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The effects of genetic and environmental factors on writing development[☆]

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ABSTRACT

Researchers have identified sources of individual differences in writing across beginning and developing writers. The aim of the present study was to further clarify the sources of this variability by investigating the extent to which there are differences in genetic and environmental factors underlying the associations between lexical diversity, syntactic knowledge, and semantic cohesion knowledge in relation to writing. Differences were examined across two developmental phases of writing: beginning (i.e., elementary school) and developing (i.e., middle school). Participants included 262 twin pairs (*M*age = 10.88 years) in elementary school and 247 twin pairs (*M*age = 13.21 years) in middle school. Twins were drawn from the Florida Twin Project on Reading, Behavior, and Environment. Biometric models were conducted separately for subgroups defined by phase of writing development. Results indicated significant etiological differences in writing components across the two phases, such that effects associated with genes and non-shared environment were greater while effects associated with shared environment were lower in developing writers as compared to beginning writers. Furthermore, results showed that child-specific environment was the largest contributor to individual differences in writing components and their covariation for both beginning and developing writers. These results imply that even direct instruction about writing in schools may be having different effects on children based on their unique experiences.

1. Introduction

The Common Core of State Standards Initiative, an educational initiative in the United States that details what K-12 students should know in English language arts at the end of each grade, provides standards for writing skills needed to meet expectations for academic success as well as in the workforce (National Governors Association Center for Best Practices, Council of Chief State School Officers [CCSSO], 2010). The guidelines outline that "… in writing, students should demonstrate increasing sophistication in all aspects of language use, from vocabulary and syntax to the development and organization of ideas, and they should address increasingly demanding content and sources" (CCSSO, 2010, p. 19). However, the National Assessment of Educational Progress (NAEP, 2002, 2011; NAEP is the largest nationally representative assessment of what American students know and can do in various subjects) results show that only 28% of fourth graders and 27% of eighth graders perform at or above proficient level in writing. Concerns over low levels of writing achievement in elementary and middle school, together with evidence that children with writing disabilities are at greatly enhanced risk of difficulties in reading and math (Mayes & Calhoun, 2006; Sumner, Connelly, & Barnett, 2013), have motivated a large body of work to identify the sources of individual variability in writing (Abbott & Berninger, 1993; Arfe, Dockrell, & De Bernardi, 2016; Babayigit, 2014; Berninger, Abbott, Abbott, Graham, & Richards, 2002; Berninger et al., 1992; Graham, Berninger, Abbott, Abbott, & Whitaker, 1997; Graham, McKeown, Kiuhara, & Harris, 2012; Kim, Al Otaiba, Folsom, Greulich, & Puranik, 2014; Kim, Al Otaiba, Wanzek, & Gatlin, 2015; Kim et al., 2011; Kim, Park, & Park, 2013; Limpo & Alves, 2013; Olinghouse, 2008; Olinghouse, Graham, & Gillespie, 2015). One line of research that would further clarify variability in writing in elementary and middle school is investigating the etiological (genetic and environmental) factors associated with individual differences in writing.

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1.1. A model of writing and relations between its components

"A writer(s) within community model of writing," recently proposed by Graham (in press), serves as the theoretical framework for the current study. The model establishes the importance of personal and environmental influences for successful writing and suggests that information about writing be gathered from two units that work in tandem: a writer's cognitive architecture (cognitive components of an individual that are necessary for writing and are assumed to be universal) and the writing community (specific sociocultural contexts or environments which shape writing). Components in Graham's model account for developing and skilled writing and are consistent with other developmental writing models such as the "not-so-simple view of writing" model (Berninger & Winn, 2006).

According to Graham's (in press) model of writing, four cognitive components within the individual support writing. (1) Long-term memory resources include knowledge about oral language, listening and reading skills, as well as specialized knowledge about writing. Oral language is related to linguistic aspects of text generation. It includes phonological, lexical, syntactic, semantic, and pragmatic knowledge. (2) Control mechanisms refer to processes, such as attention, working memory, and executive control. (3) Production processes include conceptualization, ideation, translation, transcription, and reconceptualization. (4) Lastly, modulators involve emotions, personality traits, and physiological state. All four components are interrelated and contribute to a written product. There is abundant empirical evidence to support this. For example, oral language knowledge, including phonological, lexical, syntactic, and semantic knowledge (Arfe et al., 2016; Babayigit, 2014; Hooper et al., 2011; Kim et al., 2014; Kim et al., 2015; Kim & Schatschneider, 2017; McCarthy & Jarvis, 2007; McNamara, Crossley, & McCarthy, 2010), as well as control mechanisms (Altemeier, Abbott, & Berninger, 2008; Graham, Harris, & Olinghouse, 2007; Hayes, 2000; Hooper et al., 2011; Kim & Schatschneider, 2017; Limpo & Alves, 2013), and production processes (Abbott & Berninger, 1993; Arfe et al., 2016; Graham et al., 1997; Hayes, 2012; Kim et al., 2013, 2015; Kim & Schatschneider, 2017; Limpo & Alves, 2013) have been shown to contribute to writing. These cognitive resources are not fixed, but are assumed to be modifiable. As such, their development is shaped by one's experiences in different environments (Graham, in press).

As to the environmental influences, Graham's (in press) model suggests two aspects that are of particular interest for the current report, because they could represent potential environmental sources underlying variability in writing. Settings in which children's writing mostly takes place, such as home or school setting, as well as members of a writing community, including peers or teachers, may both underpin individual differences in writing. Overall, Graham's (in press) model provides a clear statement on the importance of personal and environmental influences in writing. Moreover, it indicates that cognitive components involved in writing and the environments writers seek to produce text work in concert rather than independently. They both add their contribution to explaining to what extent differences in writing can be attributable to personal versus environmental factors. This has implications for research such as the present study, which is aimed at understanding to what extent children differ in their performance in writing as well as in the cognitive components related to writing due to genetic and environmental factors.

1.2. Individual differences in writing

Like reading, language, and essentially any other achievement outcome, writing shows clear individual differences. Graham's (in press) model as well as other developmental models of writing (e.g., not-so-simple view by Berninger & Winn, 2006; Direct and Indirect Effects model of Writing [DIEW] by Kim & Schatschneider, 2017) highlight cognitive components that likely provide some of the sources for individual differences in writing. Unpacking the broad etiological sources associated with individual differences in a phenotype like writing can be accomplished using twin study methodology. A twin study methodology may help identify sources of variation in writing skills, such as conditions that are due to shared and/or individual specific environment (e.g., oral language environment; Hart & Risley, 1995, and/or experience with independent reading; Fukkink, Blok, & de Glopper, 2001; Swanborn & de Glopper, 1999) as well as those aspects that are due to genetic factors (e.g., working memory and other executive functions; Little et al., 2015).

This study examined the extent to which genetic and environmental influences underlie covariance between what Graham (in press) would refer to as the component of long-term memory resources and writing. Specifically, we examined in three separate models to what extent lexical diversity, syntactic knowledge, and semantic cohesion knowledge are etiologically related to writing. From an empirically informed point, a focus on these specific components of writing is justified by the fact that although other cognitive mechanisms (e.g., working memory; Kim & Schatschneider, 2017) account for substantial portions of variation in writing, they do not account for all the variation. Thus, this leaves room for investigation of other components, which contribute to individual differences in the compositional quality (Abbott & Berninger, 1993) and are malleable by instruction. Moreover, focus on these components lends itself well to word (lexical diversity), sentence (syntactic knowledge), and discourse level (semantic cohesion knowledge) activities children engage in at school when learning about writing. Indeed, the findings from examination of the variation and covariation of these components could inform interventions to prevent low achievement in writing, in a way that components could themselves be targets of educational interventions to boost writing achievement.

