this study showed that responses of gifted children had stronger magnetic current at a late time point compared to children with average IQ in the semantic-syntactic judgment task. These results indicate the complex task might engage deeper processing in a brain network and that gifted individuals show greater brain activation than their average peers. Task complexity or difficulty needs to be taken into consideration when the neural efficiency hypothesis of intelligence is proposed.

Keywords: *magnetoencephalography (MEG), giftedness, verbal ability, semantic-and-syntactic error, Neural Efficiency Hypothesis of Intelligence*

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Intelligence and Neural Efficiency Hypothesis

Neuropsychological evidence suggests a neural efficiency hypothesis of intelligence on various tasks assessing cognitive abilities as less brain activation was found in the gifted individuals than in the non-gifted ones (Deary & Caryl, 1997; Haier et al., 1992; Liu et al., 2015; Liu et al., 2011; Neubauer & Fink, 2009; van Hees et al., 2017). In a review study on brain structures, Jung and Haier (2007) concluded that individuals with thicker gray matter and white matter in the frontal and parietal cortices usually perform better on psychometric measures of intelligence, such as intelligence quotient (IQ). It is suggested that an efficient brain may consume less energy to accomplish a cognitive task.

Experts with talents in lexical decision (e.g., Scrabble) showed stronger specific ERP components associated with visual word processing, working memory, and stimuli classification (van Hess et al., 2017). Zhang et al. (2006) stated that gifted children showed a neural network better coordinated in space and time than their peers with an average IQ. Electrophysiological responses associated with intelligence showed that gifted children showed weaker neural responses than intellectually average children in the conflict control tasks (Liu et al., 2015). A further study revealed that high IQ youths showed shorter response latency and lager amplitude of ERP than their average IQ counterparts in facial identification tasks and thus suggested that adolescents with different IQ levels might have varied neural processing (Liu et al., 2015). Also, lager ERP amplitude (P3) was elicited among individuals with higher intelligence than those with lower intelligence (De Pascalis et al., 2008; Jaušovec & Jaušovec, 2001).

Other studies also supported that less neural function/activation was found in gifted individuals. For instance, higher-IQ adults showed less ERD (event-related desynchronization) than lower-IQ adults in a sentence verification task (Neubauer et al., 1995). In another study, adults with better reading performance showed less activation in bilateral frontal and right lingual gyri in a sentence comprehension task (Prat et al., 2007). In a spatial and verbal test, individuals with higher spatial abilities had lower cortical activation and a smaller activated area (Smith et al., 1999; Vitouch et al., 1997). Highly intelligent individuals were also observed to have less activation in a problem solving (Jaušovec, 2000) or letter-matching task (Neubauer et al., 1999).

Task Difficulty Challenging the Hypothesis of Neural Efficiency

Interestingly, less activation for more intelligent individuals is not universally observed. The cortical activation is not only a function of general information processing but also a function of specific tasks or domain-specific competencies. Neural efficiency may manifest itself only when tasks are below a moderate level of cognitive load or performed after sufficient practice. Under such circumstances, the subject could handle the tasks in an automatic process (Kelly & Garavan, 2005; Neubauer & Fink, 2009). A complex task might engage deeper processing in a brain network so that brighter individuals would have even greater brain activation than those with lower intelligence. Dunst et al. (2014) used person-specific tasks (numerical-inductive reasoning: easy and difficulty) to investigate the brain function-intelligence relationship in participants with higher and lower intelligence. The results indicated that group differences in brain activation were statistically shown only in the same sample-based difficult task but not in the easy task. A study further showed that adults with a high language proficiency demonstrated slightly faster lexical access over the left anterior brain regions for closed class items and a reduced reliance on contextual information contained in sentence processing (Weber-Fox et al., 2003).

Though previous studies have discussed the neuropsychological point of view between gifted and average-ability individuals, few studies examined how a gifted brain may manifest its verbal ability. Neural efficiency seems to reflect differential engagement of the brain network to meet with various task demands. This argument about the task-dependency is still a debating issue and has not been tested in young groups, especially in gifted children (Geake, 2008). It is expected that results

from neurological studies can improve our understanding of the functional operation of the brain in the gifted children on language processing, which in turn will help to enhance the implementation of differentiated teaching and counseling strategies to gifted children.

Task Difficulty and Language Processing

Weber-Fox et al. (2003) compared brain activation of young adults who exhibited normal and high language proficiencies. Their findings showed that temporal and amplitude measures of ERPs were elicited by closed-class words, open-class words, and best completions; their findings also showed that detecting semantic anomalies in sentences engaged different neural functions of young adults who exhibited normal and higher-than-normal language proficiency. In general, higher-than-normal language proficiency may be characterized by faster lexical access over the left anterior brain regions, particularly for closed-class words. Individuals with high language proficiency may also engage post lexical processes differently.

In a neuroimaging study, Friederici et al. (2003) investigated how their subjects responded when listening to correct, syntactically incorrect and semantically incorrect sentences. They found that detecting sentence errors recruited a larger portion of the superior temporal region than listening to correct sentences. Processing of semantic violations relied mainly on the mid-portion of the superior temporal region and the insular cortex in both hemispheres, whereas processing of syntactic violations specifically involved the anterior portion of the left superior temporal gyrus, the left posterior frontal operculum adjacent to the Broca's area and the putamen in the left basal ganglia. When comparing the two anomalous conditions, they found higher levels of activation in the left basal ganglia for the syntactic over the semantic anomalies and more activation in the mid-portion of the superior temporal gyrus bilaterally for the semantic over the syntactic anomalies, suggesting that both semantic and syntactic processes were supported by a temporo-frontal network with distinct areas specialized for semantic and syntactic processing.

A further fMRI study by Friederici et al. (2006) also suggested that brain activation effects in the inferior portion of BA 44 are specific to the processing of hierarchical stimuli when contrasting brain activation associated with syntactic violation and with varying degrees of linguistic complexity. They found two distinct sub-regions in the posterior portion of the left inferior frontal lobe selectively responding to these two different kinds of language comprehension. Increasing linguistic complexity, but not presence of syntactic violation, recruited more activation in a core region of the Broca area (i.e., BA 44), while the more posterior deep frontal operculum selectively was engaged in processing sentences with an ungrammatical word order.

Studies on sematic and/or syntactic violation of visually-presented sentences have also shown that specific ERP waveforms were elicited by certain language-related components (Brito, 2017; Hagoort, 2003; Molinaro et al., 2011). The semantic processing component for the incongruent effect of language comprehension, reflected in N400, is a very crucial neuropsychological evidence for the brain sensitivity to the semantic context between 250 and 550 ms after presenting the sentence and with a maximum around 400 ms (Kutas & Hillyard, 1980). The N400 effects could be evoked by words matched with an incongruent picture, word, sentence, or discourse (van Berkum et al., 1999; Henderson et al., 2011). Children aged between eight to ten showed greater N400 component in the incongruent than congruent conditions in word-picture paired tasks. Incongruent effects are also positively correlated with listening comprehension and non-word reading (Henderson et al., 2011).

