Cross-lagged cross-subject bidirectional predictions among achievements in mathematics, English language and Chinese language of school children

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This study aimed to explore the cross-lagged association of achievements in mathematics and languages. While the effect of language on achievements in mathematics is well-documented, few studies have examined the reciprocal relationships among mathematics, the Chinese language, and the English language in the same study. This study conducted a secondary analysis of longitudinal achievement data collected through the Territory-wide System Assessment (TSA) in Hong Kong. The sample comprised 48,547 third-grade, unbalanced bilingual students who were measured three times over six years: in 2007 (in Grade 3), 2010 (Grade 6), and 2013 (Grade 9). Multilevel cross-lagged analysis found prior achievement in a subject was the strongest predictor of achievement in that subject three years later. Furthermore, cross-subject bidirectional prediction was found among achievements in mathematics, Chinese language, and English language for students from Grade 3 to Grade 6 and from Grade 6 to Grade 9.

Introduction

There is a growing body of international research evidence on the interrelationship between language and mathematics skills, after taking into account the mother tongue language of the students in each reported study. The bidirectional effects of mathematics and language skills are especially intriguing. Evidence abounds that early language skills affect later achievements in mathematics (Purpura & Ganley, 2014; Rabiner et al., 2016; Vukovic & Lesaux, 2013), and early mathematics skills predicts reading achievement later on (Duncan & Magnuson, 2011). These longitudinal studies highlighted the role of language in decoding, logical thinking, and expression, all of which apply to problem solving and data interpretation in mathematics (Purpura & Ganley, 2014; Vukovic & Lesaux, 2013). Research (Sarama, Lange, Clements, & Wolfe, 2012) has also demonstrated the ability of early mathematics performance to predict later achievements in language.

Research remains to be done on the bidirectional relationship between achievements in language and mathematics for bilingual English language learners whose mother tongue was Chinese. First, there is a dearth of cross-lagged research on the reciprocal predictions among the mother tongue (L1), the second language (L2), and mathematics in bilingual learners when achievements in the two languages and in mathematics were included in the same study. This means the specific constellation of relationships among growth in L1, L2, and mathematics is still not well understood. Second, most previous studies were conducted in English or other European languages rather than in an Asian language such as Chinese. Few studies (e.g., Zhao, Valcke, Desoete, Verhaeghe, & Xu, 2011) have examined the concurrent and bidirectional relationships over time between achievements in mathematics and the Chinese language. It is uncertain whether the findings of previous research conducted on the English language are applicable to other languages. Pfost, Hattie, Dörfler, and Artelt (2014) found no strong evidence to support the speculation that reading development is dependent on the orthographic characteristics of European languages, and warned against generalising their findings to non-European languages. The central goal of the current study is to address these gaps in the research literature.

This study aimed to examine the longitudinal cross-lagged association among achievements in the English language, Chinese language, and mathematics for unbalanced bilingual learners – that is, learners who speak and learn in both Chinese (L1) and English (L2) but do not have equal facility in both languages. The study explored the reciprocal relationship direction of participants' growth in these three subjects over a period of six years. The main research question was: what predicts what?

Effects of language proficiency on achievements in mathematics

Previous studies have identified the instrumental role of language in mathematical understanding, reasoning, problem solving, and expression of solutions (Purpura & Ganley, 2014; Shin et al., 2013; Vukovic & Lesaux, 2013). Reading skills were found to be prerequisites for mathematical problems, especially mathematical word problems (Guglielmi, 2012). At the primary school level, the ability to associate number word names and computational process names (e.g., "Five minus three equals two") with their Arabic numerals and the magnitudes they represent ("five"), linguistic–mathematical concepts ("equals"), and mathematical procedures ("minus") is fundamental to numeracy development (Purpura & Ganley, 2014). Fuchs et al. (2010) reported language proficiency correlates with primary students' performance in story problems but not in computation problems.

Fuchs et al.'s (2010) findings were supported by other studies, which found a strong correlation between language ability and assessment outcomes in mathematics (e.g., Bjork & Bowyer-Crane, 2013). Zhao et al. (2011) used a multilevel modelling method on data from 10,959 students in Grades 1 to 6 from rural and urban areas in China. They found Chinese language proficiency (that is, reading comprehension using simplified Chinese characters) to be a significant predictor of students' mathematics performance, even after controlling for self-efficacy and variables at home and in school, although its importance decreased after controlling for students' metacognition.

The generalisation of findings across cultural groups must be done with caution because of differences in different languages' representations of numbers and mathematical operations. Pixner, Moeller, Hermanova, Nuerk, and Kaufmann (2011) investigated the effects of language specificities on the nonverbal processing of two-digit numbers for Primary 1 students with backgrounds in the Austrian-German, Italian, and Czech languages. The three languages differ in their verbal description of tens and units in digital notation (e.g., 27 is read as "seven-and-twenty" in German, "twenty-seven" in Italian, and as either "twenty-seven" or "seven-and-twenty" in Czech). Their results demonstrated language properties had a substantial impact on the processing of nonverbal numerical tasks.

To date, most research on the relationship between abilities in languages and mathematics has been conducted in English or other European languages (except Zhao et al., 2011). There is a dearth of research on the Chinese language or with students from Chinese language backgrounds. This is unfortunate because the systems of nomenclature of numbers in the Chinese and English/European languages are actually quite different (e.g., "sixty-five" in English is read as "six-ten-five" in Chinese), and students sometimes learn mathematics differently in different languages (e.g., young Chinese children learn to count in multiples of five, "five, ten, ten-five, two-ten…"). Another research gap is that few previous studies have studied adolescents. The present study examines longitudinal relationships among achievements in mathematics, the English and Chinese languages, by following a group of Primary 3 (Grade 3) students until Secondary 3 (Grade 9).

Effects of mathematics ability on achievements in language

Few studies have examined the effect of mathematics on achievements in language. An exception was an experimental study by Sarama et al. (2012) which found the experimental group, who used an early mathematics curriculum called *Building Blocks,* and had no intervention in mathematics on four (out of six) subtests of oral language, outperformed the control group. Sarama et al. (2012) argued that the mathematics curriculum in the intervention contributed to the students' abilities in accuracy and reasoning which, in turn, affected their oral language competencies.

