Cognition, Emotion & Education
CEE

# A Systematic Review of Language Aptitude and Proficiency: EEG and ERP Measurements

**Zahra Ashofteh[1], Razieh Bahri Roudposhti[1*], Elmira Farkhondehfal[2]**
*[1]Ferdowsi University of Mashhad, Iran, [2]Università degli Studi di Siena, Italy*

**Abstract** How to evaluate and predict the degrees of language aptitude and language proficiency is one of the controversial issues in the world of second language learning. To address this matter, the use of clinical devices such as EEG (electroencephalogram) and ERP (Event-related potential) has recently been a hotly debated area of discussion. In the current paper, a history of using such devices has been collected and discussed to depict a comprehensive map for further research. The online search was accomplished using two major and reliable databases (Google Scholar and Research Gate). The study found some interesting investigations on the theory of language aptitude defined in various articles as well as the different uses of EEG and ERP in evaluating brain function of participants with different levels of language aptitude and proficiency showing various degrees of brain waves while performing a task or at the resting state of the brain.

***Keywords:*** *Cognition, Language Aptitude, Language Proficiency, EEG, ERP*

## 1. Introduction

Aptitude in learning a new language, a varied general theoretical concept across the human population, has recently been a topic of interest in individual difference research. Language learning aptitude is defined as a talent in acquiring a new language, measured by means of paper-based test scores (Pishghadam et al., 2023; Yue et al., 2019). Fluctuation in ease and difficulty of language learning during the life span has been the focus of extensive investigations on neural plasticity research (Kliesch et al., 2022; Reiterer et al., 2011; Prat et al., 2016). According to Carroll (1981), language aptitude consists of four components, including phonemic coding ability, associative memory, grammatical sensitivity, and inductive language analytic ability. Phonemic coding ability deals with the capability of segregating and coding alien sounds to make it possible to be evoked in the future. While associative memory refers to the ability to make relationships between native language vocabularies and their foreign language equivalents, grammatical sensitivity deals with one's capability of pinpointing the functions of each word in sentences. The fourth component, inductive language analytic ability, is associated with correct recognition and extrapolation of patterns between form and meaning.

**[*]Corresponding Author:**
Razieh Bahri Roudposhti
rzhbahri@yahoo.com

**Received:** August 2023
**Revised:** September 2023
**Accepted:** September 2023
**Published:** October 2023



https://doi.org/10.22034/cee.2023.419986.1013

Language proficiency refers to an individual's capability to use language effectively and accurately in disparate contexts. One of the primitive models for measuring language proficiency, proposed by Lado (1961) and Carroll (1961), was on the basis of the incorporation of four skills (listening, speaking, reading, writing) and different components of knowledge, including knowledge such as vocabulary, grammar, phonology, and graphology without taking into account the association between these skills and knowledge. Another limitation of this skill/component model was its defeat in considering the full context of language use. Later on, Hymes (1972, 1976) identified the sociocultural factors in the speech situation, leading to the growth of the conception of language proficiency and paying attention to the significance of context beyond the sentence to the appropriate use of language. Finally, Bachman (1990) proposed a communicative competence model entailing language competence, strategic competence, and psychophysiological mechanism, with a focus on both knowledge of language and the ability to implement that knowledge in communicative language use.

Language aptitude tests are mostly acclaimed based on the content they are measuring. Similar to proficiency tests, language aptitude tests are among the theory-based language tests; however, the theory by which they are being based comprises abilities connected to acquisition rather than focusing on the use of language (Bachman, 1990). This review study aims to look further into those investigations of measuring language aptitude and proficiency that utilized EEG and ERP. The findings of these studies will be discussed briefly.

## 2. Language Aptitude

It is important to make a distinction between aptitude and ability right at the beginning. John Carroll (1993), the 'founding father' of aptitude research, distinguished the terms 'ability', 'aptitude', and 'achievement' in this regard. He defined an association between ability and performance or potential for performance. He referred to 'ability' as 'the possible differences among individuals in the liminal levels of task difficulty (emotional and metaphorical) at which, under every circumstance in which all conditions appear commending, individuals perform the act quite successfully on a defined class of tasks. Carroll also highlighted the stability of abilities: An ability can be considered as a trait to the extent that it demonstrates some degree of stability or permanence even across an extended period of time.

Under this definition, the notions of 'aptitude' and 'ability' can be used interchangeably. However, some researchers make a distinction between ability and aptitude; these two are used quite in a synonymous sense (Dornyei, 2005). Arguably, they exhibit different functions when employed in different contexts rather than with different meanings. Based on Carroll's (1981) definition, foreign language aptitude is defined as 'an individual's initial state of being ready to acquire and the capacity for learning a foreign language, and also showing some latent facility in doing so [in case of presence of motivation and opportunity]'. Therefore, he viewed aptitude as a type of ability, in other words, a latent trait that is quite stable and somehow resistant to training and which relates to the potential for achievement given adequate teaching.

