Received: 2 October 2017 | Revised: 15 March 2018 | Accepted: 9 April 2018
DOI: 10.1002/mpr.1718

ORIGINAL ARTICLE

WILEY

Handwriting assessment to distinguish comorbid learning difficulties from attention deficit hyperactivity disorder in Chinese adolescents: A case–control study

Cecilia W.P. Li-Tsang[1] | Tim M.H. Li[1] | Mandy S.W. Lau[1] | Choco H.Y. Ho[1,2] | Howard W.H. Leung[2]

[1] Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hung Hom, Hong Kong

[2] Department of Computer Science, City University of Hong Kong, Kowloon Tong, Hong Kong

Correspondence
Cecilia W.P. Li-Tsang, Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong.
Email: cecilia.li@polyu.edu.hk

Funding information
The Hong Kong Examinations and Assessment Authority, Hong Kong, Grant/Award Number: (13) in T72

Abstract

Objectives: Attention deficit hyperactivity disorder (ADHD) and learning difficulties (LDs) are proposed as 2 overlapping disorders. The objective of this study was to investigate the handwriting performance in ADHD and comorbid ADHD-LD adolescents.

Methods: The study examined the Chinese and English handwriting performance and sensorimotor skills of 32 ADHD, 12 ADHD-LD, and their matched controls.

Results: Participants with ADHD had comparable writing time and speed, but the readability was lower than their controls. Participants with ADHD-LD had lower writing speeds in both Chinese and English handwriting than their controls. The ADHD and ADHD-LD groups also showed larger variations in either speed or pen pressure than their controls. Chinese handwriting assessment effectively classified ADHD and ADHD-LD with good sensitivity and positive predictive value.

Conclusions: Clinicians should be aware of the fundamental difference between the 2 disorders and make good use of handwriting assessment as a reference to deliver effective therapies and trainings.

KEYWORDS

ADHD, adolescent psychiatry, behavior, learning disability

1 | INTRODUCTION

Attention deficit hyperactivity disorder (ADHD) and learning difficulties (LDs) are proposed as "overlapping spectrum disorders" (Mayes, Calhoun, & Crowell, 2000). Molitor et al. (2016) estimated that 70% of students with ADHD have a specific learning difficulty. The average rate of comorbidity of ADHD-LD among adolescents across studies was also found to be as high as 45% (DuPaul, Gormley, & Laracy, 2013). The high comorbidity and the interaction effect of both disorders suggest that learning and attention problems are likely to be on a continuum. There are different hypotheses considering the origins of the comorbidity of ADHD and LD. Although many researchers have suggested that both disorders share similar deficits and etiological mechanisms (Saudino & Plomin, 2007), some have argued that it is merely the hyperactivity and inattention problems of individuals with ADHD, making them perform significantly worse than typically developing individuals in LD assessment, and leading to misdiagnosis (Adler et al., 2017; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). In other words, the poor performance of individuals with ADHD in the LD assessment does not necessarily represent that they would be also at a higher risk of having LD (DuPaul et al., 2013). LD can appear as a manifestation of ADHD instead of a comorbidity.

Learning requires a variety of skills such as information processing, working memory retrieval, and visual motor integration (Talero-Gutierrez, Van Meerbeke, & Reyes, 2012). LD is referring to some specific deficits during the process of learning, which significantly hinder the individuals from acquiring the knowledge and hence have an adverse impact on the academic performance. Given that handwriting is an important skill for learning, handwriting assessment can be considered as one of the most useful measures to investigate the manifestation of ADHD. In fact, handwriting difficulties are commonly found in students with ADHD (Borella, Chicherio, Re, Sensini, & Cornoldi, 2011). For instance, a study in the United States found that approximately 70% of students with ADHD showed impairments in handwriting (Brossard-Racine et al., 2015). On the other hand, growing consensus has been reached in previous findings that the handwriting impairments in individuals with ADHD are characterized by fast and more efficient movements but with poorer quality and legibility of handwriting (Adi-Japha et al., 2007; Racine, Majnemer, Shevell, & Snider, 2008; Rosenblum, Epsztein, & Josman, 2008). One hypothesis regarding handwriting patterns of individuals with ADHD was that they tend to exhibit more hyperkinetic and efficient movements during handwriting (Langmaid, Papadopoulos, Johnson, Phillips, & Rinehart, 2014), which may contribute to faster but inaccurate writing.

Handwriting is composed of various graphic patterns, and only a few of them could be stored, combined, and frequently instantiated to become a “preferred” pattern (Kostrubiec, Danna, & Zanone, 2013). Such production of preferred patterns is often characterized by researchers of higher accuracy and handwriting stability (Sallagoïty, Athènes, Zanone, & Albaret, 2004). Traditionally, training on handwriting skills focused on cognitive abilities such as memory and attention; students were asked to repeatedly copy words in order to develop handwriting proficiency (Hoy, Egan, & Feder, 2011). However, handwriting is a complex mental and visual perceptual–motor processing (Re & Cornoldi, 2015). It requires not only advanced cognitive skills, but the proficiency in various sensorimotor domains is also of significant importance in achieving stable and fluent handwriting patterns. In fact, sensorimotor performance components including fine motor skills (Langmaid et al., 2014), visual perceptual skills (Amundson, 2001), visual motor integration (Shen, Lee, & Chen, 2012), and oculomotor control (Hurst, 2013) are widely investigated to understand students' handwriting. These sensorimotor functions are synchronized and integrated at various levels to produce words and substantially affect students' handwriting performance (Tse, Thanapalan, & Chan, 2014). Hence, one should not jump to conclusion and fully attribute attentional deficit within individuals with ADHD to poor performance in handwriting without evaluating the influence from sensorimotor performance components. In addition, we believe that the association between sensorimotor performance and handwriting skills, if any, would be important for clinicians to provide targeted intervention and treatment to these individuals.