The effect of mathematics on language might be explained by shared components in the two subjects. Some mathematicians regard mathematics as a language (Ringler & Bossé, 2013) because both mathematics and language contain a symbolic component, require abilities in symbolic representation, and have rules (formula in mathematics and grammar in language) regarding how symbols can be used (Lefevre et al., 2010). In addition, cognitive neuropsychology evidence shows a parietal site in the brain, called the left angular gyrus area, used in language and calculation processes (Dehaene, Piazza, Pinel, & Cohen, 2013), suggesting an interdependent relationship between language and mathematics might exist.

Mutual effects of language achievements for bilingual students

Recent research with bilingual individuals identified evidence of cross-language transfer (Choi, Tong, & Cain, 2016; Kuo, Uchikoshi, Kim, & Yang, 2016). The transfer was bidirectional and task-dependent, according to the meta-analyses conducted by Prevoo, Malda, Mesman, and van IJzendoorn (2016). Strength of transfer depends on the type of language proficiency tasks and school subject. Idea transfer is task-dependent was supported by Chen, Yanke, and Campbell (2016), who trained 32 Chinese (Cantonese)-English bilingual adults on simple addition and multiplication problems either in English or in Chinese, subsequently testing them in trained and untrained arithmetic problems presented in two blocks, one in English and the other in Chinese. They reported Chinese (Cantonese)-English bilinguals used language-specific representations to remember simple addition and multiplication facts. The study found when trained in Chinese (L1), participants translated their training into English (L2) when solving arithmetic problems presented in English, but when trained in English and required to solve problems presented in Chinese, little translation was used by the participants. Chen et al. (2016) explained the findings in terms of language transfer in solving arithmetic problems by bilinguals.

One specific language (e.g., Chinese) might affect the other (e.g., English) by forming segmental phonological representation and improving word retrieval efficiency. Segmental phonological awareness of and lexical sensitivity in Cantonese predicts English word reading (Choi et al., 2016). Knowledge of English letter names has been found to predict recognition of Chinese characters (McBride-Chang & Ho, 2005). In addition, one language might affect the other via morphological awareness, which can be transferred from one language to another, and compound morphological awareness which predicts Chinese character reading and its comprehension (Wang, Cheng, & Chen, 2006).

Effects of prior achievement

Prior mathematical achievement is one of the strongest predictors of subsequent mathematics achievement across a diverse sample of learners (e.g., Geary, 2011; Jõgi & Kikas, 2016; Lefevre et al., 2010; Rabiner et al., 2016). This might be explained by the cumulative nature of mathematics learning. Learning more advance concepts and skills in mathematics is built on the mastery of earlier concepts and skills and the learner's ability to establish connections between new and prior knowledge (Nguyen et al., 2016). Such progressive development is also found in language learning. Language development is highly dependent on previous language achievement (e.g., Pfost et al., 2014; Shin et al., 2013), although genetic factors also play a crucial role in literacy and numeracy achievements (Grasby & Coventry, 2016). The current study explores the relationships between prior and later achievements in mathematics and languages.

Effects of gender, medium of instruction, and school banding

Gender differences have repeatedly been found in achievements in mathematics, Chinese language, and English language (Organisation for Economic Co-operation and Development, 2014; Reilly, Neumann, & Andrews, 2015). Furthermore, school banding (Salili & Lai, 2003), medium of instruction (MOI) (Lo & Lo, 2014; Salili & Lai, 2003), and medium of test (MOT) of academic achievements (Gablasova, 2014) also affect student achievement. These variables were included as covariates in this study.

Theories on Observed Relationships between Language and Mathematics

Several theories have been proposed in explaining the observed association between language and mathematics proficiencies. Third factor variables, which might affect both language and mathematics achievement either directly or indirectly through other mediators, were used to explain the association. Such variables reported in the literature included, (1) Cognitive processes shared between mathematics and languages: research showed rapid automatized naming (RAN) was significantly related to both mathematics fluency (Cui, Georgiou, Zhang, Li, Shu, & Zhou, 2017) and reading fluency (Georgiou, Aro, Liao, & Parrila, 2016) for a range of languages differing in orthographic consistency (Chinese, English, and Finnish). Recent studies on school readiness also highlighted executive function skills (Samuels, Tournaki, Blackman, & Zilinski, 2016), including attention shifting, cognitive flexibility, effortful engagement, working memory, self-regulation, and inhibitory control as precursors for numeracy and literacy school success (Purpura, Schmitt, & Ganley, 2017). (2) Neural perspective: recent brain and neuroimaging research has found neural correlates of language and numeracy processing (Alt, Arizmendi, & Beal, 2014). (3) Genetic factors: research has found mathematics problem solving, reading decoding, and general cognitive processing shares a genetic overlap. Meta-analysis by de Zeeuw, de Geus, and Boomsma (2015) on twin studies showed genetic factors accounted for over half of the variance in literacy and mathematics school performance. Their findings were consonant with a twin study (Grasby & Coventry, 2016), in which stability and growth over time from Grades 3 to 9 in literacy and numeracy in Australian school students were explained in terms of genetic factors. (4) Home resource theory: parental expectation (Lazarides et al., 2016), parental involvement style (Gubbins & Otero, 2016), mother's educational level (Petridou & Karagiorgi, 2016), and children's access to learning resources at home (Petridou & Karagiorgi, 2016) were found to affect their language and mathematics achievements.

Several theories have been presented to explain observed relationships between the achievements in two languages of bilingual children. Some have predicted positive relations (Cummins, 1979; Hornberger, 2013; Prevoo et al., 2016; Proctor, August, Snow, & Barr, 2010) and others negative relations (Cha & Goldenberg, 2015; Wright, Taylor, & Macarthur, 2000). Positive associations across language developments have been explained in terms of the interdependence between languages and enriched linguistic repertoire fostering biliteracy development, particularly for languages sharing similar language features. Theories along this line of argument included Cummins' (1979) interdependence hypothesis, Homberger's (2013) bilingual continua model, and the interdependence continuum theory of Proctor et al. (2010). Recent brain research identified support of interdependence theories (Buchweitz & Prat, 2013). Positive relations between cross-language developments of bilingual learners were also explained in terms of bilingual learners' favourable socio-economic status, and language resources at home fostering development in both languages (Buckingham, Beaman, & Wheldall, 2014), although the strength of parental influence on children's language proficiency seemed to attenuate with time (Place & Hoff, 2011). Alternatively, there were reports on subtractive bilingualism (Wright, Taylor, & Macarthur, 2000) – when increased proficiency in the bilingual learner's heritage language was associated with a decrease in L2 proficiency (Cha & Goldenberg, 2015). Wright, Taylor, and Macarthur (2000) observed the larger the difference in social prestige between the two languages, the greater was the subtractive power of the more socially prestigious language.