In adult syntactic processing, sentences with syntactic violation can elicit the P600 component; this late time window with posterior positivity and sometimes following an early left anterior negativity (ELAN) reflected the unexpected syntactic violation (Steinhauer & Drury, 2012). Furthermore, even two-year-old toddlers showed sensitivity to ungrammatical sentences, inducing early left anterior negative amplitude between 100 and 400 ms and a late posterior positive amplitude from 700 to 900 ms (Brusini et al., 2016); besides, a few early

components could be identified as M100 (75-130 ms) for an early response to the visual stimulus in the bilateral occipital area, M170 for the response to orthographic and morphological processing in the left occipito-temporal lobe, M250 in the central and parietal regions of the left hemisphere, and finally M350 for reflecting the integration of semantic information in the MEG studies (Tsai et al., 2013).

However, not many studies have investigated sentence processing by combining semantic and syntactic violation (Hagoort, 2003). Studies showed the N400 and P600 effects in combining these two types of violation (Ainsworth-Darnell et al., 1998; Osterhout & Nicol, 1999; Hagoort, 2003). For instance, the N400 effect was stronger, and P600 had less change in semantic and syntactic violations in Hagoort's study (2003), but the N400 was not found in processing combination of the two violations (Friederici, 2011); the P600 effect in double violations was reduced to the syntactic violation only (Gunter et al., 1997). So far, investigation of semantic-syntactic violation detection is rarely done in gifted children.

Summary of Literature Review and Research Goal

To sum up, the aforementioned neurological studies have shown observation of semantic/syntactic processes in 150-600ms: the imaging studies have implicated a network of the temporal area in semantic violation and the network of the inferior frontal and temporal area in syntactic violation (for review, Kwon et al., 2005). If the neural efficiency hypothesis can be applied to the brain network involving the frontal and temporal cortex, the N400 and P600 components would be reduced when a gifted individual is processing the sematic-syntactic violation, even in an easy task.

This study aimed to explore the brain activation of gifted children when detecting sematic-syntactic violations and to test the neural efficiency hypothesis of intelligence via language processing tasks. We proposed that gifted children are supposed to have more efficient neural processing associated with their cognitive performance compared with their non-gifted counterparts. However, under the in-depth processing of a more difficult task, gifted brains are supposed to activate more than their regular peers.

Research Methods

Behavioral measurement of this study relied on four instruments, including WISC-IV (the Chinese version), Reading Comprehension Screening Test (RCST), Chinese Character Recognition Test (CCRT), and Phonological Awareness Composite (PAC). MEG task used is Semantic-Syntactic Error Detection (SSED). After receiving written consent forms from the parents and oral assent from the participants, we conducted SSED in a quiet area in the participants' schools or the auditory lab at National Taiwan Normal University. The whole testing was divided into two sessions in order to reduce fatigue from the tests. The two sessions were presented in a counterbalanced order across the subjects.

Participants

The current study was approved by the Research Ethics Office of National Taiwan University. Forty-four children aged between nine to ten were recruited with consent forms signed by all of them and their parents. After preprocessing for MEG data, due to many bad channels (over 10 channels: 3 persons), noise (6 persons), and Hydrocephalus (1 person), only 34 children's raw MEG data were analyzed; among them, 19 were in the gifted (GT) group (8 males, 11 females; average age 120.32 months) and 15 were in the non-gifted (NG) group (9 males, 6 females; average age 120.33 months). Results from the identification by the Committee of Disabled Student Identification Board of local authority government showed that the GT group has a mean IQ of 136.00 (max: 152; min: 128; *SD*: 6.87), and the NG group has a mean IQ of 112.47 (max: 126; min: 94; *SD*: 8.80). None of the participants had psychiatric or neurological disease or any sensory problem according to reports from the parents.

Instruments

Wechsler Intelligence Scale for Children 4th Edition-Chinese version

The Wechsler Intelligence Scale for Children 4th Edition-Chinese version (WISC-IV-Chinese) has been in clinical use in Taiwan since 2007. To estimate full scale IQ (FSIQ), ten subtests were used in this study. The verbal comprehension index (VCI) contained three sub-tests including Similarities, Vocabulary, and Information. We also used two sub-tests, Digital Span and Letter-Number Sequencing, as the working memory index (WMI).

Reading Comprehension Screening Test (RCS)

This instrument was designed by Ko (1999) to examine reading comprehension of school children from 2nd to 6th grades. The two sections include: paragraph review and text comprehension. Children were asked to name the topics, to find out the synonyms, to reason and to interpret the text. The accuracy of children's responses was recorded. The test-retest reliability coefficient of this test was .87.

Chinese Character Recognition Test (CCRT)

In this character recognition measure devised by Huang (2001), children were asked to read aloud a series of 200 words arranged in a descending order of the printed word frequency. All characters are irrelevant in meaning with typical orthographic correspondences (real characters). The accuracy of children's responses was also recorded. For this timed test, the split-test reliability coefficients were .99.

Phonological Awareness Composite (PAC)

The Phonological Awareness Composite is a self-developed instrument, comprised of Tone Awareness (TA) and Onset-Rime Awareness (ORA). To increase the test's level of difficulty, test items were not presented in any specific order. The options as a whole included an equal number of genuine speech sounds and segment combinations that did not exist in Mandarin Chinese (i.e., fake speech sounds); half of the options were two-segment combinations and the other half were three-segment combinations. Participants' answers and response times were recorded through a test interface developed using MATLAB software.

Semantic-Syntactic Error Detection (SSED)

The Semantic-Syntactic Error Detection (SSED) task engaged participants in making error judgment on Chinese sentences presented in a term-by-term fashion. A correct judgment requires semantic and syntactic knowledge of the Chinese language. The experiment consists of a SSED task and a word recall (WR) task. In the SSED task, there are 40 well-formed experimental sentences for the congruent condition and 40 semantic-syntactic-error sentences for the incongruent condition. Forty well-formed sentences are for the filler condition in the WR task, and 10 preparation sentences are testing trials; all the fillers are well-formed sentences and none of them contain the features under inspection or prediction.