Research in Chinese handwriting performance of adolescents with ADHD or ADHD-LD is relatively scarce in the literature. Although handwriting in alphabetic languages relies heavily on the concept of phoneme and the association between letters (i.e., graphemes) and phonemes, handwriting in Chinese, on the contrary, is governed by syntactic and orthographic rules, which no longer works with phonemes but with syllables or other sublexical units (Georgiou, Parrila, & Papadopoulos, 2008). In view of this classification, alphabetic language and Chinese, an orthographic language, are two entirely different language systems in terms of their natures, logics, and hence acquisition mechanisms (Wang, Perfetti, & Liu, 2005). Any attempt to generalize the results from alphabetic languages to Chinese, or other orthographic languages, could lead to a risk of flawed conclusion. Therefore, looking at the difference between Chinese handwriting patterns and that of other languages among individuals with ADHD would be meaningful, in the sense that we can investigate how the difference in the nature of the two languages might affect individuals' handwriting performance.

As research in the handwriting performance of individuals with comorbid ADHD-LD is limited as well, it would be worthy to investigate the problem, because the comorbidity of ADHD and LD is considered to be high as mentioned, and its influence on students' handwriting can play a crucial role in academic performance. Therefore, the objectives of this study were to (a) compare the Chinese and English handwriting performance among ADHD and comorbid ADHD-LD adolescents with reference to typically developing adolescents, (b) whether and, if any, how ADHD and LD affect the association between the sensorimotor performance components and handwriting performance in adolescents, and (c) investigate the use of handwriting assessment to screen ADHD and comorbid ADHD-LD individuals from the population.

2 | METHOD

2.1 | Study design and participants

Participants with ADHD and ADHD-LD and typically developing controls were recruited by responding to invitation letters sent to schools in Hong Kong. Some participants were recruited directly from support groups for parents of children with ADHD and clinicians' referrals. All participants with ADHD had been previously diagnosed with ADHD combined type. Diagnosis of ADHD was made by psychiatrists based on International Classification of Diseases, Tenth Revision (World Health Organization, 1992). Diagnosis of LD was made by educational psychologists or clinical psychologists based on *Diagnostic and Statistical Manual of Mental Disorders*, 4th Edition, Text Revision (American Psychiatric Association, 2000), and a locally relevant test (Ho, Chan, Tsang, & Lee, 2000).

In this study, adolescents who were (a) between 12 and 18 years of age, (b) Cantonese speaking, and (c) able to write Traditional Chinese and English were included. Adolescents who had (a) intelligence quotient < 80, (b) any physical disability affecting the upper limb, and (c) other comorbid neurodevelopmental disorders (such as autism spectrum disorder, Asperger's disorder, and cerebral palsy) were excluded. Five adolescents diagnosed with ADHD comorbid with autism spectrum disorder were excluded from the study. Thirty-two participants (mean age = 14.47, SD = 1.52, 88% male) diagnosed with ADHD were recruited. Twelve participants (mean age = 15.33, SD = 2.02, 83% male) diagnosed with comorbid ADHD-LD were recruited. Thirty-two and 24 age-matched, gender-matched, and handedness-matched typically developing adolescents were recruited to serve as the controls for the ADHD and ADHD-LD groups, respectively.

All parents and adolescents were informed about the voluntary basis of participation and gave written informed consent. All ADHD and ADHD-LD participants were assessed after their usual medication with methylphenidate. None of the participants received any remuneration for participating. The study was approved by the Human Subjects Ethics Subcommittee of The Hong Kong Polytechnic University.

2.2 | Measures

The Computerized Handwriting Speed Test System, Version 2 (CHSTS-2), is used to measure handwriting process and readability. All handwriting tasks were performed on A4-sized paper affixed to the surface of a Wacom Intous Pro L tablet using a wireless electronic pen (Li-Tsang et al., 2013). The handwriting assessment consists of Chinese and English handwriting tasks. In Chinese handwriting task, participants were asked to copy 130 traditional Chinese words from a notebook screen to the affixed A4-sized grid paper. In English handwriting task, participants were asked to copy 120 English words from a notebook screen to the affixed A4-sized lined papers. Participants were asked to write as legibly and quickly as possible in the two tasks. Using the CHSTS-2 system, the on-paper time (or ground time) and on-air time (or air time) were recorded to the nearest 0.01 s. The pen pressure and handwriting trajectory were also recorded. CHSTS-2 would provide information on the ground time, air time, handwriting speed (characters per minute), standard deviation of writing time per character, pen pressure (Newton), and standard deviation of pressure. Accuracy of handwriting products was analyzed by Microsoft Windows XP Tablet PC Edition 2005 Recognizer Pack (Microsoft Corporation, 2005), and the result was readability (number of correct words/number of recognized word by the system).

The *Beery-Buktenica Developmental Test of Visual-Motor Integration*, 6th Edition (VMI), is used to assess coordination of visual perceptual and motor abilities in individuals aged 2–18 years (Beery, Buktenica, & Beery, 2010). The VMI consists of 30 geometric forms that are progressively more complex to assess visual motor skills by examining the participant's drawings that attempt to replicate the geometric stimulus. The score is the number of correctly copied forms based on the standard rating criteria. The score ranges from 0 to 30. A higher score indicates greater function in visual motor integration. The test has high split-half reliability (r = .74), test–retest reliability (r = .62–.84; Ryckman & Rentfrow, 1971), and interrater reliability (κ = 0.94–0.98; Bo et al., 2014). In this study, the test also had high split-half reliability (r = .72).

The *Motor-Free Visual Perception Test*, 3rd Edition (MVPT), is used to assess non-visual motor–perceptual skills (Colarusso & Hammill, 2003). The MVPT requires no motor involvement to measure six different visual–perceptual skills, namely, spatial relationships, visual discrimination, figure-ground, visual closure, visual memory, and form constancy. The test consists of totally 65 items, but participants who are over 10 years of age only need to answer Items 14–65. Each item is presented in a multiple choice format and scored as 0 (*wrong answer*) or 1 (*right answer*). The score ranges from 0 to 65. A higher score indicates greater function in visual perception. The test has high internal consistency (α = 0.89; Colarusso & Hammill, 2003). In this study, the test also had high internal consistency (α = 0.79).