Research questions and hypothesis

The following research questions were formulated:

1. Are students' achievements in mathematics, Chinese language, and English language stable? This was an important question because stability in these subjects implies that intervention strategies for the identification and remediation of learning difficulties must start early. In this study, evidence of stability was established by examining the ability of previous achievements to predict later achievements in the same subject. It was expected that previous achievements in mathematics, Chinese language and English language would affect later achievements in these subjects (Hypothesis 1).
2. Does student achievement in mathematics contribute to achievement in language (English or Chinese), or is it rather, achievement in language that predicts mathematics achievement? This question was important because learning in a particular subject does not occur in isolation. All factors contributing to academic growth in a subject need to be considered, in order to formulate appropriate intervention strategies. In this study, evidence of cross-subject contributions to growth was established by examining the ability of previous achievements in one

subject in order to predict later achievements in another subject. It was expected that reciprocal relationships would exist between mathematics and the English language. That is, children who achieved success in the English language in an early grade were expected to achieve success in mathematics in a later grade (Hypothesis 2a). Similarly, based on previous research, a reciprocal relationship between mathematics and the Chinese language was hypothesised (Hypotheses 2c and 2d).

3. Does prior achievement in L1 contribute to later achievement in L2, and does L2 achievement contribute to later achievement in L1 for bilingual learners? This question was important because the answer should inform educators on the nature of cross-language transfer for unbalanced bilingual learners. Evidence of cross-language contributions to the language growth of bilinguals was established in this study by examining the ability of previous achievements in L2 (L1) to predict later achievements in L1 (L2). It was expected that prior achievement in Chinese (L1) would predict later achievement in English (L2) (Hypothesis 3a), and prior achievement in English (L2) would predict later achievement in Chinese (L1) (Hypothesis 3b).

The above research questions are represented diagrammatically in the hypothesis model, as shown in Figure 1.

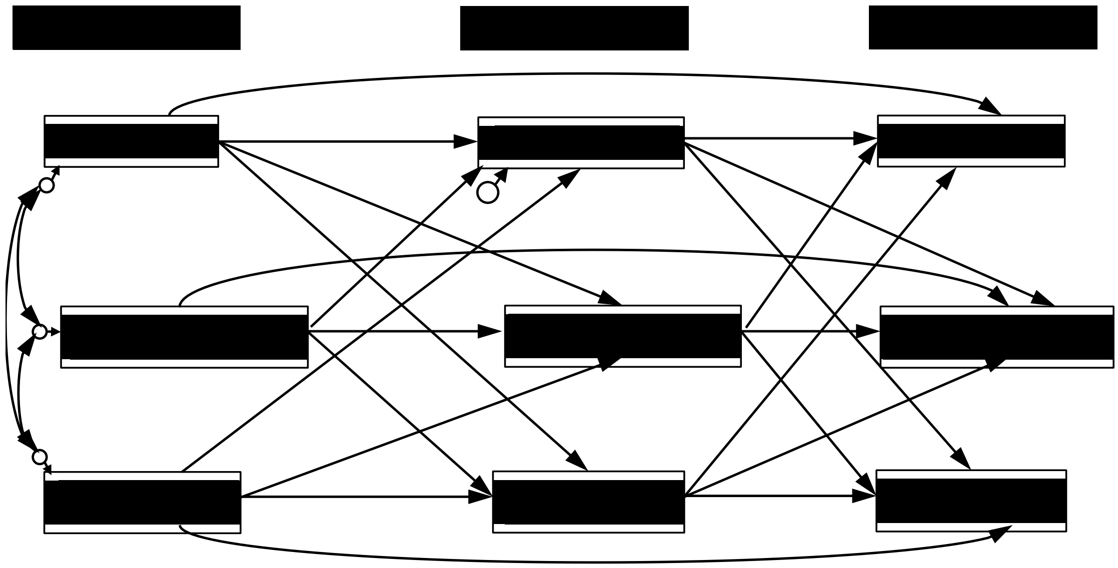

Figure 1. Hypothesised model
Notes: Gender effect on the variables are not indicated explicitly for brevity. Gender affected all achievement variables in the model.

Method

Sample

This study used secondary longitudinal data originally collected by the Hong Kong government through the Territory-wide System Assessment (TSA) (Mok, 2010). The TSA was administered each year (until 2012, after which the assessment was administered only every other year to Grade 6 students) to all students in Grade 3 (G3), Grade 6 (G6), and Grade 9 (G9) in all Hong Kong schools (except private, international, and English Foundation). Data comprised performance (in the form of Rasch measures) in mathematics, Chinese language, and English language on the TSA collected from the 2007 cohort of 49,526 G3 students from 451 primary schools, again in 2010, when the students were in G6, and for a third time in 2013, when the same students were in G9. Missing data for the assessments ranged between .70% (for mathematics in 2010) and 2.21% (for Chinese language in 2007). 145 students from schools with fewer than 10 students were excluded because schools of that size in Hong Kong are for students with special educational needs. Students with missing data for any one of the independent variables were also excluded. Consequently, data from 48,547 students (24,684 or 50.85% males) from 526 schools (i.e., 92.295 students per school) were used in the final analysis.

This study was conducted in full compliance of all ethical standards of the University at which it was undertaken.

Language and mathematics education in Hong Kong

The Hong Kong government has a bi-literate (Chinese and English) and trilingual (Cantonese, a Chinese dialect; Putonghua, the official language of Mainland China; and English) policy. Students learn English, traditional written Chinese characters, and spoken Cantonese in parallel in primary (G1 to G6) and secondary (G7 to G12) schools (Evans, 2013). Government statistics (Census and Statistics Department, 2016) indicate 95.7% of the population speak Chinese (88.1% Cantonese, 3.9% Putonghua, 3.7% other Chinese dialects), 1.4% speak English, and 2.8% speak other languages at home. Typical Hong Kong students can be classified, therefore, as unbalanced Chinese-English bilinguals.