The connection between foreign language aptitude and general intelligence is another issue that needs to be considered and further investigated. Sasaki's (1996) study, with the objective of investigating the extent, as well as the aspects of language aptitude that are closely connected to general intelligence, can be helpful to elaborate on this issue more. She studied the aspects of language aptitude, which can be language-specific. Better to say, in this study, she explored the association between three measures of second language proficiency, foreign language aptitude, and two types of intelligence (verbal intelligence and reasoning). The results of first-order factor analysis of the aptitude and intelligence scores evidenced that they were quite separate notions. Analytic ability, which is a common component accounting for the variance in some of the aptitude variables and also in the intelligence quotients (IQ), was demonstrated by a second-order factor analysis. In Carroll's (1962, 1981) original model, other aptitude factors, namely phonetic coding ability and memory, were not associated with intelligence. Therefore, Sasaki (1996) declared the interrelation between intelligence and analytic ability; in contrast, phonetic coding ability and memory factors are distinct components of foreign language aptitude (Grigorenko et al., 2000).

It is fortunate that at the beginning of the twenty-first century, there has been a more focused investigation on foreign language aptitude. To a great degree, Peter Robinson's (2002) edited anthology can be considered a turning point in the re-conceptualization of the construct of foreign language aptitude.

The fundamental tenets of the LCDH model Sparks, sustained by a series of empirical studies (Sparks et al., 1995, 2008) exhibit themselves in the discussion of whether native language (L1) literacy skills are vital in predicting L2 learning (Sparks & Ganschow 2001). As was proposed by a factor-analytical study (Sparks et al., 2011), four basic components of L2 aptitude, including students' L1 and L2 phonology/orthography skills (subsuming phonemic coding and phonological processing ability), their L1 and L2 language analysis skills (comprising comprehension, grammar, vocabulary, and inductive language learning); their IQ/memory skills (including L1 intelligence and L2 paired-associate learning measures); and self-perceptions of L2 motivation and anxiety, are corroborated to identify 76% of the variance in ultimate oral and written L2 proficiency. Therefore, in developing the LCDH, Sparks and Ganschow claimed that it is quite vital to explore the similarities and differences between the two languages in question (participants' L1 and L2). The investigators suggested including a certain phonological measure of L1 and L2 in FL aptitude tests (Sparks & Ganschow, 2001).



Grigorenko et al. (2000) proposed a novel interpretation of foreign language aptitude: The Cognitive Ability for Novelty in Language Acquisition-Foreign (CANAL-F) theory, which was drawn on Sternberg's (1997, 2002) triadic conception of human intelligence (or 'successful intelligence' perspective in which intelligence includes three distinct levels: analytical, creative and practical). The ability to handle novelty and ambiguity while acquiring an L2 is what is emphasized in this theory. In association with this notion, the authors also hypothesized a new approach to assessment procedures for measuring foreign language aptitude, i.e., the CANAL-F test. The CANAL-F test exclusively concentrates on measuring test takers' recall and inferencing ability to process and acquire new linguistic materials while performing under both immediate and delayed settings (Dornyei & Skehan, 2003).

Skehan (2002, 2012, 2015), Dornyei and Skehan(2003), and Chan et al. (2011) invented an aptitude model that was evidenced and created based on the developments from gathering SLA research, which was in contrast to previous attempts to theorize foreign language aptitude. The so-called studies have regarded this concept as self-contained and unassociated with broader issues in SLA. Skehan demanded that different putative aptitude components be effectively connected to various SLA developmental stages and their related cognitive processes. For instance, it is investigable that the aptitude components of 'phonetic coding ability' and working memory could possibly be related to the onset stage of input processing and to noticing. According to Skehan, language analytical ability (a combination of Carroll's original 'grammar sensitivity' and 'inductive language learning' and working memory) should be linked to the stages of pattern identification, restructuring, and extending. Later, Skehan (2016) made a connection between these stages and the developing 'micro' literature on language aptitude, preventing the pre-post correlational design typical of the past and usually with quite brief quasi-experimental designs, which concentrates on different types of instruction or feedback (Skehan, 2015). Such studies clearly exhibit the impact of aptitude variables such as working memory or the capacity to benefit from different types of feedback at the process level. Therefore, Skehan's conception of foreign language aptitude creates significant implications for theoretical advancement since instead of merely taking an aptitude score to predict L2 learning results (typical in Carroll's time), Skehan attempts to use an approach that can identify the latent causes in the final learning outcome of an L2.

Robinson's (2005, 2007, 2012) 'Aptitude Complexes/Ability Differential' framework is another attempt to re-conceptualize foreign language aptitude in applied linguistics. The framework contains two closely incorporated hypotheses, as is clearly indicated in the name of it. The first one, the Aptitude Complexes Hypothesis (based on the ideas of 'aptitude complexes' by Snow (1987, 1994), proposes that a set of basic cognitive abilities (such as 'processing speed', 'pattern recognition', 'phonological working memory capacity,') collaborate to form higher- order aptitude complexes (for instance, 'noticing the gap' and 'memory for contingent speed') that are used in learning a certain task. The second, the Ability Differentiation Hypothesis, declares that L2 learners exhibit variations among the set of cognitive abilities (show strength in some of them and weaknesses in others), therefore resulting in differentiated profiles in analogous aptitude complexes.

The creation of the 'High-Level Language Aptitude Battery' (Hi-LAB) done by the investigators at the University of Maryland Center for Advanced Study of Language (Doughty, 2013, 2014; Doughty et al., 2010; Linck et al., 2013) was one of the most significant improvements in aptitude theory construction and testing in the recent decade. The starting point to create such a test can be found in the perceived necessity to make an aptitude battery suitable for the prediction and explanation of high levels of L2 proficiency. This battery is specifically targeted at talented post-critical-period language learners. The developers proposed the possibility of differences between the components of aptitude suitable for high-level learning and those at lower levels. Later, they defined high-level aptitude 'as a combination of domain-general cognitive abilities and specific perceptual abilities' (Linck et al., 2013) that are associated with high-level achievement.