The *Bruininks-Oseretsky Test of Motor Proficiency*, 2nd Edition, is used to assess proficiency in four motor area composites (Bruininks & Bruininks, 2005). Two composites—fine manual control (FMC) and manual coordination—were assessed in the study. Fine manual control is divided into fine motor precision (seven items, score range = 0–41) and fine motor integration (eight items, score range = 0–40) subtests that measure the motor skills involving control and coordination of the distal musculature of the hands and fingers. Manual coordination is classified into manual dexterity (MD; five items, score range = 0–45 points) and upper-limb coordination (seven items, score range = 0–39 points) subtests that evaluate motor skills involving control and coordination of the arms and hands, especially for object manipulation. A higher score indicates better motor skills. The tests have high internal consistency (α = 0.78–0.97), test–retest reliability (r = .52–.95), and interrater reliability (κ = 0.92; Bruininks & Bruininks, 2005). In this study, the tests also had high internal consistency (α = 0.73–0.81).

The Developmental Eye Movement (DEM) test is used as a clinical visual–verbal oculomotor and automaticity assessment tool (Richman, 2015). The test consists of two subtests with each containing two vertical lines of 20 digits (totally 80 digits) and a subtest with 80 unevenly spaced digits in 16 horizontal rows. Participants were asked to read aloud the numbers as accurately and rapidly as possible while the times taken for the vertical and horizontal subtests were recorded to the nearest 0.01 s. The times were adjusted for the number of omission and addition errors made. The outcomes from the DEM test were vertical time, horizontal time, and ratio (horizontal time/vertical time). Higher vertical time indicates poor automaticity of number naming. Higher horizontal time indicates poor automaticity of number naming and oculomotor control. A DEM score was the absolute value of ratio of horizontal time and vertical time minus one. Higher score indicates higher degree of oculomotor dysfunction.

2.3 | Statistical analysis

Internal consistency of the measurement items was examined by split-half reliability and Cronbach's α. The split-half method divides a measurement into even and odd items, and the scores are correlated using Pearson's correlation and adjusted using the Spearman–Brown prophecy formula. A Cronbach's α coefficient (>0.7) means items have a high contribution to the measurement (Churchill, 1979).

Descriptive statistics for continuous variables were illustrated by means and standard deviations, whereas categorical variables were shown by numbers and percentages. Fisher's exact test and the Mann–Whitney–Wilcoxon test were used to compare the categorical and continuous variables, respectively, between ADHD, ADHD-LD, and controls. Moderator analysis was then conducted to determine whether the associations between sensorimotor performance and handwriting are different for ADHD, ADHD-LD, and controls. The presence of ADHD and ADHD-LD served as the dichotomous moderators in the analyses. Simple linear regression was used that handwriting performance was the dependent variable (DV), sensorimotor performance was the independent variable (IV), and interaction term between sensorimotor performance and the presence of ADHD and ADHD-LD was added. The coefficients and 95% confidence intervals of the significant interactions were presented. For a significant interaction, simple linear regression was used to examine the association between handwriting (as DV) and sensorimotor performance (as IV) in ADHD, ADHD-LD, and controls, separately. The coefficient and 95% confidence interval were also presented. Adjusted R^2 was presented to show the proportion of the variation in DV explained by IV in linear regression model.

Random Forest, an ensemble learning-based classification and regression technique (Liaw & Wiener, 2002), was employed to build algorithms for automatically classifying whether a student had ADHD or ADHD-LD. Sensorimotor performance and handwriting variables were included as the predictors for the classifications. The classifications also requested the outcome variable to be binary. All the classification results were generated with leave-one-out cross-validation, which was found to be able to provide an almost unbiased estimator of the generalization properties of statistical models. Receiver operating characteristic curve analysis was operated for analyzing and comparing the accuracy of the classifications. The primary outcomes of the study were the area under the receiver operating characteristic curves (AUC) and its 95% confidence interval, sensitivities, specificities, positive predictive values (PPVs), and negative predictive values (NPVs) of the classifiers. For each classification, sensitivity, specificity, PPV, and NPV at the optimal cutoff were reported. All statistical computations were performed by using statistical software R (R for Windows, V.3.4.3).

3 | RESULTS

3.1 | Characteristics of ADHD and ADHD-LD participants

Both the ADHD and ADHD-LD groups consisted of over 80% of male. There were no significant differences between the ADHD and ADHD-LD groups in terms of age (p = .1343) and gender (p = .6577). There was only one left-handed in the ADHD group, and all the others were right-handed.

Because the number of words in Chinese and English handwriting tasks was different, it is noted that the writing times should not be compared directly. In general, the participants had slower writing speed (p = .0247), lower variations in writing speed (p = .0021), higher

TABLE 1 Comparison of handwriting and sensorimotor performance of the ADHD group, ADHD-LD group, and controls