Lexical diversity was defined in the present study as the range of different words used in a text, with a greater range indicating a higher diversity (McCarthy & Jarvis, 2010). It has been found to be indicative of writing quality (McCarthy & Jarvis, 2007), and to be a significant predictor of other important constructs such as language proficiency, language complexity, and lexical proficiency (Crossley, 2013; Crossley, Salsbury, McNamara, & Jarvis, 2011). Syntactic knowledge was operationalized as syntactic complexity, which refers to diversity and complexity of sentences used in written composition (Graesser, McNamara, Louwerse, & Cai, 2004). Syntactic complexity in written composition has been shown to predict essay quality (McNamara, Crossley, & McCarthy, 2010). Semantic cohesion knowledge was operationalized as semantic cohesion and defined as conceptual similarity between each sentence and the text. It has been shown to be related to writing (McNamara, Louwerse, McCarthy, & Graesser, 2010). Finally, writing was operationalized as writing quality. It refers to aspects of writing such as ideas and organization (Kim & Schatschneider, 2017). It is an essential, and arguably the most important aspect to be evaluated in writing (Kim et al., 2015). Taken together, examining the common genetic and environmental effects underlying writing and each of the components will extend our understanding of factors individual differences in writing can be attributed to.

1.3. Developmental differences in writing

Writing development undergoes considerable changes during the individual's years in school. Beginning writing starts to emerge in elementary school grades, and continues to develop in middle and high school grades and beyond (Berninger & Swanson, 1994). As noted, writing is underpinned by cognitive components and their contribution to writing may vary during different phases of writing development (Berninger & Swanson, 1994). The present study focuses on two phases: (1) beginning or elementary school writing, and (2) developing or middle school writing. Three differences between these two phases in terms of contributions of cognitive components to writing are worthy of mentioning.

The first dissociation is related to what Graham's (in press) model refers to as long-term memory resources. Specifically, the difference lies in diversity of oral language skills, which affects translating ideas into acceptable sentences. While beginning writers can generate ideas, they might have difficulty generating language to express those ideas. Moreover, even if they can readily generate the oral language to express ideas, they can lack knowledge of how to represent that oral language orthographically (Berninger et al., 1992). Developing writers, on the other hand, become more proficient in their skills of how to turn their ideas into acceptable sentences compared to beginning writers. They can draw on their knowledge of oral language, such as sentence structure, usage, and vocabulary to do this (Graham, in press).

The second difference is based on the role of control mechanisms. To illustrate, individual differences in working memory have been shown to be more predictive of compositions in middle school than in elementary school (Berninger & Swanson, 1994). This is because writing processes become increasingly constrained by working memory span as writing develops. Developing writers are more engaged in non-automated composing activities which take place in working memory. They are also better at self-regulatory processes such as attention and other control mechanisms necessary for advanced writing in comparison to beginning writers.

The third difference pertains to the role of what Graham's (in press) model of writing refers to as production processes, in particular conceptualization, translation, and transcription. Elementary school writers have difficulty separating conceptualization from translation. They form a mental conceptualization of the writing task while they generate text. Whatever comes to mind is written down (Berninger, Fuller, & Whitaker, 1996). Moreover, beginning writers might lack accuracy and fluency in transcription skills, which in turn constrains writing by interfering with processes such as preplanning. In contrast, middle school writers do some preplanned conceptualization before they start writing. This results in the text content, which is relevant to the goals and the topic of the writing task. Also, their transcription skills are much more automatized as compared to the beginning writers, thus leaving room in the cognitive processing system for other processes involved in skilled writing (Berninger et al., 1996).

In summary, the relative weighting of various cognitive components on writing might change with development of writing. Elementary schoolers apply most of their cognitive efforts to oral language skills and transcription processes. As a result, there is not much room left in the cognitive processing system for other resource intensive cognitive actions, such as preplanning. That in turn can relate to the quality of writing, such that, for instance, the topic of the writing is not fully developed or relevant information is missing in the produced text. Middle schoolers, conversely, can devote their cognitive processes to generating ideas. Their oral language skills and transcription processes are expected to be more developed at this phase, thus leaving more room in the cognitive system for working memory and advanced planning of the text. This might reflect in higher quality of written compositions compared to those of beginning writers.

1.4. Twin studies on writing

As noted, the sources underlying variation in children's writing at different writing development phases have been studied extensively (e.g., Berninger & Swanson, 1994). Sources reflect both genetic and environmental factors. Genetically sensitive studies, such as twin studies, can estimate how much of that variability in writing is associated with genetic factors versus environmental factors. Specifically, twin study methodology allows for the examination of the proportion of variance attributable to genetic influences (heritability; A), shared environmental influences (non-genetic influences that make siblings more similar, C), and non-shared environmental influences (non-genetic effects that make siblings different, plus measurement error; E). Moreover, using a multivariate genetic method, researchers can also examine genetic and environmental influences upon the covariance among phenotypes (in our study, phenotypes are writing components).

Twin studies on writing are limited. Only two studies were found that examined genetic and environmental contributions to the association of different writing components. Oliver, Dale, and Plomin (2007) reported significant genetic estimates of 0.66 (in terms of proportions of phenotypic variance accounted for), and non-shared environmental effects of 0.27 in writing performance using teacher assessments in 7-year-old twins. Teacher assessments of achievement in writing in Oliver et al.'s (2007) study covered diverse aspects of the writing domain, which would correspond to Graham's (in press) writing components of long-term memory resources, such as lexical and syntactic knowledge, and to components of production processes, such as ideation and transcription. Bivariate analyses between writing and reading showed significant common genetic, shared, and non-shared environmental influences with reading, but there was also unique genetic and non-shared environmental influences on writing, above and beyond the overlap with reading.

Another twin study on writing was conducted by Olson et al. (2013). They examined the etiological influences among the writing components of production processes in 8 through 18-year-old twins. Writing fluency, which refers to automaticity and effortlessness in writing (Berninger et al., 2010; Kim et al., 2015), was measured by the Woodcock-Johnson Writing Fluency subtest. It appeared to be significantly influenced only by non-shared environmental effects (estimate of 0.43). The other two subcomponents of production processes – sentence production and paragraph copying – seemed to be, however, weakly influenced by non-shared environment (estimates of 0.23 and 0.28, respectively), but substantially by genetic effects (estimates of 0.66 and 0.77, respectively). Results from these early twin studies on writing provide important evidence about writing components being influenced mostly by genetic and non-shared environmental factors.

The conclusion that writing owes largely to genes and non-shared environment, however, might mask potential developmental differences across developmental phases of writing. The two twin studies on writing include either a young sample (Oliver et al., 2007) or a sample of a broad age range (Olson et al., 2013). There are a number of studies examining individual differences in development of various academic domains related to writing, including general cognitive development (e.g., Haworth et al., 2010), reading (e.g., Hart et al., 2013), and language (e.g., Hayiou-Thomas, Dale, & Plomin, 2012). These studies reported a consistent trend of greater genetic influences (and relatedly, lower shared environmental influences) on academic outcomes with increasing age. However, researchers have not tested this hypothesis for writing yet. Given the evidence from this research together with the evidence showing differences in contributions of cognitive components to writing between beginning and developing writers (e.g., Berninger & Swanson, 1994), we expect to find developmental etiological differences also in the domain of writing.