According to Pishghadam et al. (2023), aptitude tests should be enhanced by incorporating cultural and emo-sensory constructs in addition to cognitive ones. They argue that current aptitude tests may not fully capture individuals' range of abilities and tend to focus on specific cognitive constructs, ignoring non-cognitive ones. They suggest that by integrating culture, emotion, and sense into general and foreign language aptitude testing, they can provide a more accurate and comprehensive assessment of individuals' potential, allowing them to understand their strengths and weaknesses better. They also claim that their newly developed Pishghadam Language-based General Aptitude Test (PL-GAT) measures a wide range of cognitive abilities, along with non-cognitive abilities, and provides an evaluation of individuals' foreign language aptitude as well.

Finally, In the recent decade, there have been copious cognitive neuroscience research paradigms and techniques intruding into the territory of SLA (Dien et al., 2011; Dornyei, 2009; Gullberg & Indefrey, 2006). In contribution to the earlier reliance on behavioral research conventions, results from these brain-based neurological studies have turned into a comprehensive source of evidence (Li & Grant, 2015; Schumann, 2004). The bulk of empirical studies on the neurological substrates of foreign language aptitude is expanding, leading to the accumulation of evidence that is consistent and replicable across studies (Biedroń, 2015; Li et al., 2014).

Generally speaking, these brain-based neurological investigations can be categorized into two types: those concentrating on the structural dimensions of brain anatomy and those focusing on functional dimensions of brain activation. The distinct dimensions and levels of L2 learning and processing are connected to the anatomical or activation differences. Considering the research methodology, most of these neurolinguistic investigations have implemented a series of hemodynamic methods such as positron emission tomography (PET; measures radioactive tracers), event-related potential (ERP; measures temporal aspects of neural events), functional magnetic resonance imaging (fMRI; measures the magnetic resonance signals) and magnetoencephalography (MEG; measures the magnetic resonance signals as a result of electrical activity), and finally diffusion tensor imaging (DTI; maps white matter fiber tracks of the brain) (Biedroń, 2015).

## 3. Language Proficiency

Recording ERPs during English speaker's deciding on the grammaticality correctness of English sentences, Qi (2017) analyzed the effect of individual differences in native language processing on L2 achievements. The data revealed that better future performance in L2 learning can be predicted by great N400 during processing English semantics. N400 has an association with processing syntactic information through its connection with vocabulary learning. On the other hand, the P600 effect during the processing of syntactic information is anticipated only for syntactic processing, not vocabulary learning. In addition, results indicated the important role of aptitude in L2 attainment in earlier stages, whereas, after various sessions, other factors such as motivation, self-monitoring, and sleep may intervene in the learning process.

In two investigations, the participants were asked to read Dutch sentences that occasionally contained a syntactic error and, in some cases, a semantic error. All syntactic errors were word category violations. The design eliminated varying contributions to expectancy to affect the syntactic error effects. The syntactic errors evoked an Anterior Negativity between 300 and 500 ms. This negativity was frontally distributed as well as bilateral. The same errors were elicited over posterior sites at a P600/SPS starting at about 600 ms. An N400 effect was evoked by the semantic violations. The AN was topographically distributed more in the frontal area compared to the distribution of the classical N400 effect. This matter indicated that the underlying generators of the AN and the N400 are approximately non-overlapping. The investigators partly replicated the design of Experiment 1 in Experiment 2; however, in the rate of presentation and in the distribution of items among subjects, and without semantic violations, some differences were observed. The same effects were obtained as they were observed in Experiment 1 concerning the word category violations, which led to demonstrating their independence in some cases of the specific parameters of Experiment 1. The discussion offered a tenuous account of the functional distinctions between the AN and the P600/SPS (Hagoort et al., 2003).

There has been an ongoing discussion concerning the absolute critical period for acquiring language. Comparing the processes of second language (L2) learning after childhood and those of first language (L1) learning during childhood can be one way to consider this matter. In a study conducted by Ojima et al. (2005), a comparison was made between event-related brain potentials obtained from two groups of adult Japanese speakers with either high or intermediate proficiency in English after childhood (J-High and J-Low) and adult native English speakers (ENG) in order to study the cortical process of post-childhood L2 learning. The sole difference between the groups was the time course of the brain activation since semantic anomalies embedded in English sentences elicited a clear N400 component in all groups. Syntactic violations evoked a left-lateralized negativity in ENG and J-High but not in J-Low, which was analogous to the left anterior negativity. Additionally, a P600 component was found in ENG. The findings declared the robustness of semantic processing from early on in L2 learnin; however, the development of syntactic processing proved to rely more on proficiency, as confirmed by the lack of the left-lateralized negativity found in J-Low.

Ellis (2006) claims that additional research toward deeper investigation of the difference between implicit and explicit grammatical knowledge will be quite productive for modeling, comprehending, and assessing second language proficiency if the future of the application of a dual explicit-implicit learning system to the L2 theory is concerned. Mirzaei et al. (2011) investigated how differently accessible EFL learners' explicit and implicit grammatical knowledge is based on their language proficiency. To collect the data, a test battery comparing a timed grammaticality judgment test (GJT), an untimed GJT, and a TOEFL was used. The findings revealed no statistically significant correlation between the EFL learners' implicit grammatical knowledge and their TOEFL (sub-components) scores, however, a strong relationship between the EFL learners' explicit grammatical knowledge and their general proficiency was found. A medium relationship between the explicit knowledge and the TOEFL sub-components was detected. Also, it was demonstrated that explicit knowledge can act as a better predictor of the EFL learners' general L2 proficiency. Furthermore, learning explicit grammatical knowledge is necessary in EFL contexts, and it should be considered more seriously when one has concentrated on cognitive academic language proficiency or skills.