	Control (n = 32)	ADHD (n = 32)	p	Control (n = 24)	ADHD-LD (n = 12)	p
Chinese handwriting						
Ground time	142.23 (31.73)	144.91 (23.62)	.4192	135.20 (26.42)	150.59 (44.45)	.4303
Air time	230.82 (87.26)	223.55 (67.88)	.8781	206.70 (67.24)	300.86 (124.43)	.0359*
Speed	22.04 (4.85)	22.22 (4.63)	>.9999	24.13 (5.40)	19.49 (5.98)	.0304*
SD of writing time per character	3.78 (5.24)	4.74 (5.45)	.4282	2.79 (2.71)	7.63 (9.43)	.0245*
Pressure	0.53 (0.41)	0.70 (0.38)	.0123*	0.47 (0.27)	0.54 (0.18)	.1109
SD of pressure	0.29 (0.20)	0.48 (0.28)	.0023**	0.27 (0.19)	0.36 (0.13)	.0536
Readability	90.69 (9.65)	85.74 (12.22)	.0256*	83.58 (23.00)	87.42 (8.48)	.3921
English handwriting						
Ground time	185.18 (58.23)	187.12 (52.73)	.7743	173.55 (63.15)	179.58 (37.68)	.4706
Air time	193.80 (72.69)	189.45 (73.24)	.7642	164.91 (55.93)	277.24 (158.52)	.0136*
Speed	20.13 (4.58)	20.08 (4.79)	.7238	22.68 (5.18)	17.54 (5.18)	.0093**
SD of writing time per character	1.78 (0.69)	1.70 (0.49)	.8985	1.48 (0.58)	2.13 (0.90)	.0084**
Pressure	0.69 (0.54)	0.87 (0.47)	.0393*	0.51 (0.30)	0.67 (0.27)	.0698
SD of pressure	0.35 (0.23)	0.57 (0.32)	.0032**	0.28 (0.20)	0.44 (0.27)	.0625
Readability	96.30 (5.06)	94.27 (6.76)	.0296*	96.68 (3.46)	93.90 (5.68)	.1036
Sensorimotor performance						
VMI	26.69 (3.12)	27.50 (1.99)	.4673	26.70 (3.05)	26.92 (1.73)	.8287
MVPT	53.45 (6.36)	54.68 (4.30)	.7205	53.26 (6.19)	54.67 (4.98)	.6690
BOT	100.88 (19.27)	103.82 (25.69)	.6565	101.26 (14.28)	93.25 (22.99)	.2911
FMP	39.53 (1.67)	40.21 (2.20)	.1499	40.32 (0.95)	39.83 (1.64)	.4784
FMI	38.25 (2.81)	38.11 (2.22)	.5746	38.32 (1.38)	38.33 (2.67)	.5612
MD	34.41 (4.15)	36.00 (3.33)	.1827	35.74 (3.57)	35.08 (4.58)	.3269
ULC	35.09 (4.28)	35.79 (2.30)	.9401	36.32 (2.26)	35.83 (2.44)	.5783
DEM						
Vertical	0.10 (0.10)	0.15 (0.23)	.5278	0.12 (0.08)	0.14 (0.12)	.9845
Horizontal	28.39 (5.97)	28.54 (6.68)	.8254	26.95 (5.25)	30.74 (7.59)	.1443
Score	30.34 (7.56)	31.15 (7.22)	.5478	28.60 (6.10)	33.65 (8.94)	.1062

Note. VMI = *Beery-Buktenica Developmental Test of Visual-Motor Integration*; MVPT = *Motor-Free Visual Perception Test*; BOT = *Bruininks-Oseretsky Test of Motor Proficiency*; FMI = fine motor integration; MD = fine motor integration; ULC = fine motor integration; DEM = Developmental Eye Movement; SD = standard deviation; ADHD = attention deficit hyperactivity disorder; LD = learning difficulties.

*p < .05.

**p < .01.

pen pressure (p = .0251) and pen pressure variation (p < .0001), and better readability (p < .0001) in English handwriting compared with Chinese handwriting.

The handwriting and sensorimotor performance of the ADHD group, ADHD-LD group, and controls are shown in Table 1. Participants with ADHD had higher pen pressure, larger pen pressure variations, and lower readability than their matched controls in both Chinese and English handwriting. Participants with ADHD-LD had longer air time (around 100 s more), slower writing speed, and larger variations in writing speed than their matched controls in both Chinese and English handwriting. ADHD-LD shared a common characteristic with participants with ADHD of having less handwriting stability with larger variations in either writing speed or pen pressure. There was no significant difference in terms of sensorimotor performance between the ADHD group, ADHD-LD group, and controls.

3.2 | Moderating effect of ADHD on sensorimotor performance and handwriting

Table 2 shows how the associations between sensorimotor performance and handwriting were moderated by ADHD. There were four significant moderating effects of ADHD in Chinese handwriting and two significant moderating effects of ADHD in English handwriting. In Chinese handwriting, for every 1-point increase in VMI, air time reduced by 13.43 s, and writing speed increased by 0.69 character per minute, respectively, in typically developing participants, however, these associations became nonsignificant in participants with ADHD. On the other hand, for every 1-point increase in fine motor precision and VMI, pen pressure and readability increased by 0.07 N and 3.23%, respectively, in AHDH participants, but these associations were not significant in their matched controls. The adjusted R^2 of the four significant associations was ranged from .1364 to .2284, which means that about 13–22% of the variance of the handwriting performance could be explained by the sensorimotor performance alone. In English handwriting, for every 1-point increase in fine motor integration and MVPT, ground time reduced by 7.98 s and pen pressure increased by 0.04 N, respectively, whereas these associations were not significant in their matched controls. The adjusted R^2 of the two significant associations was ranged from .1107 to .1227, which means that about 12% of the variance of the handwriting performance could be explained by the sensorimotor performance alone.

Table 3 shows how the associations between sensorimotor performance and handwriting were moderated by ADHD-LD. There were four significant moderating effects of ADHD-LD in Chinese handwriting and one significant moderating effect of ADHD-LD in English handwriting. In Chinese handwriting, for every 1-point increase in upper-limb coordination, air time and variation in writing speed reduced by 14.25 and 0.68 s per character, respectively, in typically developing participants, but these associations became nonsignificant in participants with ADHD-LD. On the other hand, for every 1-point increase in VMI and MD, variation in writing speed increased by 3.41 and 1.44 s per character, respectively, in participants with ADHD-LD, whereas these associations were not significant in their matched controls. The adjusted R^2 of the four significant associations was ranged from .1843 to .4344, which means that about 18–43% of the variance of the handwriting performance could be explained by the sensorimotor performance alone. In English handwriting, for every 1-point increase in MD, readability reduced by 0.89%; however, this association was not significant in their matched controls. The adjusted R^2 was .4619, which means that about 46% of the variance of readability could be explained by MD alone.