One way to test developmental hypotheses regarding etiology is conducting multi-group analyses using structural equation modeling. With this approach, the fit of the model is evaluated under two conditions: (1) when the variances and covariances between writing components are constrained to be equal at each writing development phase, and (2) when these parameters are allowed to vary at each developmental period. It is assumed that the etiological estimates for phenotypes are different across writing development if a statistically significant different pattern of etiology (e.g., a significant difference in genetic effects) is found at each writing development phase. Using a multi-group analysis approach, such a finding has been indicated, for instance, for general cognitive ability (Haworth et al., 2010).

1.5. Present study

"A writer(s) within community model of writing" (Graham, in press) provided a framework for why it is important to examine personal (genetic) and environmental influences to explain individual differences in writing. Researchers on developmental differences in writing have shown that contributions of cognitive components to writing are different between beginning and developing writing (e.g., Berninger & Swanson, 1994). Finally, twin research suggested that individual differences in writing are mainly due to genetic and non-shared environmental factors (e.g., Olson et al., 2013) and that genetic effects in academic domains, which are related to writing, tend to increase with age (Haworth et al., 2010; Hayiou-Thomas et al., 2012). Drawing from these lines of research, our purpose was to examine the extent to which there are differences in genetic and environmental factors underlying the associations between lexical diversity, syntactic knowledge, and semantic cohesion knowledge in relation to writing across the beginning and developing phase of writing development. To date, no studies have examined etiological sources for variability in writing components as a function of writing development phase.

Models of writing (Berninger & Winn, 2006; Graham, in press; Hayes, 2012) posit that similar underlying cognitive components, such as working memory, are involved in writing. Hence, we expected to find common genetic influences among the writing components. Consistent with the literature on developmental etiological differences in academic domains related to writing (e.g., language; Hayiou-Thomas et al., 2012), we expected genetic effects to be more substantial for middle schoolers than elementary schoolers. Conversely, for elementary schoolers we expected variability in writing components to owe mostly to common shared environmental influences. In line with twin studies on writing (Oliver et al., 2007; Olson et al., 2013) as well as the implication drawn from Graham's (in press) model of writing, we predicted that the variation and covariation between writing components would also be explained by common underlying non-shared environmental influences for both age groups. Based on developmental differences in writing (e.g., Berninger & Swanson, 1994), it was expected that non-shared environmental influences would increase from beginning to developing writing development phase.

2. Method

2.1. Participants

Data came from 197 monozygotic (MZ; 104 female-female pairs, 93 male-male pairs) and 312 dizygotic (DZ; 122 female-female pairs, 89 male-male pairs, and 101 opposite sex) twin pairs from the wave 1 (currently, wave 3 is in progress) database of the Florida Twin Project on Reading, Behavior, and Environment (FTP-RBE; Taylor, Hart, Mikolajewski, & Schatschneider, 2012). The twin pairs were in grades 2 through 8, with an average age of 12 years and 4 months ($M = 12.34$, $SD = 1.40$, range = 8.72–15.03). The sample was broken down into two age groups in terms of what phase of writing development the participants were in. The first age group was the beginning writers or elementary schoolers (grades 2 through 5), which included 105 MZ and 157 DZ pairs (mean age $M = 10.88$ years, $SD = 0.79$, range = 8.72–13.39). The second age group was the developing writers or middle schoolers (grades 6 through 8), which included 92 MZ and 155 DZ pairs (mean age $M = 13.21$ years, $SD = 0.88$, range = 11.29–15.03). This twin sample reflects the ethnic and socioeconomic diversity in Florida. According to parent report, 2.1% of the twins were Asian, 13.8% Black, 22.0% Hispanic, 53.4% White, and the remainder was mixed or other race/ethnicity. Of the available data, 50.1% of the participants qualified for Free or Reduced Lunch Status. See Supplementary Materials for additional information on twins in the current study, the FTP-RBE, and the ascertainment method.

2.2. Measures

Three writing components (lexical diversity, syntactic knowledge, and semantic cohesion knowledge) were assessed by indices employed from Coh-Metrix (http://cohmetrix.com/), a tool which analyzes English texts on various measures of cohesion, language, and readability (Graesser et al., 2004; Graesser & McNamara, 2011). Writing was measured by a measure that came from the 6 + 1 Trait Writing Model of Instruction and Assessment (Northwest Regional Educational Laboratory, 2011). All the assignments were same for all pairs of twins for both age groups.

2.2.1. Lexical diversity

Lexical diversity was measured by two indices. Index of lexical diversity for all words (VOCD) was the first measure. Values usually range from 10 to 100, and higher values indicate greater lexical diversity. The second measure was Measure of Textual Lexical Diversity (MTLD). MTLD values do not vary as a function of text length. MTLD is calculated as the mean length of word strings that maintain a given type token ratio value (McNamara, Graesser, McCarthy, & Cai, 2014). For more details on how VOCD and MTLD are created, how they work, and their validity and reliability, see Supplementary Materials, and McCarthy and Jarvis (2010).

2.2.2. Syntactic knowledge

Syntactic knowledge was operationalized as syntactic complexity and measured by an index Minimal Edit Distance in Coh-Metrix (MED; McNamara et al., 2014). MED calculates the average minimal edit, or the distance that parts of speech, words, or lemmas (a semantic morpheme, a meaning stem) is from one another between consecutive sentences in a text. MED is a measure of syntactic variability in a text, namely how variable the syntactic constructions are from sentence to sentence. One MED variation was used in the present study: the distance that words were from one another between consecutive sentences in a text (MEDW). MEDW calculates the extent to which one sentence needs to be modified (edited) to make it have the same syntactic composition as a second sentence (McNamara et al., 2014). See Supplementary Materials for further information on MEDW.

2.2.3. Semantic cohesion knowledge

Semantic cohesion knowledge was conceptualized as semantic cohesion. Latent Semantic Analysis (LSA) provides measures of semantic cohesion between sentences or between paragraphs. Coh-Metrix uses LSA to calculate text givenness, which is referred to as LSA Given/New (LSAGN) (Crossley, Allen, & McNamara, 2014). LSAGN is a proxy for how much given versus new information exists in each sentence in a text, compared with the content of prior text information. It is conceptualized as Given/(New + Given). The central intuition is that the meaning of new information is captured by the company of other information that surround it. When there is less given information (e.g., 10%), then Given/New approaches 0 and indicates that there is low cohesion. When there is more given information in a text (e.g., 100%) and less new information, then Given/New approaches 1, indicating greater cohesion (McNamara et al., 2014). Validity was identified through a review that determined Coh-Metrix indices of cohesion (individually and combined) significantly distinguished the high- versus low-cohesion versions of texts (McNamara, Louwerse, et al., 2010). For more illustration of LSAGN, see Supplementary Materials.