Language proficiency, a pivotal item of perceiving text, is acknowledged to be associated with learners' academic accomplishment. Previous investigations have revealed how academic performance in one subject can be associated with performance in another subject. For instance, June (2013) and Wang (2005) acknowledged that scores in math can have a strong correlation with science grades. Moreover, in Adegboye's (1993) and Aina et al.'s (2013) studies, it has been revealed that science and math scores can be significantly influenced by English grades. Therefore, possessing problem-solving information in one subject can be utilized to anticipate accomplishment in other subjects. Assembled data from an authentic online learning platform, Jung et al. (2023) examined the relationship between students' language proficiency and their competence in solving math problems. Consistent with previous studies, the data indicated a strong correlation between the sentence length of the math problem and the language proficiency of the students who answered the question accurately.

Finally, with the goal of assessing the association between non-native speakers' language proficiency and characteristics of EEG signals while listening to a second language, Ihara (2021) recruited 205 native Japanese speakers with different degrees of English proficiency. The findings indicated that neural features during listening to natural speech make it possible to estimate foreign language ability in the absence of any traditional paper test.

## 4. Measuring Language Aptitude and Proficiency by EEG

EEG plays a vital role in many aspects of second language aptitude research. It's necessary to mention that out of a range of different studies, two main streams of approaches are prevalent: 1. Task-free EEG, 2. Resting state EEG. Regarding task-free EEG, a study conducted by Bice et al. (2020) examined how bilingual language experiences affect brain function and connectivity using task-free EEGs. In this study, bilinguals exhibited greater alpha power and coherence in the alpha and beta frequency ranges compared to monolinguals. These discrepancies were associated with a number of factors, including language proficiency, second-language use, native-language proficiency, and age of second-language acquisition.

The contribution of resting-state brain connectome to individual differences in learning ability has been a constant area for research over the years. Examining the associations between resting-state alpha band (8–12 Hz) connectome and individual learning ability whilst learning novel words in a foreign language by the use of EEG, Huang et al. (2022) found a significant difference while performing a novel word learning task. A sort of positive coherence between the occipital and frontal regions of the brain in terms of individual resting-state alpha band was detected, which was in correlation with differential word learning performance. This robust difference was also replicated by an independent cohort of 35 healthy adults. In general, resting-state EEG connectome plays the role of a reliable marker for having a high aptitude during new language learning.

The attempt to predict the acquisition of a second language by employing quantitative electro-encephalography (qEEG) was started in a study by Prat et al. (2016). They employed eye-closed resting-state qEEG in order to anticipate the rate of language learning during eight weeks of exposure through virtual language and cultural immersion software. The data revealed a strong positive relationship between beta and low-gamma frequency and SLA. Although nearly 60% of differences in the final level of language can be predicted through resting-state qEEG indices like right hemisphere low-beta power, there was no significant correlation between the rate of learning and behavioral indices of fluid intelligence, executive functioning, and working memory amplitude. In terms of the laterality effect, the findings showed high-frequency use of RH by native language speakers with less linguistic proficiency, compared to those individuals with high linguistic proficiency, which was consistent with previous investigations (Prat et al., 2007, 2011). In line with previous studies (Thatcher et al., 2005), it has been found that the more lateralization happens in the distribution of alpha power, the faster the language learning. Therefore, the data are compatible with (Prat et al., 2011), which indicated the positive correlation between lateral patterns of brain activity and linguistic competence of first language learners. In addition, the findings confirmed the efficacy of resting-state EEG in neurobiological-based studies of SLA.

An interesting attempt to show that resting-state brain rhythms may predict language learning ability and language aptitude in bilingual' individuals was recently conducted by Prat et al. (2019). The study aimed to gain a better understanding of the neurocognitive bases of L2 aptitude by characterizing individual differences in resting-state neural rhythms and relating them to first-language proficiency and subsequent second-language learning ability. To this end, neural oscillations and properties of intrinsic brain function known to be related to subsequent cognitive performance and L2 learning ability were examined. In order to evaluate the cognitive abilities researchers used behavioral assessments which were divided into four parts of the test of fluid information processing, executive functioning, probabilistic learning, and English reading ability, including Raven's Advanced Progressive Matrices (Arthur & Day, 1994), Reading Span and Operation Span (Unsworth et al., 2005), Simon Task (Stocco et al., 2017), 3-back updating task, color-shape-switching task (Monsell, 2003), Continuous Performance Test (Cohen et al., 1999), Attentional Blink task (Broadbent & Broadbent, 1987; Raymond et al., 1992); Probabilistic Stimulus Selection task (Frank et al., 2004), and Nelson Denny Reading Test [NDRT] (Brown et al., 1993). The results revealed that combined neural metrics explained 48% of the variance in subsequent L2 learning rates. Interestingly, the study provided evidence that age at second language acquisition is related to differences in the brain's white matter organization and that this white matter organization may predict subsequent learning success.