Three types of Aspect-Particle-final sentences—congruent condition (correct particle), incongruent condition (incorrect particle), and filler control condition (correct particle) were employed to examine participants' sensitivity to Mandarin Chinese knowledge. For the semantic-syntactic violation task, the manipulated features are "*yi-jing* 已經" (already), and "*zheng-zai* 正在" (is doing something), and the perfect particle "*le* 了" and the progressive particle "*zhong* 中". Both particles appear at the sentence final position. The perfect particle *le* indicates the action denoted in the sentence has been completed, while the progressive particle *zhong* indicates the action denoted in the sentence is still in progression. Therefore, co-occurrence of *zheng-zai* and *le* in a sentence would cause anomaly as the former denotes action progression whereas the latter indicates action completeness. Co-occurrence of *yi-jing* and *zhong* in a sentence would also result in an anomalous sentence. Of the experimental sentences, 20 of them were well-formed, 20 sentences contained *yi-jing* violation, and 20 sentences contained *zheng-zai* violation. Half of the experimental sentences contained the marker *le* and the other half contained *zhong*. The fillers did not contain *yi-jing* or *zheng-zai*. The preparation sentences were well-formed sentences

expressing either the perfect or the progressive aspects.

The word order of the sentences is subject-adverb of aspect-verb-particle.

- Congruent condition:

媽媽	正在	化妝	中
Mama	zheng-zai	hua-zhuang	zhong
Mother	in progression	put on makeup	particle
(Subject)	(adverb of aspect)	(verb)	(progressive particle)

"Mom is putting on makeup now."

- Incongruent condition:

媽媽	已經	化妝	中
Mama	yi-jing	hua-zhuang	zhong.
Mother	already	put on makeup	particle
(Subject)	(adverb of aspect)	(verb)	(perfect particle)

"*Mom had put on makeup now."

- Filler condition:

比賽	就要	開始	了
Bi-sai	jiou-yao	kai-shi	le
Game/Contest	being about to	begin	particle
(Subject)	(adverb of aspect)	(verb)	(perfect particle)

"The game/contest is about to begin."

To prevent the effect of prediction, the sentence construction of the filler condition is similar to that of the congruent condition, but the question that followed a filler sentence asked the participant to judge whether a certain word appeared in the precedent sentence, instead of asking the participant to judge the grammaticality of the sentence. Therefore, for the filler condition, the task was a word recall task.

At the beginning of a new trial, a black fixation point appeared at the center of the screen for 500 ms as a warning signal; then the Chinese sentence appeared in a term-by-term fashion. (e.g., 他 (ta)- 已經 (yi-jing)- 回家 (hui-jia)- 了 (le)); each term was shown at the center of the screen for 500 ms with the last word of the sentence appearing with a period. The presentation of a sentence took between 3000 to 5000 ms; then a question mark appeared at the center of the screen as a signal for participants to respond; participants pressed the green button on a response device for a correct sentence, and pressed the red button on the response device for an incorrect sentence. Ten preparation sentences as practice trials preceded the actual test session; none of the practice trials was used as an experimental sentence.

Procedure

There were four sessions in the MEG experiment. The participants underwent the sessions individually. They were seated in front of a reflected screen at a visible and comfortable distance and in a magnetically shielded room to perform a Semantic-Syntactic Error Detection (SSED) task and a Word Recall (WR) task. During MEG recordings, the participants were to judge the correctness of a sentence when they saw the question "Is the sentence correct?", or they were to recall if the target word was shown in the sentence when they saw the question "Did you see the target word in the sentence?" The session was self-paced in that participants could control the beginning of the next trial by pressing either button on the response device.

MEG Data Recording

Continuous neural responses were recorded by using a 306-channels MEG system (Elekta-Neuro-image, Helsinki, Finland) located at the Image Center for Integrated Body, Mind and Culture Research of National Taiwan University, but only 128 sensors of magnetometers were recruited for data analysis by the Brainstorm program (low-pass filtering: 40 Hz; sampling rate: 1000Hz; Tadel et al., 2011). Bad channels were alternated with interpolated sensors. To diminish the noise from head movement, MEG recording was individually corrected with head position indicator (HPI) coils in the nasion and two preacuricular anatomical points by using signal space separation method (MaxFilter, Elekta-Neuriomag). Also, the fiducial reference points were used to manually align the registration of MEG data with individual MRI (Siemens 3T MRI Prisma). Heart beats and eye movements were linearly reduced by using ICA (Independent Component Analysis) and the epochs were visually inspected and manually rejected for any huge artifact. A baseline correction was performed with a segment from -200 ms to 0 ms. Averaged waveforms from 100 ms to 700 ms in all conditions were filtered off-line with low-pass filter at 40 Hz.

Research Results

Behavioral Data

The independent *t* test was conducted to detect significant difference of the behavioral data between the GT group and the NG group. As Table 1 shows that besides FSIQ ($p < .001$), VCI ($p < .001$), and WMI ($p < .001$), children from the GT group also had better performance in character recognition ($p < .05$), reading comprehension ($p < .01$) and reaction time of phonological awareness ($p < .05$) than the NG group.

The independent *t* test also was used to verify the difference of SSED and WR task between the two groups (see Figure 1). As far as the accuracy (percentage) of SSED is concerned, the GT group had a better performance ($M = 94.01$, $SD = 4.78$) than the NG group ($M = 93.50$, $SD = 5.67$), but the difference between them did not reach a significant level. In the WR task, likewise, the two groups had similar accuracy (GT: $M = 94.08$, $SD = 3.14$; NG: $M = 92.92$, $SD = 5.66$). Graphical comparison of results of SSED ($t = 0.286$, $p = 0.78$) and WR tasks ($t = 0.713$, $p = 0.48$) are shown in Figure 1a.

Figure 1b demonstrates a graphical comparison of the reaction time of the two groups in the SSED and in WR tasks. The GT group showed shorter reaction time both in the SSED task ($M = 893.13$, $SD = 188.57$) and the WR task ($M = 888.11$, $SD = 187.28$) than the NG group (SSED: $M = 1071.66$, $SD = 188.91$; WR: $M = 1079.51$, $SD = 197.96$). The difference reaches the significant level (SSED: $t = -2.739$, $p < .05$; WR: $t = -2.886$, $p < .01$).