2.2.4. Writing

Writing was conceptualized as writing quality and measured as the degree of quality of ideas (IDEAS) represented in written composition, similar to the Ideas aspect in the 6 + 1 Trait Writing Model of Instruction and Assessment (Northwest Regional Educational Laboratory, 2011). Ideas as one aspect of the 6 + 1 traits were chosen because ideas are the content of the writing. Students develop their piece of writing by selecting the idea, remaining focused on it, and elaborating on it. Handwritten personal narratives were elicited using the typed prompt on ruled writing paper, “One day when I got home

Table 1
Descriptive statistics, *t*-tests with Cohen's *d* effect sizes, and phenotypic correlations for all variables by age group - elementary schoolers (group 1) versus middle schoolers (group 2).

Variable	Group	M (SD)	N	Min	Max	Skew	*t*-test (df)	*p*	Cohen's *d*	1.	2.	3.	4.	5.
1. VOCD	1	34.37 (32.24)	524	0.00	115.07	0.21	− 9.25 (1016)	< 0.0001	0.58	1	0.59**	0.38**	0.45**	0.70**
	2	53.06 (32.33)	494	0.00	125.90	− 0.52								
2. MTLD	1	46.67 (18.79)	524	0.00	114.01	0.59	− 11.67 (1016)	< 0.0001	0.73	0.60**	1	0.33**	0.02	0.47**
	2	60.54 (19.19)	494	0.00	132.66	0.39								
3. MEDW	1	0.82 (0.29)	524	0.00	1.00	− 2.15	− 2.55 (1016)	0.0001	0.16	0.37**	0.46**	1	0.30**	0.39**
	2	0.86 (0.20)	494	0.00	1.00	− 2.41								
4. LSAGN	1	0.25 (0.09)	523	0.00	0.54	− 1.04	− 2.92 (984.75)	0.0036	0.18	0.50**	0.16**	0.40**	1	0.46**
	2	0.27 (0.07)	494	0.00	0.41	− 1.44								
5. IDEAS	1	3.43 (1.05)	524	1.00	7.00	0.21	− 9.48 (984.92)	< 0.0001	0.59	0.73**	0.46**	0.41**	0.62**	1
	2	4.10 (1.19)	494	1.00	7.00	0.19								

Note. The *t*-values result from comparing group 1 to group 2. The *p*-value is the significance test for the *t*-test, and Cohen's *d* is the corresponding effect size. Phenotypic correlations are presented in columns 11–15. Correlations for group 1 are below the diagonal, and for group 2 above the diagonal. M = mean, SD = standard deviation, N = numerus, Min = minimum, Max = maximum, Skew = skewness. VOCD = lexical diversity for all words, MTLD = measure of textual lexical diversity, MEDW = minimal edit distance of words, LSAGN = latent semantic analysis new/given.

** < .001

from school…", similar to written prompts used in other studies (Connelly, Dockrell, Walter, & Critten, 2012; Dockrell, Ricketts, Charman, & Lindsay, 2014; McMaster & Espin, 2007). The writing task was untimed and not constrained in length; although parents were told in their own instructions the activity should take approximately 10 min (regardless of the grade the twins were in) to ensure the twins did not spend more time than necessary on the task. Writing quality was measured on the extent of idea development on a rating scale from 1 to 7. High scores were given to compositions with clear, well-developed, solid, original ideas with unique perspectives, which were logical in sequence, accurate, and engaging. The coding frame is included in the Supplementary materials. IDEAS was examined as an indicator of writing quality in previous studies (Kim et al., 2014, 2015) and face validity was also reported (Espin, Weissenburger, & Benson, 2004). Cohen's kappa (0.63) was calculated between two raters on a writing sample of 154 written compositions. Sim and Wright (2005) refer to the kappa coefficients in the range from 0.61 to 0.80 as substantial.

2.3. Procedures

Detailed information on task administration and procedures is provided in the Supplementary Materials.

2.4. Data analyses

First, to account for age (writing development) differences in the written products, descriptive statistics for the writing measures were calculated separately for elementary schoolers and middle schoolers. We compared the means between the two groups for the writing measures using *t*-tests and Cohen's *d* effect sizes. Following that, raw data on all writing measures for every twin were residualized on gender. Data were also residualized on text length (number of words) to overcome a potential confound of text length on the writing measures. Residualized data were subsequently *z*-scored. Next, phenotypic correlations were calculated by age group for all writing variables. Intraclass (ICC) and cross-twin cross-trait (CTCT) correlations were calculated by age group for each of our three models separately (lexical diversity and writing, syntactic knowledge and writing, and semantic cohesion knowledge and writing). All these analyses were conducted in SAS 9.4 (SAS Institute Inc., Cary, NC, USA).

To examine potential age (writing development) group differences in genetic and environmental influences on writing, multi-group analyses using structural equation modeling were performed across the two age groups for each model in our study. That resulted in three separate multi-group analyses (for lexical diversity and writing, syntactic knowledge and writing, and semantic cohesion knowledge and writing, respectively).

Each of the best fitting models from the multi-group analyses yielded estimates of genetic and environmental components of variance by age group for writing measures in the lexical diversity, syntactic knowledge, and semantic cohesion knowledge model, respectively. Next, a trivariate and two bivariate genetic Cholesky decompositions (Neale & Cardon, 1992) for those best fitting models were assessed by age groups. We examined the degree of overlap in genetic and environmental effects between variables VOCD, MTLD, and IDEAS for the overlap between lexical diversity and writing; MEDW and IDEAS for the overlap between syntactic knowledge and writing; and LSAGN and IDEAS for the overlap between semantic cohesion knowledge and writing. Biometric models on all available data were fit using full information maximum likelihood in Mx (Neale, Boker, Xie, & Maes, 2006). Significance of parameter estimates was based on the 95% confidence intervals not including zero. For more detailed descriptions of data analyses, please refer to the Supplementary Materials section.

3. Results

3.1. Descriptive statistics and correlational analyses by age groups

Descriptive statistics, *t*-tests with Cohen's *d* effect sizes for writing measures by age groups are presented in Table 1. The *t*-test and effect size results indicated significantly lower mean values for all writing measures for elementary schoolers compared to middle schoolers. These differences were small to moderate. Table 1 also presents phenotypic correlations (post residualizing) by age groups. The magnitudes of correlations were similar for elementary and middle schoolers.

Intraclass and cross-twin cross-trait correlations by age groups for variables in each model are provided in Table 2. As seen there, MZ and DZ intraclass correlations for VOCD and IDEAS were similar in magnitude for elementary schoolers, suggesting that etiological contributions for these writing variables were primarily shared environmental in origin in elementary school. For VOCD and IDEAS in middle school, however, the MZ intraclass correlations were significantly larger than the DZ ICCs, signaling the probable presence of genetic influences on those variables in middle school. Also, intraclass correlations in MZ twins were relatively low for MEDW and LSAGN for both age groups, pointing toward a large amount of non-shared environmental influences on the variation among these variables and/or measurement error in the assessment of these variables.

Cross-twin cross-trait correlations further revealed some etiological relations between the writing variables. Moderate MZ and DZ cross-twin cross-trait correlations were observed between VOCD and IDEAS as well as between MTLD and IDEAS for elementary schoolers, suggesting that shared environmental factors may be contributing to their respective relations. By contrast, cross-twin cross-trait correlations

Table 2
Intraclass and cross-twin, cross-trait correlations by age group – elementary schoolers (age group 1) and middle schoolers (age group 2).