Some of the researchers of EEG have also focused on learning grammar. Kepinska et al. (2017) attempted to map the initial phases engaged while learning novel grammar on a neural level. It's clear that different individuals utilize different sorts of mechanisms. To do so, an Artificial Grammar Learning (AGL) task, including learning and test phases, was employed to test two groups of participants, one with high and one with average language abilities. By analyzing the recorded EEG signals, especially the epochs responsible for the learning phases, learning effects were recognized; however, highly qualified learners' obtained a steeper learning curve and higher ultimate attainment. Another issue investigated in this study was cortical connectivity patterns and profiles of spectral power modulations, which proved to have a differentiating effect on L2 learners. By means of beta band frequency, the whole-brain functional connectivity between the neural assemblies was detected. The local synchronization within the right hemisphere regions also became stronger as the proficiency of AGL increased. Taken together, less mental effort and a reduction in mental effort after the learning had been exerted by the highly qualified learners, which was shown by higher alpha band power.

Saito (2019) employed EEG and language aptitude tests with the goal of analyzing the sensitivity of Chinese learners of English to segmental and supra-segmental features in explicit and implicit modes. The findings revealed a significant relationship between the segmental achievement of participants and both explicit and implicit aptitude, including phonemic coding and enhanced neural encoding of spectral peaks, respectively. Therefore, L2 segmental achievement can be predicted by both explicit and implicit tests. In other words, with respect to suprasegmental achievement, to some extent, findings indicated the association between acquiring suprasegmental features and rhythmic imagery, which is called explicit aptitude. Moreover, a strong association was found between L2 suprasegmental learning and experience, which can be due to the fact that suprasegmental features, in comparison with segmental features, cause better comprehension.

## 5. Concluding Remarks

Systematic literature reviews are comprehensive, thorough literature syntheses that are centered on well-defined research questions. The aim of this systematic review was to inspect studies that pertain to language proficiency, language aptitude, or EEG and ERP-based studies that provide a more comprehensive view of language proficiency and language aptitude. To the best of our knowledge, this is the first systematic review scrutinizing the prominent role of neural signature, measured by EEG, and reflecting the second or foreign language proficiency. In the current study, we presented the summary of articles aimed to explore the relationship between language aptitude and the future achievement of second or foreign language learners whose proficiency is diverse and also predicted the acquisition of a second language by employing the EEG or LLAMA test.

Although employing EEG has some limitations, it's quite possible to directly assess real-time brain activity, markedly in the absence of any supplementary tasks. In addition to the pervasive utilization of EEG in the language domain, ERPs underline the transient unraveling of neural activity relevant to different cognitive aspects of conception and production of language.

Researchers in most of the articles reviewed in this study exclusively analyzed EEG data by employing statistical tools. Therefore, suggesting a prediction model or taxonomy with the aim of anticipating individuals' cognitive, emotional, and behavioral forms and going beyond the statistical tools is highly recommended in future studies (Akbari & Pishghadam, 2022). Moreover, there is a need for further inspection of the relationship between Brodmann areas in the brain and cognitive effects while an individual engages in intellectual processing, that is, exploring the relationship between the placement of electrodes on different lobes and the subsequent results that might be demanded in future studies.

Finally, we can refer to the employment of multimodal apparatus such as eye tracking, fMRI, and interviews besides EEG as an important suggestion for further research in order to expand the generalizability of our outcomes, leading to meticulous and thorough results.

This review was an attempt to collect a united body of data around measuring Language aptitude and language proficiency with the help of EEG, ERP, and other common paper and computer-based tests. In the first section of this paper, the definition of language aptitude and language proficiency, as well as their distinctions with ability and intelligence, were considered. Then, some frameworks and models regarding language aptitude and language proficiency were discussed, followed by the summary of several investigations concerning Language aptitude and language proficiency.

To conclude, what was quite noticeable during the preparation of this review was the lack of research concerning testing language aptitude and language proficiency using clinical devices during recent years. A copious amount of literature has focused on measuring these issues using ready-made tests online and on paper. Thus, it is recommended that further investigation be conducted to consider the brain functions tangibly to come to a precise result.



## Disclosure Statement

The authors claim no conflict of interest.

## Funding

The research did not receive any specific grants from funding agencies.

## References


Adegboye, A. O. (1993). Proficiency in English language as a factor contributing to competency in Mathematics. *Education Today*, *6*(2), 9-13.

Aina, J. K., Ogundele, A. G., & Olanipekun, S. S. (2013). Students' proficiency in English language relationship with academic performance in science and technical education. *American Journal of Educational Research*, *1*(9), 355-358. http://doi.org/10.12691/education-1-9-2

Akbari, M. H., & Pishghadam, R. (2022). Developing new software to analyze the emo-sensory load of language. *Journal of Business, Communication and Technology*, *1*(1), 1-13. http://doi.org/10.56632/bct.2022.1101

Arthur, W., & Day, D. V. (1994). Development of a short form for the Raven advanced progressive matrices test. *Educational and Psychological Measurement*, *54*(2), 394–403. https://doi.org/10.1177/0013164494054002013

Bachman, L. F. (1990). *Fundamental considerations in language testing*. Oxford University Press.