Neural Data

The random permutation *t* test at sensors level were performed for within-subject and between-subject with paired and independent comparisons respectively (iteration 1000; p = .05; two-tailed; FDR with time and frequency) (Maris & Oostenveld, 2007). To evaluate the ERF (Event-related fields) component of N400m and P600m, we conducted one time windows (100-700 ms) which widely captured N400m (around 300-500 ms) and the 500-700 ms window which captured the early P600m response (Hagoort 2003; for review, Molinaro et al., 2011). For group comparison, the same statistical analysis was conducted, but 0-700 ms time-window was selected so that the differences between the two groups can be accommodated. For ERF differences to be regarded as significant, they must cover at least a continuing time-window of 50 ms. The significantly different amplitudes

Table 1

The results of independent t test for gifted and non-gifted groups

Measure	Gifted group ($N = 19$)		Non-gifted ($N = 15$)	*t*
	Mean (*SD*)		Mean (*SD*)	
Age (month)	120.32 (5.06)		120.33 (7.38)	-0.008
FSIQ	136.00 (6.87)		112.47 (8.80)	8.765***
VCI		132.58(16.15)	110.00 (10.84)	#4.861***
WMI	124.63 (9.43)		109.27 (10.24)	4.544***
CR	69.32 (10.54)		60.73 (11.43)	2.272*
RC		27.42 (2.32)	23.00 (4.33)	#3.574**
PA		19.53 (2.78)	18.80 (2.37)	0.807
PA RT		12.72 (3.92)	17.64 (6.84)	#-2.485*

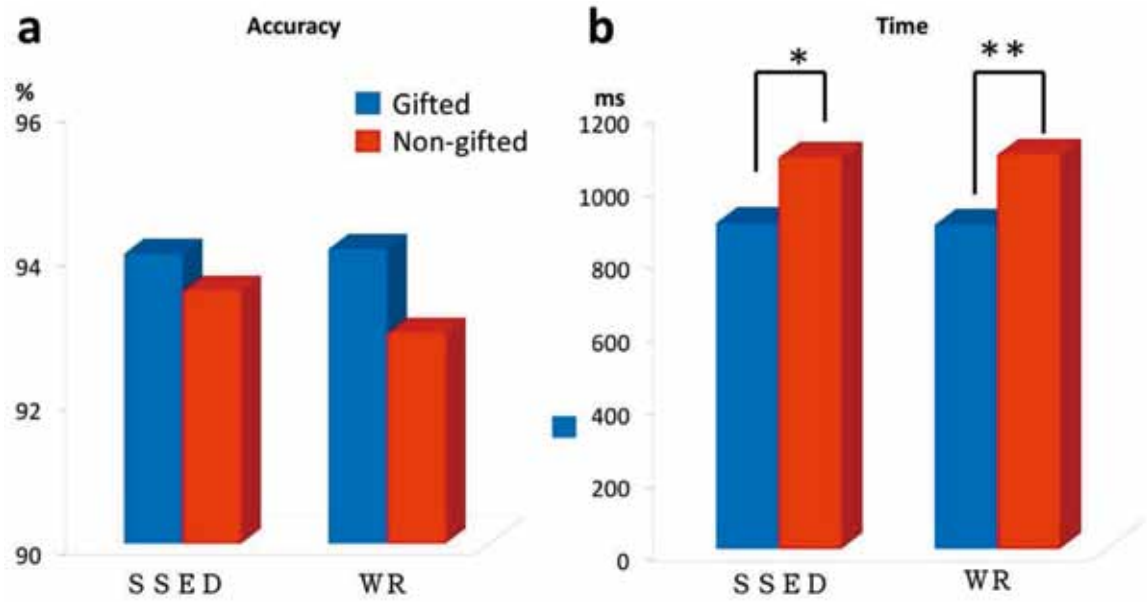
Note. FSIQ: full scale IQ; VCI: verbal comprehension index; WMI: working memory index;. CR: raw scores of character recognition; RC: raw scores of reading comprehension; PA: raw scores of phonological awareness; PA RT: the reaction time (sec.) of phonological awareness.

a. The symbol "#" means we adopted the degree of freedom for significance of Levene's test.

* $p < .05$. ** $p < .01$. *** $p < .001$.

Figure 1

The accuracy (percentage) and reaction time (ms) of Semantic-Syntactic Error Detection task (SSED) and Word Recall task (WR) for gifted (blue block) and non-gifted block (red block)



* $p < .05$. ** $p < .01$.

of all waveforms are shown in Figure 2. The GT group showed significant difference both in the temporal area and the right occipito-temporal region, whereas the NG group showed the significant area only in left temporal lobe.

Correlation Analysis

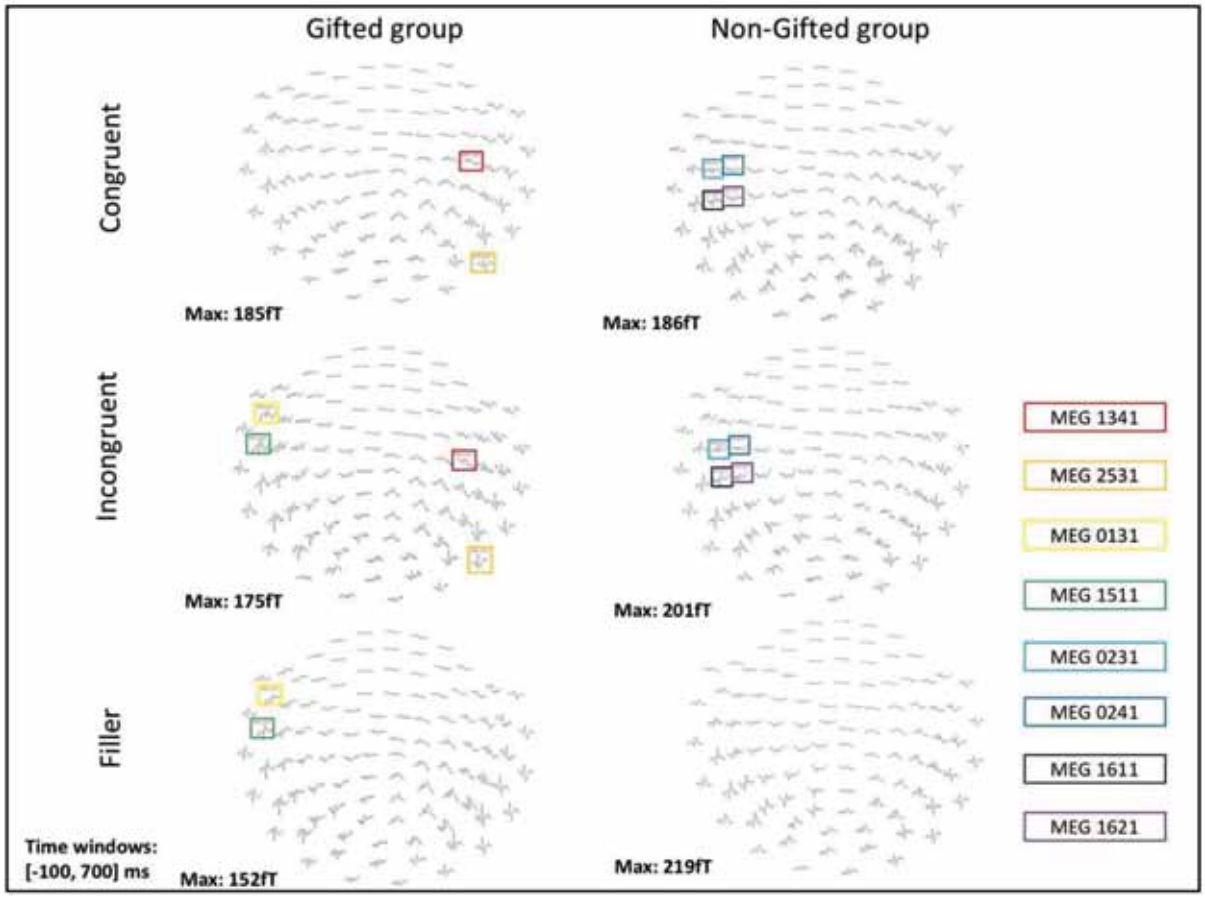
The relationship between neural and behavioral data was examined by calculating the average amplitude (624-683 ms) from the significant difference channel (M2321) for correlation analysis (Pearson, 2-tailed) with FSIQ (p = .123), VCI (p = .182), Similarity (p = .941), Vocabulary (p = .122), Information (p = .069), Character Recognition (p = .388), Reading Comprehension (p = .927), Phonological Awareness (p = .764), reaction time of PA (p = .424), Semantic-Syntactic Error Detection (SSED) (p = .609), reaction time of SSED (p = .117), Word Recall (WR) (p = .791), and reaction time of WR (p = .154). There was no significant correlation between these measurements. However, we also conducted one-tailed correlation analysis, and it showed that the average amplitude was significantly correlated with Information (r = .336, p = .035) and slightly correlated with reaction time of SSED (r = -.292, p = .058).