According to Hong Kong government guidelines, at the primary level (G1-G6), between 285-356 curriculum hours each academic year must be scheduled for mathematics, and around 223-264 for the Chinese language (Curriculum Development Council, 2000). At the junior secondary level (G7-G9), around 270-405 hours are devoted to mathematics, and 338-405 each to English and Chinese. Mathematics, Chinese, English, and Liberal

Studies are the four core subjects in the Hong Kong Diploma of School Education Examination – the only public school examination that determines university entrance in Hong Kong. Research into factors contributing to Hong Kong students' growth in mathematics and Chinese language proficiency is, thus, of great importance.

Medium of instruction and medium of test

English and Chinese (spoken Cantonese and traditional written Chinese) are the two main languages used in Hong Kong school education. According to the MOI, there are three types of schools: English-, Chinese-, and Mixed English/Chinese-medium. This classification is especially prominent at the secondary school level.

Chinese is the MOT for the Chinese language assessment in the TSA, and English is the MOT for the English language assessment. Chinese-medium and English-medium schools use, respectively, a Chinese MOT and an English MOT for the mathematics assessment. Mixed-medium schools can choose Chinese or English MOT for the TSA. Accordingly, for this study, students were classified into four groups according to their school's mathematics MOI and MOT in G9. The first group used English as both MOI and MOT (EIET); the second used Chinese as both MOI and MOT (CICT); the third used English and Chinese as MOI and English as MOT (MIET); and the fourth used English and Chinese as MOI and Chinese as MOT (MICT). If a mixed-medium school had students sitting both the English and the Chinese version of the TSA mathematics assessment, in the analysis, it was treated as two schools, one MIET and the other MICT. This classification was used as a school-level covariate for G9 students.

School banding

Hong Kong secondary schools are classified into three bands according to their student intake in G7. Band One have students with the best scores on the Pre-Secondary One Hong Kong Attainment Test in the previous year (which was taken by the cohort of G6 students last year), and Band Three have those with the poorest scores (Salili & Lai, 2003). In this study, school banding was used as a school-level covariate in G9.

Variables

The variables used were the Rasch measures (logits) of assessment scores in mathematics, Chinese language, and English language at the TSA in 2007 (Grade 3), 2010 (Grade 6), and in 2013 (Grade 9). The TSA was a system-wide standardised assessment administered by the Hong Kong government, with participation from all students. Students sat the assessment in class in-group format (except for the speaking components of the language assessments), under the supervision of school teachers (Mok, 2010).

At each grade level and each curriculum subject, four versions of the assessment papers were used for adequate coverage of the curriculum, and to provide a broad range of item difficulties to cater for learning diversity. The papers were linked by common items across versions and between year levels. The versions were randomly administered to participants. Through the linkage items, Rasch assessment measures were mapped onto a common measurement scale for each subject, enabling the interpretation of measures within subject across year levels. A variety of formats was used for the test items, including multiple-choice and constructed responses. Responses to items were scored and converted to Rasch measures (logits) by the government. For the set of secondary data used in this study, the Rasch measures of Chinese language, English language and mathematics of each participating student were given, but no information on individual items provided. Consequently, computing measures of reliability were not possible. Nevertheless, standard setting procedures in the assessment design were strictly followed (Hong Kong Examinations and Assessment Authority, 2008). Further, in an earlier study which made use of TSA data, the assessment was reported to have high internal consistency (Cronbach's Alpha ranged from 0.894 to 0.952) (Mok, McInerney, Zhu, & Or, 2015). Descriptive statistics of the variables for the current set of secondary data are given in Table 1.

Table 1

Descriptive Statistics of Variables

Subject	Year	Grade	Min (logit)	Max (logit)	Mean (logit)	SD (logit)
Chinese	2007	3	15.798	29.998	21.875	0.915
	2010	6	17.771	26.971	22.841	0.832
	2013	9	17.834	27.302	23.878	0.761
English	2007	3	14.377	30.603	21.473	1.579
	2010	6	14.988	27.304	22.328	1.524
	2013	9	16.862	29.158	23.352	1.545
Mathematics	2007	3	14.617	26.850	22.136	1.039
	2010	6	15.546	26.482	23.114	1.330

For copyright reasons, it is not possible to include example items here, but the original test papers and marking schemes can be downloaded from the website of the Hong

Kong Examinations and Assessment Authority:

TSA 2007: http://www.bca.hkeaa.edu.hk/web/TSA/zh/2007priPaper/PriIndex.html;

TSA 2010: http://www.bca.hkeaa.edu.hk/web/TSA/zh/2010priPaper/PriIndex.html;

TSA 2013: http://www.bca.hkeaa.edu.hk/web/TSA/en/2013secPaper/SecIndex.html.

Strategies of data analysis

Several data analysis strategies were considered. A simplistic approach was structure equation modelling in which earlier achievements in Chinese language, English language and mathematics were used to predict later achievements in these subjects. However, this approach ignored the nested nature of the data within clusters. That is, students were clustered within schools. Students from the same school were expected to have more similarities than students from different schools, therefore, their achievement data could not be considered independent. Ignoring the independency assumption of traditional regression analysis and SEM might lead to wrong estimates of the parameters and their standard errors and, hence, incorrect conclusions. Such errors could be avoided by using multilevel models (Goldstein, 2011).

Another data analytic approach considered was multilevel modelling (Goldstein, 2011) and included achievements at Grades 3 and 6 as predictors for achievements at Grade 9. The drawback of this approach, whilst taking care of the nested data structure, was researchers being unable to delineate the constellation of relationships among the variables, except expressing all relations in a linear format. This was less than satisfactory because, for instance, the direct effect of Grade 3 achievement, and the indirect effect of Grade 3 achievement mediated through Grade 6 achievement, could not be separately identified using the HLM approach.

This study combined the statistical and modelling benefits of HLM and SEM in the analysis and undertook a multilevel (two-level) cross-lagged analysis using the Mplus software (version 7.2) (Muthén & Muthén, 1998-2012) to identify the structural relationships across time of students' achievement in Chinese language, English language, and mathematics. Multilevel analysis was conducted because of the nested nature of the data. Students were also nested within classes which were, in turn, nested within schools, but class was not included as a level in this analysis because class-level information were not included in the TSA data. Consequently, students constituted the first level and schools the second in the two-level analysis. Student gender, gender of students at the schools (single-sex or co-educational), school bandings, MOI, and MOT in G9 were included as covariates in the analysis.