3.3 | Prediction of ADHD based on sensorimotor performance and handwriting

Table 4 demonstrates the AUCs, sensitivities, specificities, PPVs, and NPVs of the classifiers for identifying participants with ADHD or ADHD-LD from their typically developing counterparts. Only Chinese handwriting was found to be significant predictor for the classifications.

TABLE 2 The significant moderating effect of ADHD on the associations between sensorimotor performance and handwriting

	Moderating effect			ADHD (n = 32)			Control (n = 32)		
	β [95% CI]	p	Adj. R^2	β [95% CI]	p	Adj. R^2	β [95% CI]	p	Adj. R^2
Chinese handwriting									
DV: Air time IV: VMI	22.32* [5.45, 39.20]	.0104	.1228	8.89 [−5.26, 23.05]	.2077	.0242	−13.43** [−22.59, −4.26]	.0055	.2041
DV: Speed IV: VMI	−1.15* [−2.20, −0.10]	.0328	.0740	−0.46 [−1.44, 0.52]	.3475	.0031	0.69* [0.17, 1.21]	.0107	.1712
DV: Pressure IV: FMP	0.12* [0.01, 0.22]	.0329	.0938	0.07* [0.01, 0.13]	.0301	.1364	−0.05 [−0.13, 0.04]	.3104	.0021
DV: Readability IV: VMI	3.20** [0.84, 5.55]	.0087	.1712	3.23** [1.01, 5.44]	.0059	.2284	0.03 [−1.13, 1.18]	.9601	.0332
English handwriting									
DV: Ground time IV: FMI	−12.00* [−23.24, −0.75]	.0369	.0264	−7.98* [−15.84, −0.12]	.0467	.1107	4.01 [−3.58, 11.61]	.2890	.0053
DV: Pressure IV: MVPT	0.06* [0.00, 0.11]	.0408	.0642	0.04* [0.00, 0.08]	.0380	.1227	−0.01 [−0.04, 0.02]	.4350	.0126

Note. ADHD = attention deficit hyperactivity disorder; DV = dependent variable; IV = independent variable; VMI = *Beery-Buktenica Developmental Test of Visual-Motor Integration*; FMP = fine motor precision; MVPT = *Motor-Free Visual Perception Test*.

*p < .05.

**p < .01.

TABLE 3 The significant moderating effect of ADHD-LD on the associations between sensorimotor performance and handwriting

	Moderating effect			ADHD-LD (*n* = 12)			Control (*n* = 24)		
	β [95% CI]	*p*	Adj. R^2	β [95% CI]	*p*	Adj. R^2	β [95% CI]	*p*	Adj. R^2
Chinese handwriting									
DV: Air time IV: ULC	36.57* [8.03, 65.12]	.0140	.2654	22.32 [−9.93, 54.57]	.1540	.1114	−14.25* [−27.60, −0.90]	.0379	.1843
DV: SD of writing time per character IV: VMI	3.49** [1.50, 5.48]	.0013	.3768	3.41* [0.41, 6.41]	.0298	.3296	−0.08 [−0.52, 0.36]	.6965	.0464
DV: SD of writing time per character IV: MD	1.62** [0.69, 2.54]	.0013	.4564	1.44* [0.39, 2.48]	.0118	.4344	−0.18 [−0.56, 0.20]	.3338	.0004
DV: SD of writing time per character IV: ULC	2.64** [0.81, 4.47]	.0062	.2952	1.96 [−0.38, 4.31]	.0912	.1846	−0.68* [−1.19, −0.16]	.0135	.2684
English handwriting									
DV: Readability IV: MD	−0.87* [−1.64, −0.10]	.0281	.2760	−0.89** [−1.50, −0.28]	.0090	.4619	−0.01 [−0.56, 0.54]	.9580	.0586

Note. DV = dependent variable; IV = independent variable; ADHD = attention deficit hyperactivity disorder; LD = learning difficulties; ULC = upper-limb coordination; VMI = *Beery-Buktenica Developmental Test of Visual-Motor Integration*; MD = manual dexterity; SD = standard deviation.

**p* < .05.

***p* < .01.

TABLE 4 Receiver operating characteristic (ROC) curve analysis on random forest classifiers of the ADHD, ADHD-LD, and controls

Predictors	AUC [95% CI]	*p*	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)
ADHD (*n* = 32) from their control (*n* = 32)						
Chinese handwriting	0.65 [0.51, 0.78]*	.0385	62.50	62.50	62.50	62.50
English handwriting	0.53 [0.38, 0.68]	.7149	56.25	53.12	54.55	54.84
Sensorimotor performance	0.57 [0.42, 0.71]	.3561	46.88	46.88	46.88	46.88
ADHD-LD (*n* = 12) from their control (*n* = 24)						
Chinese handwriting	0.69 [0.51, 0.88]*	.0421	66.67	62.50	47.06	78.95
English handwriting	0.63 [0.43, 0.83]	.2163	66.67	66.67	50.00	80.00
Sensorimotor performance	0.49 [0.29, 0.70]	>.9999	50.00	50.00	33.33	66.67
ADHD (*n* = 32) from ADHD-LD and their controls (*n* = 68)						
Chinese handwriting	0.67 [0.56, 0.79]**	.0037	62.50	61.76	43.48	77.78
English handwriting	0.61 [0.49, 0.74]	.0782	56.25	57.35	38.30	73.58
Sensorimotor performance	0.55 [0.43, 0.68]	.3762	43.75	42.65	26.42	61.70
ADHD-LD (*n* = 12) from ADHD and their controls (*n* = 88)						
Chinese handwriting	0.79 [0.63, 0.94]***	.0003	75.00	75.00	29.03	95.65
English handwriting	0.53 [0.28, 0.77]	.8394	41.67	42.05	8.93	84.09
Sensorimotor performance	0.61 [0.45, 0.76]	.1833	33.33	37.50	6.78	80.49

Note. ADHD = attention deficit hyperactivity disorder; LD = learning difficulties; AUC = area under the ROC curve; PPV = positive predictive value; NPV = negative predictive value.