The NG Group

When comparing the incongruent condition with the congruent condition in the NG group (N = 15), several significant positive amplitudes were identified in the time-windows from 533 ms to 687 ms ($p < .05$, channel: MEG 1611, Fig. 3a), 534 to 660 ms ($p < .05$, channel: MEG 1621, Fig. 3a), 542-694 ms ($p < .05$, channel: MEG 0241, Fig. 3d) and 563-642 ms ($p < .05$; channel: MEG 0231, Fig. 3c). The positions of the above channels were located in the left middle and posterior temporal cortex (Fig. 2, right panel); the stronger current suggested the source as the P600m component. Besides, a positive amplitude was found when comparing incongruent with congruent condition. The significant time point was between 210 to 272 ms ($p < .05$; MEG channel: 1611, Fig. 3e), which resembled P200m in the left posterior temporal lobe. The grand average of incongruent condition showed no

Figure 2

All grand average amplitudes of GT (left panel) and NG (right panel) children read the perfect makers in congruent, incongruent, and filler condition. The highlight frames in various colors showed the significant difference in the magnetic channels as comparing paired conditions in each group



significantly different waveform compared with the filler condition; neither did the congruent condition compared with the filler condition.

In the within-subject comparison (the NG group), stronger positive responses, P600m, were found in incongruent condition as the effect of syntactic violation. Around the time-window from 300 to 500 ms, we didn't find any significantly different amplitude among the incongruent, congruent, and filler conditions. Therefore, no any N400m effect was detected in the NG group. However, in comparing the incongruent condition with the congruent condition, a stronger P200m was shown in the left temporal area.