This study did not perform a time series analysis because data were only collected at three time points. As such, the number of time periods covered was too small for a time series analysis. However, it is important to note that when observations from the same individuals were obtained at different points in time, the serial correlation (autocorrelation) among the observations might lead to errors in estimation (Baltagi, 2013). This was one limitation of the current study.

Results

Descriptive statistics

Table 2 shows the variance, covariance, and correlations among achievements in mathematics, Chinese language, English language, student gender, and gender of the school population in G9. Table 3 shows the students' achievements in the three subjects across different grade levels by school banding and by the four combinations of MOI and MOT. Correlations among achievements in different subjects across grade levels were positive and moderate in size. Girls outperformed boys in most assessments except mathematics in G3 and G6. Students from Band 1 schools outperformed those from Band 2 who, in turn, outperformed students from Band 3 schools across all grade levels. Students from English-medium schools outperformed their counterparts from mixed-medium schools who opted for the English-MOT mathematics assessment on the TSA in G9. Students from mixed-medium schools who took the English-MOT mathematics assessment, outperformed students from the remaining two school types.

Table 2

Variance and Covariance of Variables, and Correlations between Variables

Variable	1	2	3	4	5	6	7	8	9	10	11
MthG9 (1)	**2.104**	.692	1.503	1.265	.642	1.265	.829	.642	1.092	.065	-.091
ChnG9 (2)	.643	**.572**	.750	.526	.394	.614	.374	.393	.495	.092	-.037
EngG9 (3)	.672	.651	**2.382**	1.166	.738	1.991	.818	.852	1.813	.201	-.157
MthG6 (4)	.662	.533	.573	**1.742**	.694	1.217	.970	.684	1.022	-.003	-.083
ChnG6 (5)	.535	.648	.578	.636	**.687**	.750	.515	.514	.597	.092	-.047
EngG6 (6)	.575	.536	.850	.607	.596	**2.308**	.865	.869	1.973	.166	-.168
MthG3 (7)	.552	.485	.512	.711	.603	.550	**1.073**	.605	.832	-.007	-.060
ChnG3 (8)	.488	.583	.607	.576	.714	.629	.656	**.832**	.814	.095	-.056
EngG3 (9)	.478	.418	.746	.491	.459	.823	.509	.569	**2.492**	.135	-.187
StuGen (10)	.090	.244	.260	-.005#	.222	.218	-.014	.209	.171	/	/
SchGen (11)	-.156	-.119	-.252	-.156	-.139	-.273	-.144	-.152	-.292	/	/
Mean	23.930	23.882	23.356	23.124	22.844	22.334	22.139	21.879	21.477	/	/
SD	1.451	.757	1.543	1.320	.829	1.519	1.036	.912	1.579	/	/

Notes: Mth = Mathematics, Chn = Chinese, Eng = English. Estimates of variances (in bold) in cells on the diagonal; correlation below diagonal; covariance above diagonal. # stands for not significant at $\alpha = .01$. StuGen = Student Gender; Boys were coded as 0 and girls as 1; SchGen = Gender of School Population in G9, with single-sex schools coded as 0 and co-educational schools as 1.

Table 3

Distribution of student achievement by school banding and combination of MI and MT

	Mth G9	Chn G9	Eng G9	Mth G6	Chn G6	Eng G6	Mth G3	Chn G3	Eng G3
Banding									
Band 1	24.732	24.264	24.508	23.956	23.346	23.487	22.752	22.426	22.541
Band 2	23.750	23.813	22.943	22.935	22.715	21.908	21.979	21.713	21.013
Band 3	22.720	23.292	21.663	21.888	22.163	2.647	21.272	21.064	2.005
Combination of MOI and MOT									
CICT	23.281	23.506	22.077	22.301	22.384	21.066	21.554	21.328	2.308
EIET	24.501	24.175	24.280	23.769	23.226	23.257	22.610	22.295	22.334
MICT	23.206	23.507	22.076	22.399	22.428	21.163	21.639	21.380	2.421
MIET	23.862	23.988	23.501	23.181	22.877	22.294	22.123	21.857	21.314

Note: Mth = Mathematics, Chn = Chinese, Eng = English; CICT = Chinese MOI and Chinese MOT; EIET = English MOI and English MOT; MICT = Mixed MOI and Chinese MOT; MIET = Mixed MOI and English MOT.

Results of the two-level cross-lagged analysis

Overall, the two-level cross-lagged model fitted the data well, with CFI = .973, TLI = .932, and RMSEA = .032. The chi-squared value for the tested model (2794.031, $df = 54$, $p < .05$) was significant at $\alpha = .05$ but substantially lower than that of the baseline model (101097.115, $df = 135$, $p < .001$). The significance of the chi-square test might be explained by the large sample size (Kline, 2011). Student-level and school-level SRMR were .006 and .433 respectively, indicating a good model fit at the student level, but a poor fit at the school level.

Intra-class correlations of the dependent variables were between .433 and .652, meaning differences between schools accounted for 43.3% to 65.2% of variances in the outcome variables. The R squared of achievement in mathematics, Chinese language, and

English language in G9 ranged from .251 to .383 at the student level and from .831 to .969 at the school level.

Results of the two-level cross-lagged analysis are presented in Figure 2, Table 4, and Table 5. Figure 2 illustrates the reciprocal relationships among student achievement in the three subjects across grade levels. Table 4 shows the path coefficients of the predictors of the dependent variables and the corresponding R squared values. Table 5 shows the total, direct, and indirect effects of the predictors on achievement in G9.

Stability of achievement in mathematics, Chinese language, and English language

Stability of achievement in a subject was checked by inspecting the significance of autoregressive path coefficients. As displayed in Table 4, prior achievement in a subject significantly predicted later achievement in the same subject. At the student level, G3 mathematics predicted G6 mathematics ($\beta \cong .436$, $p < .001$), and G6 mathematics predicted G9 mathematics ($\beta \cong .373$, $p < .001$). G3 Chinese language predicted G6 Chinese language ($\beta \cong .437$, $p <. 001$) which, in turn, predicted G9 Chinese language ($\beta \cong .286$, $p < .001$). Likewise, G3 English language predicted G6 English language ($\beta \cong .507$, $p < .001$) which, in turn, predicted G9 English language ($\beta \cong .446$, $p < .001$). Similarly at the school level, with only one exception, achievement in a subject was predicted by the achievement in that subject three years ago. The exception was that the path coefficient of G6 mathematics on G9 mathematics was not statistically significant (Table 4).