**p* < .05.

***p* < .01.

****p* < .001.

For identifying participants with ADHD from their matched controls, the classifier using Chinese handwriting variables yielded the best sensitivity, specificity, PPV, and NPV of 62.50% at the optimal cutoff point. There were no other significant predictors.

For identifying participants with ADHD-LD from their matched controls, the classifier using Chinese handwriting variables yielded the sensitivity, specificity, and NPV of over 60% at the optimal cutoff point. However, the PPV was lower to be about 40%. There were no other significant predictors. Although the classifier using English handwriting variables was not robust enough with a nonsignificant AUC, the classifier yielded the best sensitivity, specificity, and NPV of over 65% and even the PPV reached 50% at the optimal cutoff point.

For identifying participants with ADHD from participants with ADHD-LD and their matched controls, the classifier using Chinese handwriting variables yielded the best sensitivity, specificity, and NPV of over 60% at the optimal cutoff point. However, the PPV was lower to be about 40%. There were no other significant predictors.

For identifying participants with ADHD-LD from participants with ADHD and their matched controls, the classifier using Chinese handwriting variables yielded the best sensitivity, specificity, and NPV of over 75% at the optimal cutoff point. However, the PPV was lower to be about 30%. There were no other significant predictors.

4 | DISCUSSION

This study compared the Chinese and English handwriting among ADHD and comorbid ADHD-LD adolescents. It is believed that the influence from ADHD and LD in terms of handwriting performance is not temporary in childhood but persistent to adolescence and even to adulthood. The current study supports previous findings that participants with ADHD showed a comparable performance with typically developing participants in terms of writing time and speed, but the readability was found to be lower than their matched controls. They tended to make more errors while spelling long words in English copying task, which was consistent with previous literatures, revealing that individuals with ADHD were more likely to make spelling mistakes such as inserting superfluous letters and omitting, substituting, or transposing letters (Adi-Japha et al., 2007). An explanation to this phenomenon is that individuals with ADHD have more hyperkinetic and efficient movements than typically developing participants due to their hyperactivity features and the lack of response inhibition (Langmaid et al., 2014). They intended to complete the task as fast as possible without considering the preciseness of the written words as well as the appropriateness of applied pen pressure. The disadvantage in readability of individuals with ADHD was observed in both Chinese and English handwriting. However, improved visual motor integration in adolescents with ADHD would only increase readability of Chinese handwriting. This suggests that Chinese and English are two fundamentally different languages such that the former heavily relies on orthographic and logographic structures (Wang & Geva, 2003) whereas the latter is highly related to sound–letter correspondences (Molitor, Langberg, & Evans, 2016). Such discrepancy may contribute to the difference in the influence from sensorimotor performance to English and Chinese handwriting.

Participants with comorbid ADHD-LD seemed to have more impairment in handwriting such as having increased air time, lower writing speed, and higher writing speed variation, comparing with their matched controls in both Chinese and English handwriting. This is consistent with previous findings that high incidence of writing problem was found in children with ADHD-LD (Mayes et al., 2000). The current study shows that the participants with comorbid ADHD-LD had lower writing speeds in both Chinese and English handwriting comparing with their matched controls. This result implies that although ADHD is affecting individual's handwriting readability, LD, on the other hand, is more responsible for the decrease in speed in handwriting assessment. Such deficit was not found in the ADHD-only group, which seems to rule out the possibility that LD is merely a manifestation of ADHD rather than a single and separate disorder (DuPaul et al., 2013). The two disorders are actually fundamentally distinguishable, even though they have been considered as "overlapping spectrum disorders" (Mayes et al., 2000) in the field, due to their high comorbidity, shared etiologies, and deficits. Our study provides a clearer picture to see handwriting problems within the ADHD and ADHD-LD groups such that ADHD and LD are affecting different aspects of handwriting. In view of this difference in manifestation, therapists or educators may need to consider different measures to improve handwriting skills and avoid treating the comorbid ADHD-LD group in the same way as treating the ADHD group.

The ADHD and ADHD-LD groups showed larger variations in pen pressure and speed then their controls, respectively. In other words, both groups exhibited weaker stability in handwriting. Handwriting is composed of various graphic patterns, and handwriting stability is achieved by developing a number of preferred graphic patterns (Kostrubiec et al., 2013). Among all possible graphic patterns, however, only a few of them could be stored, combined, and frequently instantiated to become a "preferred" pattern (Kostrubiec et al., 2013). Such production of preferred patterns is often characterized by researchers of higher accuracy and lower variability (i.e., higher stability) in speed and pressure (Sallagoïty et al., 2004). The low handwriting stability in both the ADHD and ADHD-LD groups revealed that comparing with their matched controls, ADHD and ADHD-LD participants developed less-preferred patterns in handwriting. This disadvantage may not be fully attributed to the motor problems or visual motor skill deficits among both groups, as results suggested even individuals with better performance in MD as well as visual motor integration showed larger variation in writing speed, respectively, hence weaker handwriting stability. This provides evidence that improving visual motor skills may not help students to develop handwriting stability directly. Therefore, a more in-depth word-level analysis is suggested in future to investigate the difference in the cognitive familiarity towards different words and patterns between these groups.

The current study demonstrates that handwriting assessment served as an effective predictor for ADHD and ADHD-LD diagnoses. The results show that the prediction rates of ADHD and ADHD-LD from handwriting assessment were high with good sensitivities, specificities, PPVs, and NPVs. This provides support to the idea that handwriting assessment could be a reliable reference for therapists and professionals to differentiate and predict ADHD and ADHD-LD from the population before making any thorough and actual diagnosis. In addition, the performance of Chinese handwriting assessment was even better than English handwriting assessment in screening ADHD and ADHD-LD from their typically developing counterparts. This consolidates the linguistic difference of Chinese and English in nature. Another concern of this difference would be language acquisition. As all of the subjects recruited were Hong Kong Chinese, given that Chinese was their first language (L1) and English was the second language (L2), the results from Chinese handwriting assessment would be more reliable. Because L2 acquisition may involve other learning mechanisms such as cross-language transfer (Pasquarella, Chen, Gottardo, & Geva, 2015), whether ADHD or LDs pose influence on such mechanisms remains unclear and requires further study.