Bice, K., Yamasaki, B. L., & Prat, C. S. (2020). Bilingual language experience shapes resting-state brain rhythms. *Neurobiology of Language*, *1*(3), 288-318. https://doi.org/10.1162/nol_a_00014

Biedroń, A. (2015). Neurology of foreign language aptitude. *Studies in Second Language Learning and Teaching*, *5*(1), 13–40. http://doi.org/10.14746/ssllt.2015.5.1.2

Broadbent, D. E., & Broadbent, M. H. (1987). From detection to identification: Response to multiple targets in rapid serial visual presentation. *Perception and Psychophysics*, *42*(2), 105–113. https://doi.org/10.3758/BF03210498

Brown, J., Fishco, V., & Hanna, G. (1993). *Manual for scoring and interpretation, Forms G & H.* Riverside Press.

Carroll, J. B. (1961). The nature of the data, or how to choose a correlation coefficient. *Psychometrika*, *26*(4), 347-372. https://doi.org/10.1007/BF02289768

Carroll, J. B. (1962). The prediction of success in intensive foreign language training. In R. Glaser (Ed.), *Training research and education* (pp. 87–136). University of Pittsburgh Press.

Carroll, J. B. (1981). Twenty-five years of research on foreign language aptitude. In K. C. Diller (Ed.), *Individual differences and universals in language learning aptitude* (pp. 83–118). Newbury House Publishers.

Carroll, J. B. (1993). *Human cognitive abilities: A survey of factor-analytic studies*. Cambridge University Press. https://doi.org/10.1017/CBO9780511571312

Chan, E., Skehan, P., & Gong, G. (2011). Working memory, phonemic coding ability and foreign language aptitude: Potential for construction of specific language aptitude tests – The case of Cantonese. *Ilha Do Desterro: A Journal of English Language, Literatures and Cultural Studies*, *60*, 45–73. https://doi.org/10.5007/2175-8026.2011n60p045

Cohen, J. D., Barch, D. M., Carter, C., & Servan-Schreiber, D. (1999). Context-processing deficits in schizophrenia: Converging evidence from three theoretically motivated cognitive tasks. *Journal of Abnormal Psychology*, *108*(1), 120–133. https://doi.org/10.1037//0021-843x.108.1.120

Dien, J., Weinberg, A., Blok, S., O'Rourke, P., Kayton, K., & Hamedani, N. (2011). *Cognitive neuroscience of second language acquisition.* University of Maryland Center for Advanced Study of Language.

Dornyei, Z. (2005). *The psychology of the language learner: Individual differences in second language acquisition*. Lawrence Erlbaum.

Dornyei, Z. (2009). *The psychology of second language acquisition*. Oxford University Press.

Dornyei, Z., & Skehan, P. (2003). Individual differences in second language learning. In C. Doughty & M. H. Long (Eds.), *The handbook of second language acquisition* (pp. 589–630). Blackwell Publishing. https://doi.org/10.1002/9780470756492

Doughty, C. J. (2013). Optimizing post-critical-period language learning. In G. Granena & M. H. Long (Eds.), *Sensitive periods, language aptitude, and ultimate L2 attainment* (pp. 153–175). John Benjamins. https://doi.org/10.1075/lllt.35.06dou

Doughty, C. J. (2014). Assessing aptitude. In A. Kunnan (Ed.), *The companion to language assessment* (pp. 25–46). Wiley-Blackwell.

Doughty, C. J., Campbell, S. G., Mislevy, M. A., Bunting, M. F., Bowles, A. R., & Koeth, J. T. (2010). Predicting near-native ability: The factor structure and reliability of Hi-LAB. In M. T. Prior, Y. Watanabe & S. K. Lee (Eds.), *Selected proceedings of the 2008 second language research forum* (pp. 10–31). Cascadilla Proceedings Project.

Ellis, R. (2006). Modeling learning difficulty and second language proficiency: The differential contributions of implicit and explicit knowledge. *Applied Linguistics*, *27*(3), 431–463. https://doi.org/10.1093/applin/aml022

Frank, M. J., Seeberger, L. C., & O'Reilly, R. C. (2004). By carrot or by stick: Cognitive reinforcement learning in parkinsonism. *Science*, *306*(5703), 1940-1943. https://doi.org/10.1126/science.1102941

Grigornko, E. L., Sternberg, R. J., & Ehrman, M. E. (2000). A theory-based approach to the measurement of foreign language learning ability: The Canal-F theory and test. *The Modern Language Journal*, *84*(3), 390-405. https://doi.org/10.1111/0026-7902.00076

Gullberg, M., & Indefrey, P. (Eds.). (2006). *The cognitive neuroscience of second language acquisition*. Blackwell Publishing.

Hagoort, P., Wassenaar, M., & Brown, C. M. (2003). Syntax-related ERP-effects in Dutch. *Cognitive Brain Research*, *16*(1), 38-50. https://doi.org/10.1016/S0926-6410(02)00208-2

Huang, Y., Deng, Y., Jiang, X., Chen, Y., Mao, T., Xu, Y., Jiang, C., & Rao, H. (2022). Resting-state occipitofrontal alpha connectome is linked to differential word learning ability in adult learners. *Frontiers in Neuroscience*, *16*, Article 953315. https://doi.org/10.3389/fnins.2022.953315

Hymes, D. (1972). On communicative competence. In J. B. Pride & J. Holmes (Eds.), *Sociolinguistics. Selected reading* (pp. 269-285). Penguin Books.

Hymes, D. (1976). Towards linguistic competence. *Sociologische Gids*, *23*(4), 217-239.