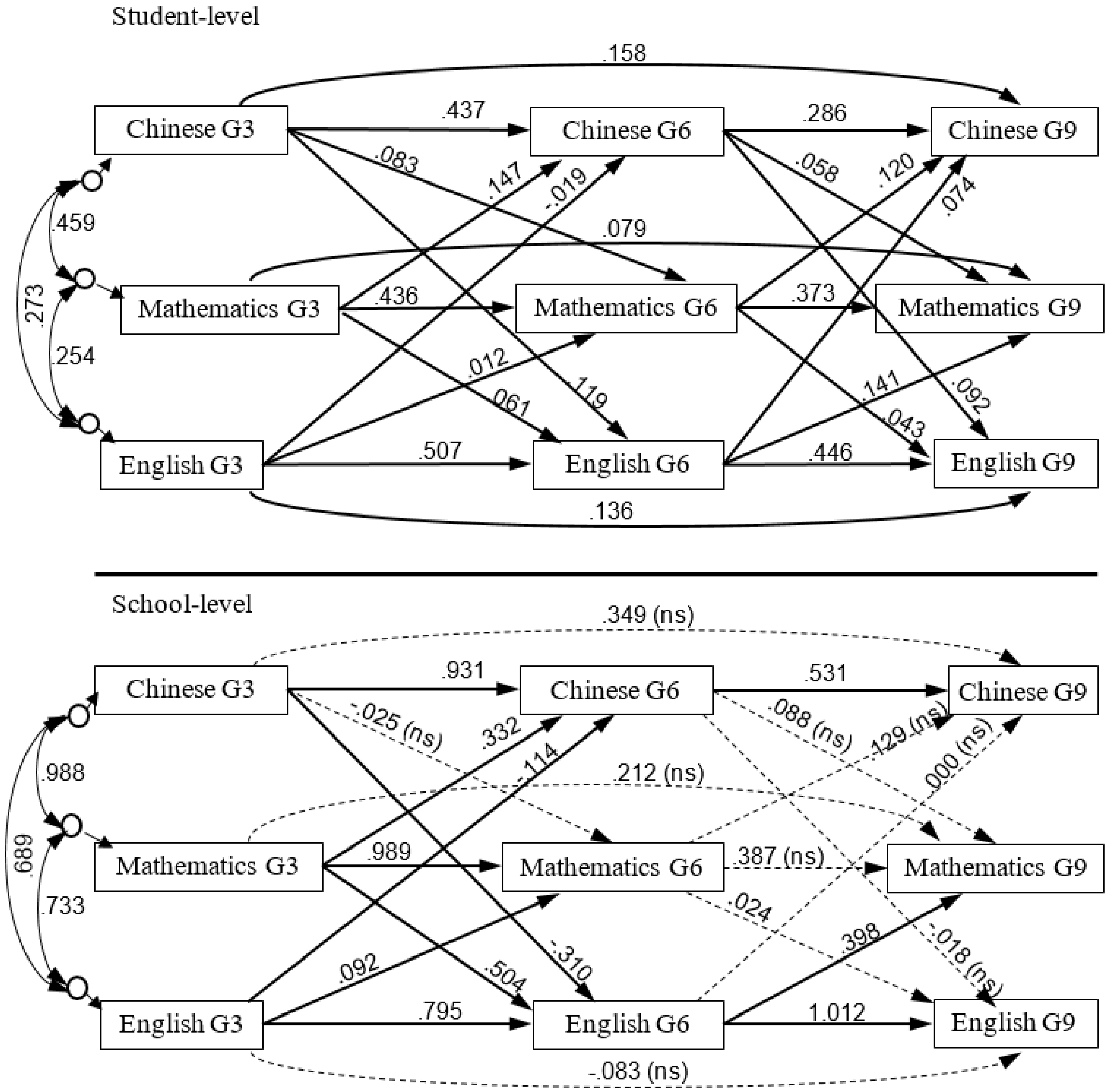

Figure 2. Standardized results (STDYX) of the two-level cross-lagged analysis.
Notes: For brevity, student gender was modelled to have affected achievement in all three subjects but it was not presented in the figure; results of the covariates and residual correlations are also not presented in this figure. Arrow printed in dotted lines are non-significant at 0.05.

Table 4

Path Coefficients of two-level cross-lagged analysis

					Dependent Variable				
Predictors	MthG3	ChnG3	EngG3	MthG6	ChnG6	EngG6	MthG9	ChnG9	EngG9
Student-Level									
MthG6							.373***	.120***	.043***
ChnG6							.058***	.286***	.092***
EngG6							.141***	.074***	.446***
MthG3				.436***	.147***	.061***	.079***		
ChnG3				.083***	.437***	.119***		.158***	
EngG3				.012**	-.019**	.507***			.136***
StuGen	-.161***	.151***	.103***	-.116***	.131***	.111***	.011	.129***	.125***
R-squared	.026***	.023***	.011***	.258***	.289***	.356***	.251***	.266***	.383***
School-level									
MthG6							.387	.129	.024
ChnG6							.088	.531*	-.018
EngG6							.398***	.000	1.012***
MthG3				.989***	.332***	.504***	.212		
ChnG3				-.025	.931***	-.310***		.349	
EngG3				.092***	-.114***	.795***			-.083
SchGen							.008	.000	.003
Band 1							.121	.099	.109***
Band 2							.094*	.122**	.064**
CICT							.075*	.035	.043**
EIET							-.182***	.047	.121***
MIET							-.081**	.139***	.151***
R-squared				.986***	.989***	.982***	.835***	.831***	.969***

Covariance between Predictors within the Same Time Period

	MthG3	ChnG3	MthG6	ChnG6	MthG9	ChnG9
Student-Level						
ChnG3	.459***					
EngG3	.254***	.273***				
ChnG6			.253***			
EngG6			.211***	.252***		
ChnG9					0.388***	
EngG9					0.431***	0.383***
School-Level						
ChnG3	0.988***					
EngG3	0.733***	0.689***				
ChnG6			0.006			
EngG6			0.621***	-0.075		
ChnG9					0.615***	
EngG9					0.544***	0.657***

Note: Mth = Mathematics, Chn = Chinese, Eng = English. *** stands for significance at $\alpha = .001$, ** at $\alpha = .01$, and * at $\alpha = .05$. Boys were coded as 0 and girls as 1; School Gender = Gender of School Population in G9, with single-sex schools coded as 0 and co-educational schools as 1.