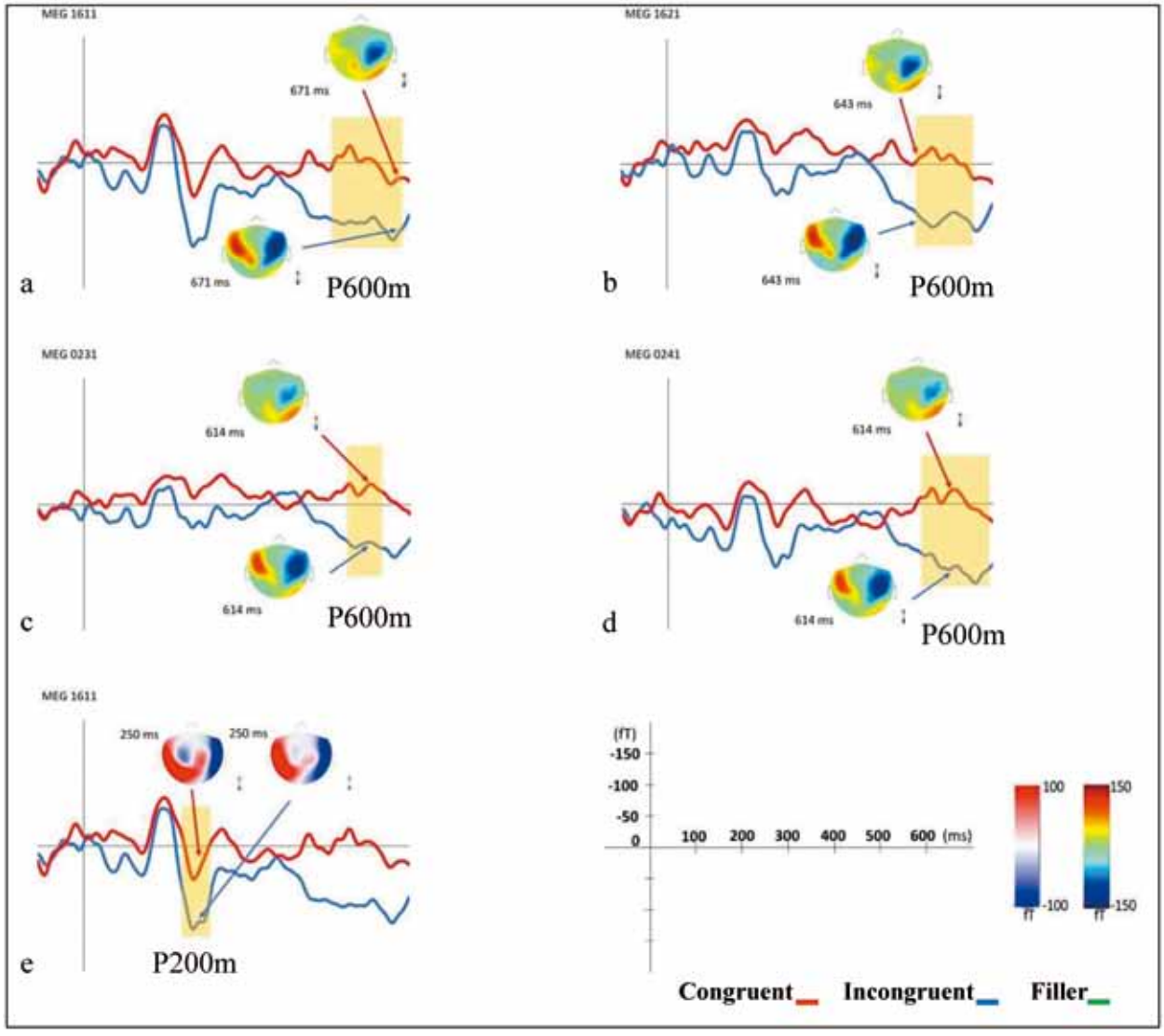
The GT group

We also conducted the same permutation *t* test for the GT group (N = 19). The pairwise comparison of the incongruent condition and the congruent condition showed significant difference in two response windows. The stronger negative amplitude ($p < .05$; time point: 565-619 ms; MEG channel: 1341, Fig. 4b) was suggested as N400m in the right middle temporal cortex (Fig. 2, left panel). The other distinct waveform ($p < .05$; time point: 634-688ms; MEG channel: 2531, Fig. 4b) was positive amplitude presented as P600m in the right occipital lobe (Fig. 2, left panel).

In comparing the incongruent condition with the filler condition, there were a few strong amplitudes ($p <$

Figure 3

The grand average amplitudes and topography of non-gifted children. Red line: congruent condition; blue line: incongruent condition; green line: filler condition



.05; time-window: 395-448 ms and 598-700 ms for MEG channel 0131 and 590-700 ms for MEG channel 1511). The stronger negative current on the topography (Fig. 4a) was suggested as N400m or early left anterior negativity (ELAN), and the stronger positive waveform (Fig. 4c, 4d) was suggested as P600m in the left anterior temporal lobe (see Fig. 2, left panel). Also, a significantly different response (Fig. 4d) resembled P600m in the left middle temporal area when comparing the incongruent condition with the filler condition. No further apparently different waveform was found in the other pairwise comparisons between the congruent and the filler conditions.

Comparison between Groups

The independent-sample permutation *t* testing (Permutation: 1000; two-tailed; $p < .05$; time windows: 0-700ms) was conducted to compare the waveforms between the GT and the NG groups in terms of ERFs of incongruent-subtract-congruent (IC) contrast,

incongruent-subtract-filler (IF) contrast, and congruent-subtract-filler (CF) contrast. In the IF condition, significant difference was only detected in one time-window between the two groups. The late time-window had group difference shown in the right occipital area at 624-683 ms ($p < .05$; MEG channels 2321). As Fig. 4a shows, the topography of the GT group in incongruent condition showed a distinct current in the right occipito-temporal area, while a weaker current was seen in the NG group (See Fig. 5d). However, no statistically significant difference of the responses was found when comparing CF and IC conditions.

Figure 4

The grand average amplitudes and topography of gifted children. Red line: congruent condition; blue line: incongruent condition; green line: filler condition

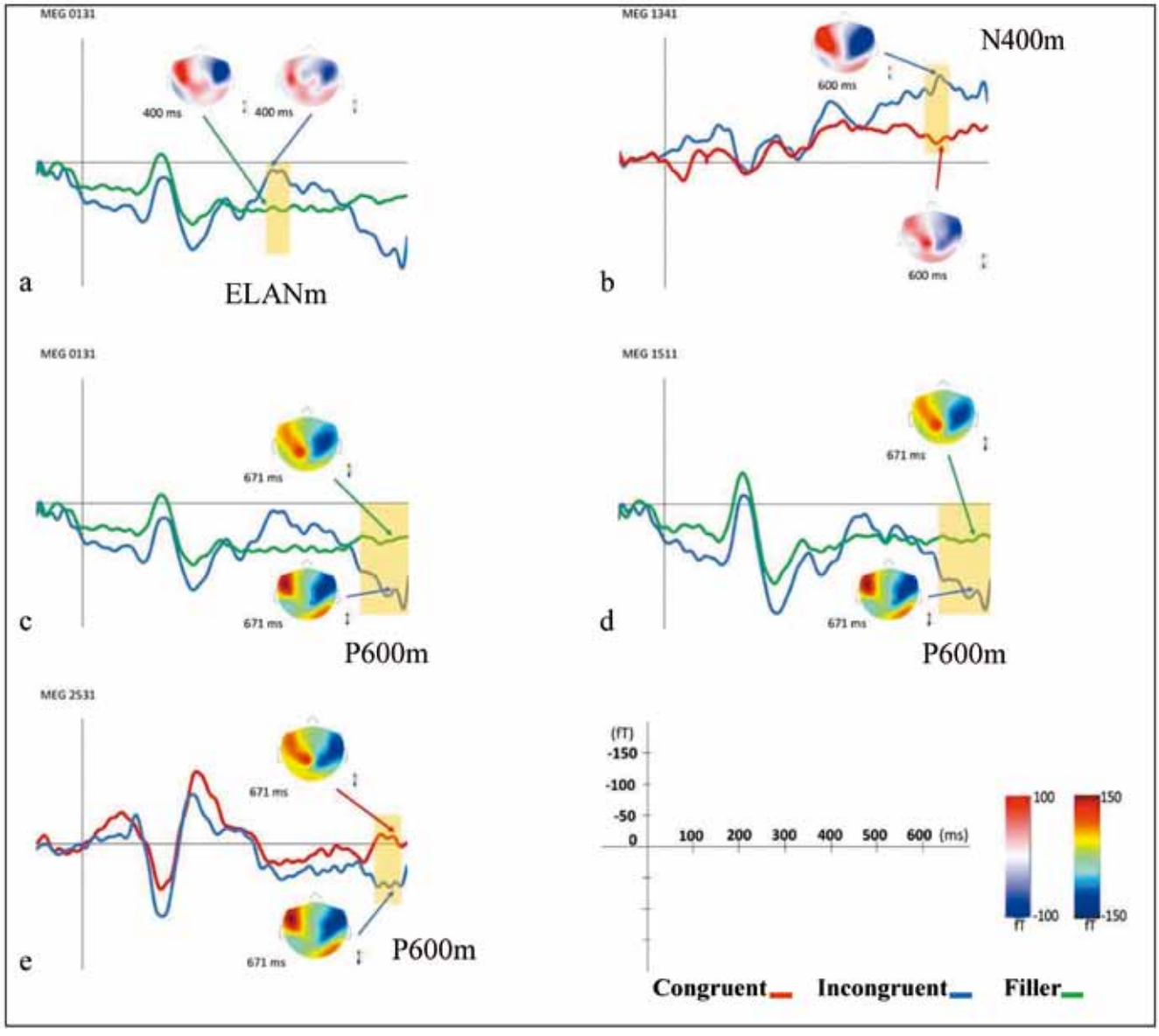
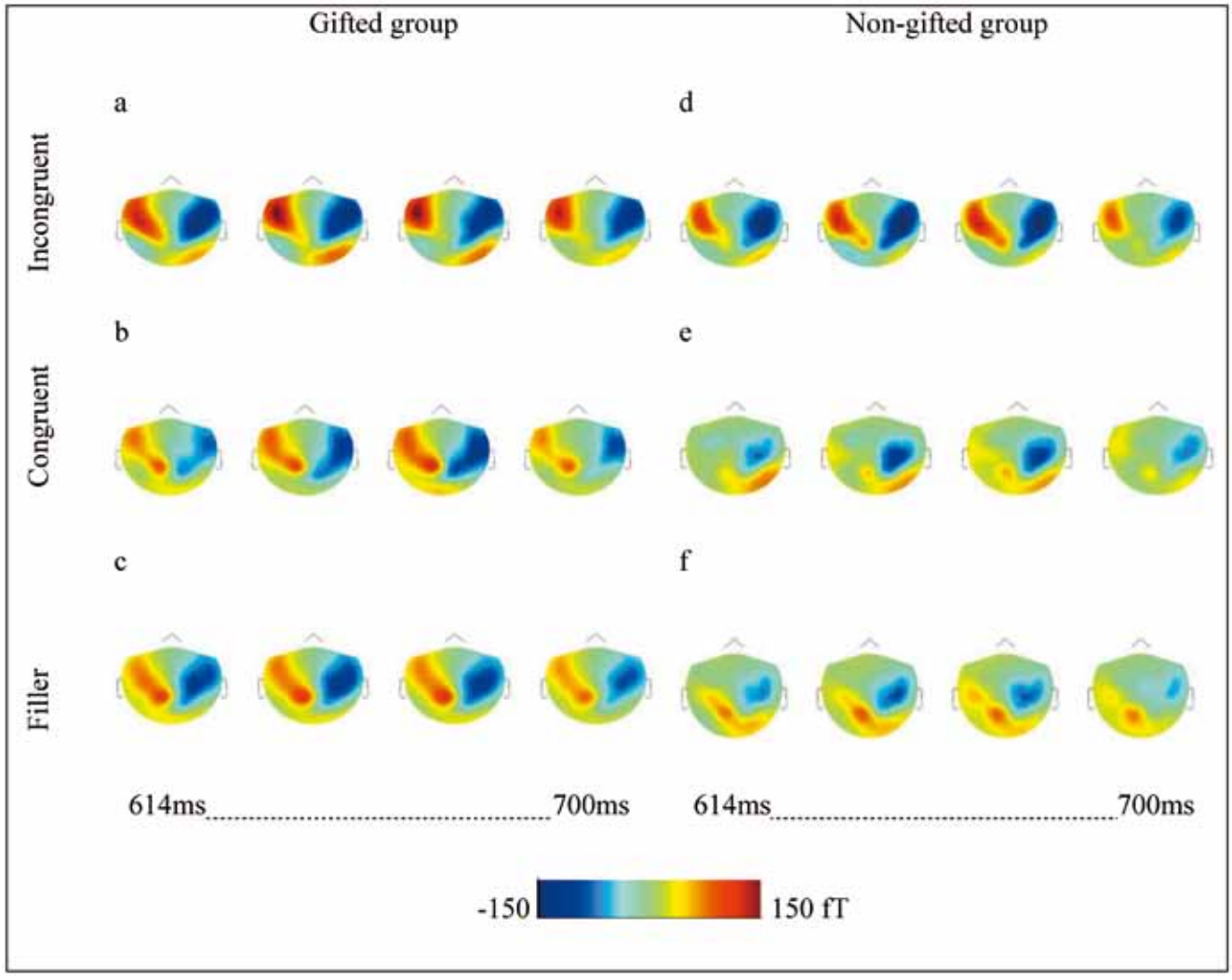