Model, variable	Group	1.	2.	3.	Group	1.	2.	3.
Lexical diversity and writing								
1. VOCD	1	0.70**/0.64**	0.36**	0.59**	2	0.67**/0.32**	0.28**	0.29**
2. MTLD	1	0.55**	0.56**/0.30**	0.35**	2	0.43**	0.32**/0.24**	0.29**
3. IDEAS	1	0.61**	0.47**	0.74**/0.60**	2	0.57**	0.33**	0.68**/0.44**
Syntactic knowledge and writing								
1. MEDW	1	0.33**/0.22**	0.10	–	2	0.53**/0.29**	0.04	–
2. IDEAS	1	0.00	0.74**/0.60**	–	2	0.19**	0.68**/0.44**	–
Semantic cohesion knowledge and writing								
1. LSAGN	1	0.32**/0.04	0.11	–	2	0.16**/0.06	0.03	–
2. IDEAS	1	0.00	0.74**/0.60**	–	2	0.17	0.68**/0.44**	–

Note. VOCD = lexical diversity for all words, MTLD = measure of textual lexical diversity, MEDW = minimal edit distance of words, LSAGN = latent semantic analysis new/given, − = N/A. Intraclass correlations are on the diagonal; the first estimate is for MZ twins, the second for DZ twins. Cross-twin, cross-trait correlations are off the diagonal. The estimates for MZ twins are below the diagonal and for DZ twins above the diagonal.

** < .001

between VOCD and IDEAS, and VOCD and MTLD, were larger for MZ twins than for DZ twins for middle schoolers, suggesting that genetic factors may be influencing their overlap. In all, the intraclass and cross-twin cross-trait correlations tended to indicate potential etiological differences among the writing components as well as among their covariations.

3.2. Multivariate analyses by age groups

3.2.1. Estimates of genetic and environmental components of variance

A summary of multi-group model fitting results is presented in Supplementary Table 2. Genetic, shared environment, and non-shared environmental influences by age groups from the best fitting model (the models in bold in Supplementary Table 2) for writing measures in the lexical diversity, syntactic knowledge, and semantic cohesion knowledge model, respectively are presented in Table 3. In the lexical diversity model, the multi-group analyses showed that genetic (A) and shared environmental (C) effects vary as a function of age (i.e., writing development phase). Results indicated significant increase in genetic effects for VOCD and IDEAS from elementary to middle school writing. In contrast, a significant drop of shared environmental effects was indicated for VOCD, MTLD, and IDEAS. The magnitude of non-shared environmental estimates (E) did not vary across the two age groups. In the syntactic knowledge model, differences in genetic and shared environmental effects were not significant across age groups. However, results showed that the magnitude of variance in non-shared environmental effects differed with age. In the semantic cohesion knowledge model, differences in variance in shared and non-shared environment were found across age groups. There was a significant drop of shared environment and a significant rise of non-shared environment for IDEAS from elementary to middle school writing.

3.2.2. Estimates of genetic and environmental overlap between writing components

Results in Tables 4–6 are from the trivariate and bivariate Cholesky compositions by age groups and reflect estimates of the overlap from the best fitting models (models in bold in Supplementary Table 2). For the lexical diversity model (Table 4), biometric factor A_1 indicated significant genetic overlap between VOCD, MTLD and IDEAS (path estimates = 0.73, 0.31, and 0.60, respectively) in the group of middle schoolers, but not elementary schoolers. The reverse was true for shared environmental overlap which was significant in the group of elementary schoolers (biometric factor C_1; path estimates = 0.81, 0.57 and 0.72, respectively). As of non-shared environmental influences, there was a significant overlap indicated by the biometric factor E_1 for both age groups (path estimates = 0.55, 0.28 and 0.19 for the younger group, and path estimates = 0.57, 0.33 and 0.23 for the older group, for VOCD, MTLD and IDEAS, respectively). In addition, there were significant unique non-shared environmental influences on MTLD (biometric factor E_2; path estimates = 0.69 and 0.74, for younger and older group, respectively) and IDEAS (biometric factor E_3; path estimates = 0.44 and 0.52, for younger and older group, respectively).

For the syntactic knowledge model (Table 5), the biometric factor of A_1 revealed no significant genetic overlap between MEDW and IDEAS. Biometric factor A_2 implied significant unique genetic effects for IDEAS alone, outside of MEDW (path estimates 0.55 and 0.50, for elementary and middle schoolers, respectively). Biometric factor E_1 indicated there was significant non-shared environmental overlap between MEDW and

Table 3
Estimates for heritability (A), shared environmental (C), and non-shared environmental (E) influences [with 95% confidence intervals] for writing measures in three best fitting models by age group – elementary schoolers (group 1) and middle schoolers (group 2).

Model	Group	A	C	E	Group	A	C	E
Lexical diversity and writing								
VOCD	1	0.06 [0.00–0.26]	0.65* [0.47–0.75]	0.29* [0.22–0.37]	2	0.54* [0.31–0.73]	0.13 [0.00–0.33]	0.33* [0.25–0.42]
MTLD	1	0.12 [0.00–0.35]	0.33* [0.15–0.53]	0.55* [0.43–0.66]	2	0.10* [0.01–0.48]	0.25 [0.00–0.40]	0.65* [0.50–0.76]
IDEAS	1	0.24* [0.05–0.44]	0.53* [0.35–0.68]	0.23* [0.16–0.32]	2	0.39* [0.13–0.67]	0.28* [0.03–0.49]	0.33* [0.24–0.45]
Syntactic knowledge and writing								
MEDW	1	0.21* [0.14–0.28]	0.00 [0.00–0.23]	0.79* [0.72–0.86]	2	0.42* [0.30–0.54]	0.00 [0.00–0.46]	0.57* [0.46–0.70]
IDEAS	1	0.32* [0.10–0.50]	0.45* [0.29–0.60]	0.23* [0.17–0.29]	2	0.27* [0.12–0.42]	0.37* [0.24–0.50]	0.36* [0.29–0.44]
Semantic cohesion knowledge and writing								
LSAGN	1	0.06* [0.05–0.17]	0.00 [0.00–0.11]	0.94* [0.83–0.99]	2	0.08* [0.05–0.22]	0.00 [0.00–0.15]	0.92* [0.78–0.99]
IDEAS	1	0.28* [0.12–0.46]	0.47* [0.31–0.61]	0.25* [0.19–0.32]	2	0.24* [0.10–0.39]	0.39* [0.26–0.51]	0.37* [0.30–0.44]

Note. * indicates significance based on confidence intervals not bounding zero. VOCD = lexical diversity for all words, MTLD = measure of textual lexical diversity, MEDW = minimal edit distance of words, LSAGN = latent semantic analysis new/given.

Table 4
Multivariate modeling path estimates of genetic and environmental influences for lexical diversity and writing [with 95% confidence intervals] by age group – elementary schoolers (group 1) and middle schoolers (group 2) for the best fitting model.