Band 1 and Band 2 are dummy variables for School Banding in G9, with Band 3 as the reference group; CICT, EIET, and MIET were dummy variables for a combination of MI and MT, with MICT as the reference group.

Table 5

Total, direct, and indirect effects on student achievement in Grade 9

Path	Unstandardized			Standardized (STDYX)		
	Total	Direct	Indirect	Total	Direct	Indirect
→ MthG9						
Student-level						
MthG6	.427***	.427***	/	.373***	.373***	/
ChnG6	.106***	.106***	/	.058***	.058***	/
EngG6	.178***	.178***	/	.141***	.141***	/
MthG3	.360***	.110***	.250***	.259***	.079***	.180***
ChnG3	.116***	/	.116***	.073***	/	.073***
EngG3	.081***	/	.081***	.075***	/	.075***
StuGen	-.071***	.023	-.095***	-.032***	.011	-.043***
School-level						
MthG6	.385	.385	/	.387	.387	/
ChnG6	.159	.159	/	.088	.088	/
EngG6	.311***	.311***	/	.398***	.398***	/
MthG3	1.063***	.273	.790**	.824***	.212	.612**
ChnG3	-.069	/	-.069	-.051	/	-.051
EngG3	.288***	/	.288***	.342***	/	.342***
SchGen	.020	.020	/	.008	.008	/
Band 1	.250*	.250*	/	.121	.121	/
Band 2	.183*	.183*	/	.094*	.094*	/
CICT	.158*	.158*	/	.075*	.075*	/
EIET	-.360***	-.360***	/	-.182***	-.182***	/
MIET	-.197**	-.197**	/	-.081**	-.081**	/
→ ChnG9						
Student-level						
MthG6	.074***	.074***	/	.120***	.120***	/
ChnG6	.279***	.279***	/	.286***	.286***	/
EngG6	.050***	.050***	/	.074***	.074***	/
MthG3	.074***	/	.074***	.099***	/	.099***
ChnG3	.257***	.135	.122***	.302***	.158	.144***
EngG3	.020***	/	.020***	.033***	/	.033***
StuGen	.230***	.153***	.077***	.194***	.129***	.065***
School-level						
MthG6	.056	.056	/	.129	.129	/

ChnG6	.416*	.416*	/	.531*	.531*	/
EngG6	.000	.000	/	.000	.000	/
MthG3	.170*	/	.170*	.304*	/	.304*
ChnG3	.494***	.205	.289*	.839***	.349	.491*
EngG3	-.018	/	-.018	-.048	/	-.048
SchGen	.000	.000	/	.000	.000	/
Band 1	.089	.089	/	.099	.099	/
Band 2	.103**	.103**	/	.122**	.122**	/
CICT	.032	.032	/	.035	.035	/
EIET	.040	.040	/	.047	.047	/
MIET	.147***	.147***	/	.139***	.139***	/

Path	Unstandardized			Standardized (STDYX)		
	Total	Direct	Indirect	Total	Direct	Indirect
→ EngG9						
Student-level						
MthG6	.041***	.041***	/	.043***	.043***	/
ChnG6	.138***	.138***	/	.092***	.092***	/
EngG6	.465***	.465***	/	.446***	.446***	/
MthG3	.068***	/	.068***	.059***	/	.059***
ChnG3	.126***	/	.126***	.097***	/	.097***
EngG3	.323***	.122	.201***	.361***	.136	.225***
StuGen	.407***	.227***	.179***	.224***	.125***	.099***
School-level						
MthG6	.028	.028	/	.024	.024	/
ChnG6	-.038	-.038	/	-.018	-.018	/
EngG6	.922***	.922***	/	1.012***	1.012***	/
MthG3	.794***	/	.794***	.529***	/	.529***
ChnG3	-.522***	/	-.522***	-.331***	/	-.331***
EngG3	.711***	-.082	.793***	.725***	-.083	.809***
SchGen	.009	.009	/	.003	.003	/
Band 1	.263***	.263***	/	.109***	.109***	/
Band 2	.146***	.146***	/	.064**	.064**	/
CICT	.106**	.106**	/	.043**	.043**	/
EIET	.278***	.278***	/	.121***	.121***	/
MIET	.431***	.431***	/	.151***	.151***	/

Note: Mth = Mathematics, Chn = Chinese, Eng = English. *** stands for significance at $\alpha = .001$, ** at $\alpha = .01$, and * at $\alpha = .05$. Boys were coded as 0 and girls as 1; School Gender = Gender of School Population in G9, with single-sex schools coded as 0 and co-educational schools as 1. Band 1 and Band 2 are dummy variables for School Banding in G9, with Band 3 as the reference group; CICT, EIET, and MIET were dummy variables for a combination of MI and MT, with MICT as the reference group.

Bidirectional prediction of mathematics and language achievements

Bidirectional prediction of mathematics and language achievements was checked by inspecting cross-lagged path coefficients between mathematics and the two languages. Table 4 shows that, at the student level, G3 mathematics predicted G6 Chinese ($\beta \cong .147$, $p < .001$) and G3 Chinese predicted G6 mathematics ($\beta \cong .083$, $p < .001$). Likewise, G6 mathematics predicted G9 Chinese ($\beta \cong .120$, $p < .001$) and G6 Chinese predicted G9 mathematics ($\beta \cong .058$, $p < .001$). At the school level, a cross-lagged bidirectional relationship between mathematics and Chinese language was not supported. G3 mathematics significantly predicted G6 Chinese language ($\beta \cong .332$, $p < .001$), but G3 Chinese language did not predict G6 mathematics (Table 4). The cross-lagged bidirectional relationship between mathematics and Chinese language from G6 to G9 was not statistically significant (Table 4).

Similarly, cross-lagged bidirectional path coefficients between mathematics and English language were statistically significant at the student level from G3 to G6 and from G6 to G9 (Table 4). However, no cross-lagged bidirectional prediction between mathematics and English language was found at the school level. G3 mathematics predicted G6 English language, but G3 English language did not predict G6 mathematics. Further, G6 English language predicted G9 mathematics, but G6 mathematics did not predict G9 English language (Table 4).