Figure 5

The successive topographies of gifted and non-gifted children from 614ms to 700ms



Discussion

The present MEG study examined gifted children's brain activities during detecting semantic and syntactic errors in reading Chinese sentences. For children in the NG group, we found that the most brain activities were P600m and that the currents were located in the left temporal lobe related to anomalous syntax (Brito, 2017; Hagoort, 2003; Molinaro et al., 2011). Meanwhile, the NG group had stronger activities in the left posterior temporal lobe around 200ms suggested as P200m. This might be due to the fact that phonology is activated automatically during Chinese sentence reading, even when the task is not focused on pronunciation (Ren et al., 2009). However, such P200m was not found in the GT group. Another important ERF component, N400m, was not found in the NG group either. This might be explained by the research findings of Holcomb et al. (1992) that N400m amplitude decreases as children become older until they reach adolescence.

The results revealed a specific organization of brain activities in gifted children who were presented with Chinese sentences with semantic-syntactic errors which were formed by wrongly used perfect or progressive

sentence-final particles. Different from what is observed in the NG group, the N400m/ELANm was identified in the GT group. The result was supported by Liu et al.'s (2011) findings that no N400m/ELANm effect was shown significantly in the NG group in the combined violation task. Comprehension of a sentence relies on both syntactic and semantic information. When anomaly occurs in a sentence, both syntactic and semantic processing will be required to detect the error. As syntactic processing is related to ELAN, the observation of N400m/ELANm is suggestive of syntactic processing in operation (Liu, et al, 2011). Although syntactic processing and semantic processing are generally believed to be separate processes, the assumption was supported that syntactic processing is given the priority over semantic processing in sentence comprehension. Therefore, the GT group had the 400-ms component, which was not found in the NG group; this indicated a different neural processing compared with the NG group.

Results from the semantic-syntactic violation detection tasks confirmed the assumption that as intelligence gets higher, increased activation of the left-lateralized anterior and middle temporal can be observed around 600ms. The topographic distribution and the time course of this effect are compatible with those of the left frontal and temporal area, which is supposed to be the critical region for syntactic processing during language comprehension (Friederici et al., 2000; Friederici et al., 2003).

Besides, another brain activity has been seen at the similar time-window around 600ms in the right occipito-temporal lobe which is close to the fusiform region. Also in the GT group, we saw 400-ms component that was suggested as an early left anterior negativity (ELAN) in the left-lateralized anterior region response to word category information (Liu et al., 2011). It might be possible that during the task the gifted participants categorized Chinese words to predict the grammaticality of the sentences they read. This is suggested as the syntax-related ELAN-P600 effect when combining syntactic and semantic violations (Friederici et al., 2004). Different from older individuals, younger individuals showed a stronger waveform N400/ELAN during semantically and syntactically anomalous sentence reading. N400/ELAN showed more delayed component latency and had a wider scalp distribution (Atchley et al., 2006).