	Group	Shared influences between 1, 2, 3	Shared influences between 2, 3	Independent influences on 3	Group	Shared influences between 1, 2, 3	Shared influences between 2, 3	Independent influences on 3
		A_1	A_2	A_3		A_1	A_2	A_3
1. VOCD	1	0.24 [0.00–0.52]			2	0.73* [0.53–0.85]		
2. MTLD	1	0.06 [0.00–0.60]	0.34 [0.00–0.49]		2	0.31* [0.08–0.57]	0.00 [0.00–0.45]	
3. IDEAS	1	0.24 [0.00–0.63]	0.04 [0.00–0.48]	0.40 [0.00–0.49]	2	0.60* [0.35–0.81]	0.00 [0.00–0.52]	0.19 [0.00–0.53]
		C_1	C_2	C_3		C_1	C_2	C_3
1. VOCD	1	0.81* [0.67–0.95]			2	0.35 [0.00–0.57]		
2. MTLD	1	0.57* [0.36–0.71]	0.00 [0.00–0.42]		2	0.50 [0.00–0.61]	0.00 [0.00–0.32]	
3. IDEAS	1	0.72* [0.54–0.82]	0.00 [0.00–0.31]	0.00 [0.00–0.31]	2	0.36 [0.00–0.73]	0.18 [0.00–0.52]	0.35 [0.00–0.52]
		E_1	E_2	E_3		E_1	E_2	E_3
1. VOCD	1	0.55* [0.49–0.61]			2	0.57* [0.49–0.61]		
2. MTLD	1	0.28* [0.18–0.38]	0.69* [0.62–0.75]		2	0.33* [0.18–0.38]	0.74* [0.62–0.79]	
3. IDEAS	1	0.19* [0.09–0.27]	0.00 [0.00–0.09]	0.44* [0.36–0.48]	2	0.23* [0.12–0.35]	0.05 [0.00–0.13]	0.52* [0.47–0.61]

Note. * indicates significance based on confidence intervals not bounding zero. The first set of biometric factors measures the genetic (A_1), shared environmental (C_1), and non-shared environmental (E_1) influences between VOCD, MTLD, and IDEAS. The second set (A_2, C_2, E_2) measures the genetic and environmental influences between MTLD and IDEAS, outside of that explained by VOCD. Finally, the third set of biometric factors (A_3, C_3, E_3) measures the unique influences on IDEAS alone, outside of the variance explained by both VOCD and MTLD. VOCD = lexical diversity for all words, MTLD = measure of textual lexical diversity.

IDEAS (path estimates = 0.83 and 0.12 for the younger group, and path estimates = 0.76 and 0.12 for the older group). Furthermore, biometric factor E_2 revealed significant non-shared environmental influence for IDEAS, independent of MEDW (path estimates 0.46 and 0.59, by age groups).

In the semantic cohesion knowledge model (Table 6), no significant genetic or shared environmental overlaps were indicated by either biometric factors A_1 or C_1 in either of the age groups. Biometric factor E_1 indicated significant non-shared environmental overlap among LSAGN and IDEAS (path estimates = 0.97 and 0.21 for elementary schoolers, and 0.96 and 0.17 for middle schoolers). Lastly, the biometric factor of E_2 suggested significant non-shared environmental influence on IDEAS alone, independent of LSAGN (path estimates = 0.45 and 0.58 for each age group, respectively).

4. Discussion

Results of national U.S. assessments show that less than one third of students perform at or above proficient level in writing in elementary and middle school. Researchers have shown that this variability in writing can be attributed to a number of factors. The aim of the present study was to further elucidate potential sources of these differences. We examined the extent to which there are differences in etiological factors underpinning the relation between writing quality and lexical diversity, syntactic knowledge, and semantic cohesion knowledge in written compositions for children in two developmental phases of writing: (1) beginning writing (i.e., elementary school), and (2) developing (i.e., middle school) writing. This study is the first to address this question. Results suggest that there are differences in genetic and environmental effects on various writing components for children at different developmental phases of writing. In addition, our results imply that non-shared environmental factors largely explain relations between components of writing.

4.1. Genetic influences on elementary and middle school writing

Consistent with the hypothesis, results from the multi-group analyses demonstrate that differences in genetic effects on writing components vary as a function of developmental phase of writing. Specifically, increases in genetic effects from beginning to developing writing were found in the lexical diversity model. Although the present study cannot answer the question whether the increase in heritability between these two phases is driven by new genetic factors coming online in middle school, the increase in heritability over the course of writing development is, nonetheless, compelling.

We propose three possible explanations for this difference in genetic influences. First, it may be that our observed increase in genetic effects is an independent example of a general pattern of increased heritability over time. For example, Haworth et al. (2010) reported a linear increase of genetic influences on general cognitive factor from early childhood, through middle childhood to adolescence. Similarly, heritability of language tends to increase from early to middle childhood, and then appears to stabilize in early adolescence (Hayiou-Thomas et al., 2012). A likely mechanism underlying the increased heritability with age is the

Table 5
Multivariate modeling path estimates of genetic and environmental influences for syntactic knowledge and writing [with 95% confidence intervals] by age group – elementary schoolers (group 1) and middle schoolers (group 2) for the best fitting model.

	Group	Shared influences between 1, 2	Independent influences on 2	Group	Shared influences between 1, 2	Independent influences on 2
		A_1	A_2		A_1	A_2
1. MEDW	1	0.45* [0.37–0.52]		2	0.66* [0.55–0.73]	
2. IDEAS	1	0.15 [0.00–0.30]	0.55* [0.35–0.73]	2	0.14 [0.00–0.27]	0.50* [0.32–0.64]
		C_1	C_2		C_1	C_2
1. MEDW	1	0.00 [0.00–0.23]		2	0.00 [0.00–0.67]	
2. IDEAS	1	0.67 [0.00–0.77]	0.00 [0.00–0.00]	2	0.61 [0.00–0.70]	0.00 [0.00–0.00]
		E_1	E_2		E_1	E_2
1. MEDW	1	0.83* [0.85–0.93]		2	0.75* [0.67–0.83]	
2. IDEAS	1	0.12* [0.04–0.20]	0.46* [0.41–0.53]	2	0.11* [0.07–0.23]	0.59* [0.53–0.65]

Note. * indicates significance based on confidence intervals not bounding zero. The first set of biometric factors measures the genetic (A_1), shared environmental (C_1), and non-shared environmental (E_1) influences between MEDW and IDEAS. The second set (A_2, C_2, E_2) measures the genetic and environmental influences on IDEAS alone, outside of the variance explained by MEDW. MEDW = minimal edit distance of words.

Table 6
Multivariate modeling path estimates of genetic and environmental influences for semantic cohesion knowledge and writing [with 95% confidence intervals] by age group – elementary schoolers (group 1) and middle schoolers (group 2) for the best fitting model.

	Group	Shared influences between 1, 2	Independent influences on 2	Group	Shared influences between 1, 2	Independent influences on 2
		A_1	A_2		A_1	A_2
1. LSAGN	1	0.24* [0.03–0.41]		2	0.28* [0.08–0.46]	
2. IDEAS	1	0.06 [0.00–0.65]	0.53 [0.00–0.67]	2	0.06 [0.00–0.60]	0.49 [0.00–0.62]
		C_1	C_2		C_1	C_2
1. LSAGN	1	0.00 [0.00–0.33]		2	0.00 [0.00–0.39]	
2. IDEAS	1	0.68 [0.00–0.78]	0.00 [0.00–0.78]	2	0.63 [0.00–0.72]	0.00 [0.00–0.71]
		E_1	E_2		E_1	E_2
1. LSAGN	1	0.97* [0.91–0.99]		2	0.96* [0.87–0.99]	
2. IDEAS	1	0.21* [0.13–0.28]	0.45* [0.40–0.52]	2	0.17* [0.08–0.25]	0.58* [0.52–0.64]

Note. * indicates significance based on confidence intervals not bounding zero. The first set of biometric factors measures the genetic (A_1), shared environmental (C_1), and non-shared environmental (E_1) influences between LSAGN and IDEAS. The second set (A_2, C_2, E_2) measures the genetic and environmental influences on IDEAS alone, outside of the variance explained by LSAGN. LSAGN = latent semantic analysis new/given.

process of gene-environment correlation. Children increasingly select, create, and modify their environments and experiences, driven by their own genetic predispositions. As such, the present results are compatible with the idea of Graham's (in press) model of writing, which argues that cognitive capabilities of the individual who creates writing and the environment he/she seeks to engage in writing are related. In terms of gene-environment correlation, this could mean that, for example, developing writers with a high genetic potential for good writing may actively start to seek environments that provide them with writing opportunities.