Bidirectional prediction of Chinese and English languages

Cross-lagged bidirectional prediction between the Chinese and English languages was found at the student level. Achievement in either language predicted achievement in the other language three years later (Table 4). However, at the school level, cross-lagged bidirectional predictions between the Chinese and English languages were significant only from G3 to G6, but not from G6 to G9 (Table 4).

Discussion

This study investigated autoregressive and cross-lagged associations among achievements in mathematics, Chinese language and English language for unbalanced bilingual learners. Secondary analysis was undertaken on longitudinal data collected by the Hong Kong government on their achievements in three curriculum subjects at G3, G6 and G9 in order to address three research questions, the first concerning the stability over time of students' achievements in mathematics, Chinese language, and English language. The second research question focused on the role of mathematics and languages (English or Chinese) in driving achievement: What drove what? The third research question addressed the bidirectional influence of L1 and L2 achievements.

The study found that, in line with previous literature (Geary, 2011; Fuchs et al., 2010; Jõgi & Kikas, 2016; Shin et al., 2013), students' previous achievement in one subject was the strongest and most significant predictor of achievement in that subject three years later. Students with lower achievement in G3 are at greater risk of poor performance in G6 and G9. Results of this study provide strong evidence on the stability of achievement in the curriculum subjects from G3 to G9, even after controlling for student gender, MOI, and MOT. The findings highlight the significance of good foundations in both mathematics and languages at early grades for future academic achievement in these subjects. They also point to the importance of early identification and intervention of at-risk students in order to prevent them from falling further behind.

Second, consistent with the literature (Purpura & Ganley, 2014; Sarama et al., 2012; Vukovic & Lesaux, 2013; Zhao et al., 2011), this study found bidirectional, cross-subject prediction between mathematics and English language from G3 to G9. This study also found bidirectional prediction between Chinese language and mathematics, after controlling for students' L2 achievement, gender, MOI, and MOT. The better students performed in mathematics in an early grade, the better their performance was in the two languages in a later grade. Higher achievement in languages, in turn, predicted higher achievement in mathematics three and six years later. Third, the study provided evidence of reciprocal prediction between L1 and L2 of unbalanced bilinguals, a result consistent with previous reports (Chen et al., 2016; Choi et al., 2016; Kuo et al., 2016; Prevoo et al., 2016). Of note was the negative effect of G3 English on G6 Chinese, quite small but statistically significant, indicating presence of subtractive bilingualism (Wright et al., 2000). The result indicates strong societal emphasis on English in Hong Kong might mean achievement in English language is at the expense of growth in Chinese language for primary school students. These findings are important additions to the literature on bilingual language and mathematics developments.

The predictive effect of prior achievement on later achievement in mathematics and languages found in this study might be explained by the cumulative nature of learning in these subjects (Nguyen et al., 2016; Pfost et al., 2014). Bidirectional cross-lagged prediction among mathematics, Chinese language and English language might be explained in terms of genetics factors (Grasby & Coventry, 2016), attribution theory (Weiner & Handel, 1985), home resources (Petridou & Karagiorgi, 2016), and parental factors (Lazarides et al., 2016). It is impossible to determine within this study which of these explanations are more feasible since no data were collected on these possible explanatory variables by the government.

The large differences between schools provided further support for using multilevel analysis in this study. These results mean that, after controlling for the covariates, the independent variables (i.e., previous achievements in the subjects) collectively explain a large proportion of variance in student and school achievement in G9.

This study has several limitations, including lack of non-mathematics and non-language explanatory variables. Prediction of later achievement by prior achievement could be because both are affected by students' working memory (Purpura & Ganley, 2014), metacognition (Dent & Koenka, 2016), or executive functioning (Samuels et al., 2016), and identified as key predictors of academic achievement. This study's non-experimental design also means no causal conclusion can be drawn based on the cross-lagged association among achievements in the subjects.

In addition, given the extremely large sample, statistical significance needs to be interpreted with caution such that minute differences, which have no practical implications, are not given undue recognition. Future research should focus on more in-depth studies, which make use of both quantitative and qualitative techniques, and include variables that have significant impact on student achievement. These include executive functioning and parental variables, in order to develop deeper understanding of the relationship among students' achievements in mathematics, English language and Chinese language over time.

Ideally, potential intervening factors (e.g., third factors which might affect both mathematics and language proficiencies) were controlled or measured in parallel with the achievement data. This study made use of secondary data. Data were not collected on possible third factors. This limitation of the study is hereby acknowledged.

Conclusion

This is the first study to identify a bidirectional association over time from G3 to G9 between achievements in mathematics and the English and Chinese languages for unbalanced Chinese-English bilinguals. The findings of bidirectional associations between mathematics and the two languages provide further support of the interdependence hypothesis of Cummin (1979) and the interdependence continuum theory for language learning of Proctor et al. (2010). As mathematics and languages share some cognitive processes (Cui et al., 2017) and mathematics can be regarded as a language (Lefevre et al., 2010; Ringler & Bossé, 2013), it is also suggested that learning of mathematics might be understood from a perspective of language learning, i.e., learning of symbols, rules and the usage of symbols (Lefevre et al., 2010).

Further, this study provides a strong evidence of the cumulative nature of learning in mathematics and languages, which means later learning is based on the mastery of knowledge and skills at previous stages (Nguyen et al., 2016). The findings are important because first, they suggest the significance of primary education to a student's entire academic career. From a reparative point of view, this implies the remediation of weaker students should start as early as possible at the primary level and because prior learning gaps predict future learning difficulties. Eventually, the gap between the intended learning and the prerequisite for that learning is beyond restoration, leading to such other issues as disengagement or school dropout (Fortin, Marcotte, Diallo, Potvin, & Royer, 2014).

Further, the reciprocal association over time of achievements in the Chinese and English languages highlighted the importance of a balanced curriculum between these two subjects. Nevertheless, Hong Kong maintains a strong emphasis on the English language in its mainstream social sentiments, with English MOI as a manifestation of its colonial legacy (Evans, 2013). Results of this study show, however, that while achievements in one language (English or Chinese) had beneficial effects on the other language for individual students, schools with a biased emphasis on one language might enhance performance in that language at the expense of development in the other for the school as a whole. It is, therefore, imperative that educators and policymakers of bilingual systems revisit and re-evaluate their respective language education policies.

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