Ihara, A. S., Matsumoto, A., Ojima, S., Katayama, J., Nakamura, K., Yokota, Y., Watanabe, H., & Naruse, Y. (2021). Prediction of second language proficiency based on electroencephalographic signals measured while listening to natural speech. *Frontiers in Human Neuroscience*, *15*, Article 665809. https://doi.org/10.3389/fnhum.2021.665809

Jung, H., Yoo, J., Yoon, Y., Jang, Y. (2023). Language proficiency enhanced knowledge tracing. In C. Frasson, P. Mylonas, & C. Troussas (Eds.), *Augmented intelligence and intelligent tutoring systems. ITS 2023. Lecture notes in computer science* (Vol. 13891, pp. 3-15). Springer. https://doi.org/10.1007/978-3-031-32883-1_1

Jun, W. (2013). A study on correlation analysis of academic performance per subject for the gifted children in IT. *Journal of Gifted/Talented Education*, *23*(3), 407–419. http://doi.org/10.9722/JGTE.2013.23.3.407

Kepinska, O., Pereda, E., Caspers, J., & Schiller, N. O. (2017). Neural oscillatory mechanisms during novel grammar learning underlying language analytical abilities. *Brain and Language*, *175*, 99-110. https://doi.org/10.1016/j.bandl.2017.10.003

Kliesch, M., Becker, R., & Hervais-Adelman, A. (2022). Global and localized network characteristics of the resting brain predict and adapt to foreign language learning in older adults. *Scientific Reports*, *12*, Article 3633. https://doi.org/10.1038/s41598-022-07629-y

Lado, R. (1961). *Language testing: The construction and use of foreign language tests, a teacher's book*. Longmans.

Li, P., & Grant, A. (2016). Second language learning success revealed by brain networks. *Bilingualism: Language and Cognition*, *19*(4), 657-664. https://doi.org/10.1017/S1366728915000280

Li, P., Legault, J., & Litcofsky, K. A. (2014). Neuroplasticity as a function of second language learning: Anatomical changes in the human brain. *Cortex*, *58*, 301-324. https://doi.org/10.1016/j.cortex.2014.05.001

Linck, J. A., Hughes, M. M., Campbell, S. G., Silbert, N. H., Tare, M., Jackson, S. R., Smith, B. K., Bunting, M. F., & Doughty, C. J. (2013). Hi-LAB: A new measure of aptitude for high-level language proficiency. *Language Learning*, *63*(3), 530-566. https://doi.org/10.1111/lang.12011

Mirzaei, A., Domakani, M. R., & Shakerian, Z. (2011). Differential accessibility of implicit and explicit grammatical knowledge to EFL learners' language proficiency. *Iranian Journal of Applied Linguistics*, *14*(2), 111-143.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, *7*(3), 134–140. https://doi.org/10.1016/S1364-6613(03)00028-7

Ojima, S., Nakata, H., & Kakigi, R. (2005). An ERP study of second language learning after childhood: Effects of proficiency. *Journal of Cognitive Neuroscience*, *17*(8), 1212-1228. https://doi.org/10.1162/0898929055002436

Pishghadam, R., Al Abdwani, T., Jajarmi, H., & Shayesteh, S. (2023). Enhancing general and language aptitude tests by incorporating cultural and emo-sensory constructs. *International Journal of Society, Culture and Language, 11*(3), 1-12. https://doi.org/10.22034/ijscl.2023.704891

Prat, C. S., Long, D. L., & Baynes, K. (2007). The representation of discourse in the two hemispheres: An individual differences investigation. *Brain and Language*, *100*(3), 283–294. https://doi.org/10.1016/j.bandl.2006.11.002

Prat, C. S., Mason, R. A., & Just, M. A. (2011). Individual differences in the neural basis of causal inferencing. *Brain and Language*, *116*(1), 1–13. https://doi.org/10.1016/j.bandl.2010.08.004

Prat, C. S., Yamasaki, B. L., Kluender, R. A., & Stocco, A. (2016). Resting-state qEEG predicts rate of second language learning in adults. *Brain and language*, *157*, 44-50. https://doi.org/10.1016/j.bandl.2016.04.007

Prat, C. S., Yamasaki, B. L., & Peterson, E. R. (2019). Individual differences in resting-state brain rhythms uniquely predict second language learning rate and willingness to communicate in adults. *Journal of Cognitive Neuroscience*, *31*(1), 78-94. https://doi.org/10.1162/jocn_a_01337

Qi, Z., Beach, S. D., Finn, A. S., Minas, J., Goetz, C., Chan, B., & Gabrieli, J. D. (2017). Native-language N400 and P600 predict dissociable language-learning abilities in adults. *Neuropsychologia*, *98*, 177-191. https://doi.org/10.1016/j.neuropsychologia.2016.10.005

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance, 18*(3), 849-860. https://doi.org/10.1037//0096-1523.18.3.849

Reiterer, S., Pereda, E., & Bhattacharya, J. (2011). On a possible relationship between linguistic expertise and EEG gamma band phase synchrony. *Frontiers in Psychology*, *2*, Article 334. https://doi.org/10.3389/fpsyg.2011.00334

Robinson, P. (2002). Learning conditions, aptitude complexes and SLA: A framework for research and pedagogy. In P. Robinson (Ed.), *Second language acquisition research and pedagogy* (pp. 113–133). Continuum.