A second explanation is related to the timing when the differences were observed. Transition from beginning to developing writing in our study coincides with the change from elementary to middle school. While effects of teacher, classroom instruction, and school may be substantial at the beginning of education when formal writing instruction commences (i.e., transition from preschool to first grade), these effects become more constant across children as they progress through schooling. One way in which this might impact the relative importance of genetic factors (and relatedly, shared environmental factors) is that shared environmental influences reduce with increasing years of schooling, thus leaving more room for genetic influences to explain individual differences in writing components and writing (Samuelsson et al., 2008).

A third explanation pertains to the role of overarching cognitive processes underlying writing components in middle school. Specifically, cognitive components that Graham (in press) refers to as long-term memory resources, such as advanced oral language skills, and control mechanisms are more salient for developing than beginning writing. As previously noted (e.g., Berninger & Swanson, 1994), the influence of production processes such as transcription drops by middle school because many children demonstrate accuracy and fluency in transcription at this point. Thus, what is left to exert influence on writing is advanced oral language skills as well as other resource intensive cognitive actions, including working memory, attention, preplanning. Our results suggest that a significant set of genetic factors is associated with writing and lexical diversity in middle, but not elementary school. Some of these factors might be tapping into similar cognitive processes, including advanced oral language skills and working memory. Both are mainly genetically influenced in middle school (Hayiou-Thomas et al., 2012; Little et al., 2015) and have been shown to be predictive of writing (Arfe et al., 2016).

The lack of genetic differences and genetic overlapping in syntactic and semantic cohesion knowledge models across the developmental phases of writing was not consistent with our hypothesis. We would have expected to find a significant shared genetic factor between writing quality and syntactic as well as semantic cohesion knowledge for middle school writing. Our expectation was, again, based on various writing models (Berninger & Winn, 2006; Graham, in press; Hayes, 2012), which predict the shared demand for various cognitive components in writing. Results of the present study suggest that in middle school, different genetic resources underlie writing and syntactic as well as semantic cohesion knowledge, at least in the way they were operationalized here. Operationalization appears to be important in this regard based on theory and evidence. Syntactic knowledge is part of overall oral language skills, and researchers have shown that it is moderately associated with other aspects of spoken language (e.g., lexical knowledge) (Gleitman, 1990; Kim, in press; Piccin & Waxman, 2007). Syntactic knowledge, however, can be operationalized in various ways (e.g., morpho-syntactic knowledge, syntactic complexity), and the vast majority of studies which reported moderate to strong correlations operationalized syntactic knowledge as morpho-syntactic knowledge. When operationalized as syntactic complexity, highly similar to the current study, syntactic knowledge in writing showed a different pattern of relations to other aspects of writing (e.g., writing quality, productivity; Kim et al., 2014). Our unexpected findings in this regard need further empirical research before firm conclusions can be drawn.

4.2. Shared environmental influences on elementary and middle school writing

Aside from differences in genetic effects, the phase of writing development seems to be associated also with differences in shared environmental effects on writing components. The pattern of shared environmental influences was the exact opposite of that of genetic influences. Significant decreases in shared environment from beginning to developing writing were found in lexical diversity and semantic cohesion knowledge models. The most substantial difference (a drop) was indicated in the lexical diversity model.

Why are shared environmental influences more substantial for beginning than developing writing? Two explanations have been fleshed out above. Shared environmental effects decrease with age, and are more substantial at the beginning of formal education. The third possibility is related to what Graham's (in press) model of writing refers to as settings in which writing related activities and writing take place. Results suggest that the environments twins share seem to be particularly salient for beginning writing. For example, parentally supplied verbal home environments of rich early oral language skills (Burgess, Hecht, & Lonigan, 2002; Hart & Risley, 1995; Whitehurst & Lonigan, 1998), joint picture-book reading by an adult and a child (Sénéchal & Cornell, 1993), or teaching the child to read and print words in a typical week (Sénéchal, Lefevre, Thomas, & Daley, 1998) may contribute to children's foundational oral language skills, which might in turn relate to writing quality of their written compositions.

Another reason could be related to the role of what Graham (in press) refers to as control mechanisms, in particular executive control. According to Berninger and Swanson (1994), executive functioning plays a limited role in the beginning phases of writing development due to children's limited capacity of working memory. Thus, children may need to rely on other adults' help, such as teacher and instruction resources, to help support their executive functioning. With increased maturation, children would eventually use their own resources of executive functions for productive writing to a greater extent.

Differences in the magnitude of variance in shared environment were not found in the syntactic knowledge model. This is unexpected as previous research indicated the importance of shared environments, such as home and school environments for acquiring syntactic knowledge in child's early years (Bates & Goodman, 1999; Schleppegrell, 2001). Another plausible explanation for this unexpected finding might again relate to the operationalization of syntactic knowledge. Our results suggest that syntactic knowledge, when operationalized as syntactic complexity, does not show much change in variability across the two developmental phases of writing. The second unexpected finding is that there was no significant shared environmental overlapping of writing quality with syntactic as well semantic cohesion knowledge for beginning writers. One possible explanation for this could lie in statistical power limitations of our models. Path estimates indicating shared environmental overlap between syntactic and semantic cohesion knowledge to writing were relatively large (0.67 and 0.68, respectively), however non-significant and encompassed wide confidence intervals. Such results could reflect lower power of our models to detect shared environmental influences. Nevertheless, the present findings are compelling, but highlight the need for continued examination of specific aspects of home and school environments that influence writing and other writing components, in particular in elementary school.

4.3. Non-shared environmental influences on elementary and middle school writing

As expected, developmental phase of writing appears to be related also with non-shared environmental differences. Differences were indicated in the syntactic and semantic cohesion knowledge models, such that non-shared environmental effects were greater with more skilled writing. What are the potential reasons for that?

First, it is possible that the twins' individual reading experiences and print exposure contribute to these differences. As Graham's (in press) model of writing suggests, development of cognitive components of writing is partly shaped by one's own experiences. As such, extended reading experience and greater print exposure may help a twin become a fluent and proficient reader and use that knowledge in writing in elementary, but more so in middle school. Reading and writing are highly related (Berninger et al., 2002; Graham, in press; Jenkins, Johnson, & Hileman, 2004) and activate overlapping brain regions (Pugh et al., 2006). As independent reading provides an opportunity for incidental word learning (Fukkink et al., 2001; Swanborn & de Glopper, 1999), which results in a quantitatively and qualitatively richer lexicon (Stanovich, 1986), and because reading is a rich source of information, a twin might learn how to explore and develop ideas and how to write creatively. In fact, previous research has shown that 50% of the variation in reading exposure was due to shared environmental factors, and a further 40% was due to non-shared environmental factors (Harlaar, Dale, & Plomin, 2007).