There are several limitations in this study. First, the sample size of the ADHD-LD group was relatively small. This may be due to the limited prevalence rate (30.6%) of comorbid diagnosis in Hong Kong (Lau, Liu, & Lee, 2012). Based on the current sample, 12 out of 44 (27.3%) ADHD students were having comorbid LD diagnosis so the proportion follows the trend in Hong Kong. Future study could increase the sample size of both the ADHD and ADHD-LD groups to improve statistical power in testing the hypotheses. Second, an LD-only group should be recruited to provide a more complete comparison in terms of handwriting performance. Third, the diagnoses of ADHD and LD were made by professionals from different disciplines. It should be noticed that the difference in the clinical judgments as well as classification systems may result in potential bias, thus affecting the interpretation of the results. Finally, the comparison between Chinese and English handwriting only among Hong Kong population may not be fair enough. Despite the fact that Hong Kong is a Chinese–English bilingual city, English is the second language for most of the local students. As mentioned, the L2 acquisition mechanism is different from and dependent on L1, and the difference between L1 and L2 performance moderated by the existence of ADHD and LD may not be fully attributed to the difference in nature between the two languages. Therefore, it is suggested that adolescents whose first language is English could be recruited to eliminate the interaction between L1/L2 abilities and ADHD/LD manifestation.

Handwriting difficulties are found to be very common among individuals with ADHD. The current study has demonstrated a more concrete handwriting profile of ADHD population and found that ADHD and LD, indeed, are fundamentally different in terms of their influences on handwriting performance. ADHD affects the readability of handwriting products, whereas LD, in general, lowers the speed of handwriting process. Nonetheless, both disorders were found to have adverse impact on individuals' handwriting stability. The analysis of moderating effect from ADHD on the association between sensorimotor skills and handwriting performance exhibited the difference between Chinese and English. This finding may need further investigations from the linguistic perspective about the issue of the orthographic nature and L1/L2 acquisition. Additionally, handwriting assessment was found to be an effective screening tool for ADHD. A good successful rate could be achieved in predicting ADHD diagnosis based on individuals' handwriting patterns. In short, although ADHD and LD have been considered as two overlapping disorders and they do share a lot of commonalities, therapists and professionals should be aware of the fundamental difference between two disorders and make good use of handwriting assessment as a reference so as to deliver effective therapies and trainings to ADHD individuals with and without LD.

DECLARATION OF INTEREST STATEMENT

The authors declare no conflict of interest.

ACKNOWLEDGEMENT

This study was funded partly by The Hong Kong Examinations and Assessment Authority, Hong Kong (grant number: (13) in T72).

ORCID

Cecilia W.P. Li-Tsang http://orcid.org/0000-0002-2141-9287

REFERENCES

Adi-Japha, E., Landau, Y. E., Frenkel, L., Teicher, M., Gross-Tsur, V., & Shalev, R. S. (2007). ADHD and dysgraphia: Underlying mechanisms. *Cortex*, *43*(6), 700–709.

Adler, L. A., Faraone, S. V., Spencer, T. J., Berglund, P., Alperin, S., & Kessler, R. C. (2017). The structure of adult ADHD. *International Journal of Methods in Psychiatric Research*, *26*(1), e1555.

American Psychiatric Association (Ed.) (2000). *Diagnostic and statistical manual of mental disorders—Text revision* (Fourth ed.). Washington: DC: American Psychiatric Association.

Amundson, S. J. (2001). Prewriting and handwriting. In J. CaseSmith (Ed.), *Occupational therapy for children* (4th ed., pp. 545–570). St. Louis, MO: Mosby.

Beery, K. E., Buktenica, N. A., & Beery, N. A. (2010). *Beery-Buktenica developmental test of visual-motor integration* (6th ed.). MN: Pearson Assessment.

Bo, J., Colbert, A., Lee, C. M., Schaffert, J., Oswald, K., & Neill, R. (2014). Examining the relationship between motor assessments and handwriting consistency in children with and without probable developmental coordination disorder. *Research in Developmental Disabilities*, *35*(9), 2035–2043.

Borella, E., Chicherio, C., Re, A. M., Sensini, V., & Cornoldi, C. (2011). Increased intraindividual variability is a marker of ADHD but also of dyslexia: A study on handwriting. *Brain and Cognition*, *77*(1), 33–39.

Brossard-Racine, M., Shevell, M., Snider, L., Bélanger, S. A., Julien, M., & Majnemer, A. (2015). Persistent handwriting difficulties in children with ADHD after treatment with stimulant medication. *Journal of Attention Disorders*, *19*(7), 620–629.

Bruininks, R. H., & Bruininks, B. D. (2005). *Bruininks-Oseretsky test of motor proficiency* (2nd ed.). Minneapolis, MN: Pearson Assessment.

Churchill, G. A. (1979). A paradigm for developing better measures of marketing constructs. *Journal of Marketing Research*, *16*(1), 64–71.

Colarusso, R. P., & Hammill, D. D. (2003). *Motor-free visual perception test—Third edition*. Novato, CA: Academic Therapy Publications.

DuPaul, G. J., Gormley, M. J., & Laracy, S. D. (2013). Comorbidity of LD and ADHD: Implications of DSM-5 for assessment and treatment. *Journal of Learning Disabilities*, *46*, 43–51.

Georgiou, G. K., Parrila, R., & Papadopoulos, T. C. (2008). Predictors of word decoding and reading fluency across languages varying in orthographic consistency. *Journal of Educational Psychology*, *100*(3), 566–580.

Ho, C. S. H., Chan, D. W. O., Tsang, S. M., & Lee, L. H. (2000). *The Hong Kong test of specific learning disabilities in reading and writing (HKT-SpLD)*. Hong Kong, China: Chinese University of Hong Kong and Education Department, HKSAR Government.