Robinson, P. (2005). Aptitude and second language acquisition. *Annual Review of Applied Linguistics*, *25*, 46–73. https://doi.org/10.1017/S0267190505000036

Robinson, P. (2007). Aptitudes, abilities, contexts, and practice. In R. M. DeKeyser (Ed.), *Practice in second language* (pp. 256–286). Cambridge University Press. https://doi.org/10.1017/CBO9780511667275.015

Robinson, P. (2012). Individual differences, aptitude complexes, SLA processes, and aptitude test development. In M. Pawlak (Ed.), *New perspectives on individual differences in language learning and teaching* (pp. 57–75). Springer. https://doi.org/10.1007/978-3-642-20850-8_4

Saito, K., Sun, H., & Tierney, A. (2019). Explicit and implicit aptitude effects on second language speech learning: Scrutinizing segmental and suprasegmental sensitivity and performance via behavioural and neurophysiological measures. *Bilingualism: Language and Cognition*, *22*(5), 1123-1140. https://doi.org/10.1017/S1366728918000895

Sasaki, M. (1996). *Second language proficiency, foreign language aptitude, and intelligence: Quantitative and qualitative analyses*. Peter Lang.

Schumann, J. H. (2004). The neurobiology of aptitude. In J. H. Schumann (Ed.), *The neurobiology of learning: Perspectives from second language acquisition* (pp. 7–23). Lawrence Erlbaum.

Skehan, P. (2002). Theorizing and updating aptitude. In Robinson, P. (Ed.), *Individual differences and instructed language learning* (pp. 69–94). John Benjamins. http://doi.org/10.1075/lllt.2.06ske

Skehan, P. (2012). Language aptitude. In S. Gass & A. Mackey (Eds.), *Handbook of second language acquisition* (pp. 381-395). Routledge.

Skehan, P. (2015). Foreign language aptitude and its relationship with grammar: A critical overview. *Applied Linguistics*, *36*(3), 367–384. https://doi.org/10.1093/applin/amu072

Skehan, P. (2016). Foreign language aptitude, acquisitional sequences, and psycholinguistic processes. In G. Granena, D. Jackson, & Y. Yilmaz (Eds.), *Cognitive individual differences in L2 processing and acquisition* (pp. 15–38). John Benjamins.

Snow, R. E. (1987). Aptitude complexes. In R. Snow & M. Farr (Eds.), *Aptitude, learning and instruction, cognitive process analyses of aptitude* (Vol. 2, pp. 11–34). Erlbaum Associates.

Snow, R. E. (1994). Abilities in academic tasks. In R. J. Sternberg & R. K. Wagner (Eds.), *Mind in context: Interactionist perspectives on human intelligence* (pp. 3–37). Cambridge University Press.

Sparks, R., & Ganschow, L. (2001). Aptitude for learning a foreign language. *Annual Review of Applied Linguistics*, *21*, 90–111. https://doi.org/10.1017/S026719050100006X

Sparks, R., Ganschow, L., & Patton, J. (1995). Prediction of performance in first-year foreign language courses: Connections between native and foreign language learning. *Journal of Educational Psychology*, *87*(4), 638-655.

Sparks, R., Ganschow, L., & Patton, J. (2008). L1 and L2 literacy, aptitude, and affective variables as discriminators among high-and low-achieving L2 learners with special needs. In J. Kormos & H. Kontra (Eds.), *Language learners with special needs: An international perspective* (pp. 11-35). Multilingual Matters.

Sparks, R. L., Humbach, N., Patton, J. O. N., & Ganschow, L. (2011). Subcomponents of second-language aptitude and second-language proficiency. *The Modern Language Journal*, *95*(2), 253-273. https://doi.org/10.1111/j.1540-4781.2011.01176.x

Sternberg, R. J. (1997). *Successful intelligence*. Plume.

Sternberg, R. J. (2002). The theory of successful intelligence and its implications for language aptitude testing. In P. Robinson (Ed.), *Individual differences and instructed language learning* (pp. 13–43). John Benjamins Publishing Company. https://doi.org/10.1075/lllt.2.04ste

Stocco, A., Murray, N. L., Yamasaki, B. L., Renno, T. J., Nguyen, J., & Prat, C. S. (2017). Individual differences in the Simon effect are underpinned by differences in the competitive dynamics in the basal ganglia: An experimental verification and a computational model. *Cognition*, *164*, 31–45. https://doi.org/10.1016/j.cognition.2017.03.001

Thatcher, R. W., North, D., & Biver, C. (2005). EEG and intelligence: Relations between EEG coherence, EEG phase delay and power. *Clinical Neurophysiology*, *116*(9), 2129–2141. https://doi.org/10.1016/j.clinph.2005.04.026

Unsworth, N., Heitz, R. P., Schrock, J. C., & Engle, R. W. (2005). An automated version of the operation span task. *Behavior Research Methods, 37*(3), 498-505. https://doi.org/10.3758/BF03192720

Wang, J. (2005). Relationship between mathematics and science achievement at the 8th grade. *International Online Journal of Science Mathematics Education*, *5*, 1-17.

Yue, J., Li, J., Wang, Y., & He, Y. (2020, January 9). A pilot investigation of measuring language learning aptitude in adults neurophysiologically. *Proceedings of the 2019, the 3rd International Conference on Education, Economics and Management Research (ICEEMR 2019), Advances in Social Science, Education and Humanities Research*, *385*, 612-615. https://doi.org/10.2991/assehr.k.191221.147