We also observed a 600-ms component in response to a semantic violation whose magnetic field pattern was similar to that of a syntactic violation, though its activity was negative. Although P600m is taken as a response to syntactic errors rather than semantic ones, a late time window with negative amplitude has been observed as N400m (Friederici & Frisch, 2000). The presence of P600m indicated a repairing process which was based on both syntactic and semantic information (Gunter et al., 1997). Thus, the 600-ms component in the semantic violation might be related to syntactic processing.

Participants from both groups reached a rather high accuracy in the semantic-syntactic error detection task and the word recall task. Observation of a clear peak at around 600 ms for a syntactic violation indicates that the participants did comprehend the sentences; yet, the GT group showed a stronger component in the early time-point around 400 ms and had shorter reaction time than the NG group. This could be supported by Weber-Fox et al.'s (2003) findings that young individuals with a high level of language proficiency had faster lexical processing and engaged lexical processes in a different way compared with their average counterparts.

In the present study, group comparison did not reveal significant differences in the incongruent-subtract-congruent (IC), incongruent-subtract-filler (IF), and congruent-subtract-filler (CF) contrasts on the early time-window. However, in the GT group there was a significant increase of syntactic effect in the IF condition in the right occipito-temporal region. It might be that the tasks we presented in this experiment included two sub-tasks, that is, the semantic-syntactic error detection task and the word recall task, which might make it more challenging for children to process, especially when they had to finish over one hundred trials. Therefore, more complex tasks might require more brain network processing (Dunst et al., 2014).

In the IF comparison, the results showed one time-window with significant difference between the two groups. A late time-window with group difference was

found around 650 ms. For the topography, the stronger responses showed in the right posterior position during the significant time-window. In contrast, no statistically significant difference of the response was found when comparing CF and IC conditions in the late time-window.

Interestingly, this study showed that responses of the GT group had stronger amplitude at the late time-window, but no difference was found at the early time point compared with the NG group in detecting semantic-syntactic errors. Both groups showed equally high accuracy in the measures of semantic-syntactic error detection and word recall tasks, which suggested that the tasks were easy for all the participants. Though stronger positive/negative ERFs represent different neural efficiency, gifted participants use a different neural network to process semantic-syntactic comprehension compared with their non-gifted peers. A complex task might engage deeper processing in a brain network so that brighter individuals would have even greater brain activation than their average peers (Dunst et al., 2014).

Implications

Several implications can be made based on the results of the study. First, as the assumption was supported that syntactic processing is given priority over semantic processing in sentence comprehension, a pedagogical implication regarding language learning is that syntactic knowledge is important in comprehending sentences, especially when learning a foreign language. With syntactic knowledge of a certain language, explicit or implicit, together with semantic knowledge, language comprehension will become easier and faster. Second, we infer that more complex tasks may require more brain network processing and that individuals with higher intelligence have more brain activation than their average peers in processing complex tasks. An implication can be thus made from such inference, that is, the gifted brain deserves more complex tasks to elicit more activation. Therefore, it is suggested that challenging tasks be continuously provided to gifted learners at various stages of learning so that they may have a better chance to fully develop their potentials. Third, gifted learners may process language in a different way from their average counterparts, suggesting that differentiated instruction is necessary and essential not just for better learning performance but also for more brain activation stimulation on the part of the gifted learners.

Limitations

Due to the limitation of the spatial resolution of MEG system, the MEG sensor type should be considered when interpreting results of spectral analysis. Here, we used the magnetometer channels for interpreting the results and the sensor level, especially magnetic field, doesn't mean the source localization. Therefore, the brain region mentioned in this study doesn't be directly related with the localization of the brain source. However, we did another fMRI study to compensate the limitation of the spectral problem. We actually tested the language process of GT students and the same participants were recruited. From the fMRI study, the result showed that the GT group had higher and more widespread bilateral brain activation during the word detection task and more activation was found in the post cingulate cortex than the non-gifted students. By now, this fMRI study was also accepted by Chinese Journal of Psychology.

In this study, we controlled the gender variable to have a similar number of male and female participants, and the results showed no significant difference between the male and female participants ($X^2(1) = 1.074$, $p = 0.30$) when Pearson's chi-squared test was adopted. Therefore, we didn't take gender as a moderating variable for analysis, though gender was considered to be a critical factor in linguistic processing (Hagoort, 2003). Besides, both the perfect particle *le* and the progressive particle *zhong* were put at the sentence-final position, which makes it difficult to discriminate between the effects of local processing and global processing, the former being due to the sentence "wrap-up" response and the latter being decision processes. Therefore, it's difficult to clearly identify the potential components when semantic integration and syntactic detection are merged (Hagoort, 2003).

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作業難度與智力神經效率假說：資優兒童與一般兒童在語意句法判斷作業之差異

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從跨文化的證據看來，神經效率假說支持資優兒童在語言能力方面是較早成熟的，在不同的作業表現中發現兒童的神經電訊反應與智力有關連。本研究為探試神經效率假說，設計語意句法判斷實驗來瞭解資優兒童處理語言句子的能力，透過腦磁儀蒐集受試者的大腦神經反應並進行事件相關磁場的分析。實驗過程中受試者必須判斷句尾語氣詞正確與否，亦即語氣詞符合句子（一致情境）或是不符合句子（不一致情境）之語意，及受試者須判斷語詞是否有出現在句子中的回憶作業（填充情境）。

研究對象為國小 19 位智能資優兒童（資優組）與 15 位一般兒童（控制組），分析方式採排序 *t* 檢定進行兩兩比較，考驗組間與組內的事件相關磁場差異，疊代次數設定為 1000，使用雙尾考驗且顯著水準需小於 .05。在組內比較分析發現，資優組在刺激出現後的 400 毫秒與 600 毫秒的時間點附近有較強的腦磁振幅，但是控制組僅在 600 毫秒出現較強的腦磁振幅。在組間比較中，發現不一致情境減去填充情境的事件相關磁場在刺激出現後的 650 毫秒右枕葉區有組間的顯著差異，腦磁圖顯示資優組兒童在枕顳葉區明顯有強大的磁流；不過，在不一致情境減掉一致情境與一致情境減填充情境的分析過程中，並沒有發現組間有其他顯著差異。

本研究發現在語意句法判斷作業中，資優兒童與一般兒童相比之下，資優兒童的大腦磁流反應較強，尤其是在刺激後較晚的時間點。因此，當提出智力的神經效率假設時，需要考量作業的複雜性或難度，如同此研究結果顯示複雜的任務可能會讓大腦網絡進行更深層次的處理，並且資優兒童表現出比一般兒童更多的大腦活化。

關鍵詞：腦磁攝影；資優；語文能力；語意句法判斷；智力的神經效率假設

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