In addition to reading experience, twin's personal experience might represent another explanation for larger non-shared environmental effects on writing and other writing components in middle school than in elementary school. As previously noted, advanced planning emerges in middle school writing (Berninger & Swanson, 1994). Organizing ideas and setting goals as part of the planning process in writing is associated with generating content. A twin generates content by searching for it in his/her long term-memory (Berninger & Winn, 2006; Limpo, Alves, & Fidalgo, 2014) according to his/her previous personal experiences, which might be different from his/her co-twin's. The exact nature of these non-shared environmental effects is unknown, though, and it is possible that non-shared environmental factors subsume measurement error, as is the case for all behavioral genetic modeling with measured variables.

Overall, non-shared environment emerged as the key element in accounting for individual differences in writing components as well as in the covariation among them in beginning and developing writing. This is consistent with other twin studies (Oliver et al., 2007; Olson et al., 2013) and implies that writing has non-shared environmental variance common with lexical diversity, syntactic knowledge, and semantic cohesion knowledge. In fact, estimates for non-shared environmental overlapping were by far largest across all three models, indicating that variability in writing and writing components is associated mainly with differences in non-shared environmental factors, regardless of the developmental phase of writing.

4.4. Educational implications

Our results indicate, first, the presence of developmental differences in etiology on writing components and, second, genetic and environmental overlapping between writing components and writing. These findings have implications for home and school environments. Evidence that genetic effects on writing increase with age, together with the evidence that genetically influenced variation in lexical diversity was related to writing achievement for middle schoolers should not be taken to imply that developing writing is determined by one's genetic makeup. On the contrary, genetic effects may disappear if the environment is changed. For educators, this implies that middle schoolers with genetic make-ups that put them at risk of developing atypically in writing should be provided with strategically designed environmental input, such as educational interventions, to at least partially compensate for genetic constraints. Under a simple intervention view, our results suggest the interventions should be targeted in particular to remediation of oral language knowledge, which underlies writing skills (Berninger & Winn, 2006; Kim et al., 2011, 2014, 2015).

Next, we found that shared environmental effects on writing drop with age. Such results indicate that home and school environment are particularly salient in initial phases of writing development. This confirms the findings in the phenotypic literature which showed that informal literacy environment at home predicted growth in English receptive vocabulary from kindergarten to first grade (Sénéchal & Lefevre, 2014), which in turn seems to be related with writing.

Finally, our results indicated an increase in non-shared environmental effects with age and a strong non-shared environmental overlap between writing components and writing in beginning and developing phases of writing development. If that is suggestive of twin's individual reading experiences and print exposure which are related to writing, then the goal of the instruction would, in part, be to support elementary and middle schoolers in engaging in such activities. This is in line with previous research which showed that reading and writing draw on similar knowledge, skills, and strategies (Shanahan, 2006). For example, readers acquire knowledge about the basic elements or features of a particular type of text as a result of reading such text (Shanahan, 2006).

4.5. Future directions and limitations

Other future directions and potential limitations for this study should be considered when interpreting the present results. As writing is a complex construct, it would be worthwhile to estimate relationships among latent factors, not observed, single variables. Estimates of relationships involving latent variables are more reliable as measurement error is accounted for (Loehlin, 2004), thereby reducing estimates of non-shared environment that owe to error. The current study should be viewed in light of its data-driven, exploratory design with the focus on gaining insights for additional investigation of etiological influences on various components of writing. Thus, its further expansion with latent factors and replication of current findings might be one of the future directions. Furthermore, inclusion of more than one writing task (one writing assignment) would be informative in future studies to account for measurement error associated with writing prompts (Kim, Schatschneider, Wanzek, Gatlin, & Al Otaiba, 2017). Relatedly, reliability of our writing measure could be further improved. Sim and Wright (2005) report arbitrary designations for the kappa coefficient, and the estimate of 0.63 falls within the range of substantial strength of agreement between raters (the next range is "almost perfect", range 0.81–1). It has to be noted, though, that the kappa coefficient is not on the same scale as other reliability coefficients (e.g. Cronbach's alpha). It is adjusted for chance agreement, whereas Cronbach's alpha, for example, is not, therefore the estimates of the kappa coefficients might, in general, be lower compared to other reliability coefficients.

A further caution while interpreting the results of our study is related to the writing task administration. There are many sources of variability that can contribute to variance in writing scores. A possible facet includes task-based factors such as the procedure for collecting writing tasks. While parents of the twins were given specific, detailed instructions on how to administer the task (e.g., twins should not receive additional help for writing from any of the family members; see Supplementary Materials, Procedure section), it is possible that not all parents and/or their twins followed the instructions verbatim. Thus, we were not able to perfectly control for potential parents' influence on the twins' written text production. However, based on our previous experience, parents do tend to follow the instructions and note any testing errors, including missed instructions. This provides us with some reassurance that this task-based factor might have not had a great influence on reliability of the writing. Nonetheless, future research needs to examine the role of this possible source of variance in the reliable assessment of writing outcomes. Another caution pertains to the writing genre. Our writing genre was a personal narration. Results may not be generalizable to other genres as cognitive demands and environments vary according to the genre (Kim et al., 2017). Thus, etiological factors found in the current study should not be treated as essentially uniform across all genres. Further caution relates to the correction of spelling errors prior to scoring for compositional quality. Graham et al. (1997) have noted that spelling errors might influence the evaluation of writing quality. Our raters were instructed and trained to use a rigorous coding frame for assessing writing quality, however that does not completely preclude from potential spelling bias in the scoring of writing quality.

Next, it would be interesting to expand the understanding of what explains our results by including correlates of different writing components. Reducing the inclusion of writing components to specific components, which are crucial in beginning and developing writing and are malleable in instructional settings, provides a useful means for presenting individual differences in writing for school aged children. However, it also has the potential disadvantage of obscuring their complexity and interrelationships. Theoretical models and empirical evidence has clearly indicated the importance of various writing components, such as transcription skills (i.e., spelling and handwriting fluency; Berninger & Winn, 2006; Graham et al., 1997; Kim & Schatschneider, 2017). Therefore, future work should aim to examine etiology of additional writing components.

Finally, our sample size by age groups was relatively small and limited in statistical power. This was reflected in large confidence intervals surrounding parameter estimates. For those estimates that are significant but encompassed in a wide confidence interval, caution should be taken when interpreting the magnitude of the estimate. Magnitudes fall in a range of potential estimates as suggested by the confidence intervals.

5. Conclusions

This study is the first to examine genetic and environmental influences that contribute to the covariation of writing with other writing components across beginning and developing phases of writing development. We have found that the transition from elementary to middle school writing involves an etiological difference in the factors that are important for variation and covariation of writing components in children. Genetic and non-shared environmental influences become more substantial, while shared environmental factors become less influential as children progress through writing development phases. Even though genes and shared environment accounted for variation and covariation of writing components, the present results suggest that non-shared environment (the child-specific aspects of the environment) plays the largest role in understanding children's performance in both beginning and developing writing. Thus, children's unique experiences with writing related activities, such as reading, may begin to explain the wide variability in writing observed among elementary and middle schoolers on national standards tests (NAEP, 2002, 2011).

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.lindif.2017.08.005.

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