Hoy, M. M., Egan, M. Y., & Feder, K. P. (2011). A systematic review of interventions to improve handwriting. *Canadian Journal of Occupational Therapy*, *78*(1), 13–25.

Hurst, C. M. (2013). Behavioural optometry: Learning difficulties and the visual process. *International Journal of Ophthalmic Practice*, *4*(3), 127–135.

Kostrubiec, V., Danna, J., & Zanone, P. G. (2013). Co-variation between graphic pattern stability and attentional cost: A clue for the difficulty to produce handwritten traces. *Human Movement Science*, *32*(5), 1010–1025.

Langmaid, R. A., Papadopoulos, N., Johnson, B. P., Phillips, J. G., & Rinehart, N. J. (2014). Handwriting in children with ADHD. *Journal of Attention Disorders*, *18*(6), 504–510.

Lau, V., Liu, S., & Lee, F. (2012). Attention deficit/hyperactivity disorder—An epidemiological study in Hong Kong from 2003 to 2009. Brainchild (Official Publication of HKCNDP). 13, 5–11.

Liaw, A., & Wiener, M. (2002). Classification and regression by randomForest. *R News*, *2*(3), 18–22.

Li-Tsang, C. W., Wong, A. S., Leung, H. W., Cheng, J. S., Chiu, B. H., Linda, F. L., & Chung, R. C. (2013). Validation of the Chinese Handwriting Analysis System (CHAS) for primary school students in Hong Kong. *Research in Developmental Disabilities*, *34*(9), 2872–2883.

Mayes, S. D., Calhoun, S. L., & Crowell, E. W. (2000). Learning disabilities and ADHD overlapping spectrum disorders. *Journal of Learning Disabilities*, *33*(5), 417–424.

Microsoft Corporation. (2005). Microsoft Windows XP Tablet PC Edition 2005 Recognizer Pack. https://msdn.microsoft.com/en-us/library/aa813362.aspx.

Molitor, S. J., Langberg, J. M., Bourchtein, E., Eddy, L. D., Dvorsky, M. R., & Evans, S. W. (2016). Writing abilities longitudinally predict academic outcomes of adolescents with ADHD. *School Psychology Quarterly*, *31*(3), 393–404.

Molitor, S. J., Langberg, J. M., & Evans, S. W. (2016). The written expression abilities of adolescents with attention-deficit/hyperactivity disorder. *Research in Developmental Disabilities*, *51*, 49–59.

Pasquarella, A., Chen, X., Gottardo, A., & Geva, E. (2015). Cross-language transfer of word reading accuracy and word reading fluency in Spanish-English and Chinese-English bilinguals: Script-universal and script-specific processes. *Journal of Educational Psychology*, *107*(1), 96–110.

Racine, M. B., Majnemer, A., Shevell, M., & Snider, L. (2008). Handwriting performance in children with attention deficit hyperactivity disorder (ADHD). *Journal of Child Neurology*, *23*(4), 399–406.

Re, A. M., & Cornoldi, C. (2015). Spelling errors in text copying by children with dyslexia and ADHD symptoms. *Journal of Learning Disabilities*, *48*(1), 73–82.

Richman, J. E. (2015). *Development eye movement (DEM), Version 2.5, examiner's manual*. IN: Bernell Corp.

Rosenblum, S., Epsztein, L., & Josman, N. (2008). Handwriting performance of children with attention deficit hyperactive disorders: A pilot study. *Physical & Occupational Therapy in Pediatrics*, *28*(3), 219–234.

Ryckman, D. B., & Rentfrow, R. K. (1971). The Beery developmental test of Visual-Motor Integration: An investigation of reliability. *Journal of Learning Disabilities*, *4*(6), 333–334.

Sallagoïty, I., Athènes, S., Zanone, P. G., & Albaret, J. M. (2004). Stability of coordination patterns in handwriting: Effects of speed and hand. *Motor Control*, *8*(4), 405–421.

Saudino, K. J., & Plomin, R. (2007). Why are hyperactivity and academic achievement related? *Child Development*, *78*(3), 972–986.

Shen, I. H., Lee, T. Y., & Chen, C. L. (2012). Handwriting performance and underlying factors in children with attention deficit hyperactivity disorder. *Research in developmental disabilities*, *33*(4), 1301–1309.

Talero-Gutierrez, C., Van Meerbeke, A. V., & Reyes, R. G. (2012). A clinical study of ADHD symptoms with relation to symptoms of learning disorders in schoolchildren in Bogota, Colombia. *Journal of attention disorders*, *16*(2), 157–163.

Tse, L. F. L., Thanapalan, K. C., & Chan, C. C. H. (2014). Visual-perceptual-kinesthetic inputs on influencing writing performances in children with handwriting difficulties. *Research in developmental disabilities*, *35*(2), 340–347.

Wang, M., & Geva, E. (2003). Spelling performance of Chinese children using English as a second language: Lexical and visual–orthographic processes. *Applied Psycholinguistics*, *24*(1), 1–25.

Wang, M., Perfetti, C. A., & Liu, Y. (2005). Chinese–English biliteracy acquisition: Cross-language and writing system transfer. *Cognition*, *97*(1), 67–88.

Willcutt, E. G., Doyle, A. E., Nigg, J. T., Faraone, S. V., & Pennington, B. F. (2005). Validity of the executive function theory of attention-deficit/hyperactivity disorder: A meta-analytic review. *Biological Psychiatry*, *57*(11), 1336–1346.

World Health Organization. (1992). *The ICD-10 classification of mental and behavioural disorders: Clinical descriptions and diagnostic guidelines*. Geneva, Switzerland: Author.

How to cite this article: Li-Tsang CWP, Li TMH, Lau MSW, Ho CHY, Leung HWH. Handwriting assessment to distinguish comorbid learning difficulties from attention deficit hyperactivity disorder in Chinese adolescents: A case–control study. *Int J Methods Psychiatr Res*. 2018;27:e1718. https://doi.org/10.1002/mpr.1718