4.

ARITHMETIC, READING AND WRITING PERFORMANCE HAS A STRONG GENETIC COMPONENT: A STUDY IN PRIMARY SCHOOL CHILDREN

Most research on educational achievement in children has focused on environmental factors and on differences between groups. However, even children taught by the same teacher differ greatly in their performance at school. Genetic research can address the extent to which these individual differences can be explained by genes or the environment. The current study aims to identify the impact of genes on variation in educational achievement in a large cohort of Dutch children (6 to 12 years). The Netherlands Twin Register has collected data on pupil monitoring tests used in all grades of primary school to measure a child’s educational achievement in four educational domains, i.e. arithmetic, reading, reading comprehension and spelling (1058 MZ and 1734 DZ twin pairs) and on an educational achievement test administered in the last grade (2451 MZ and 4569 DZ twin pairs). Genes were the most important cause of differences between children in arithmetic (60-74%), reading (73-82%) and reading comprehension (54-63%) across all grades. The common environment, i.e. socioeconomic status and the school environment had, in general, only a minor influence on educational achievement. In contrast, heritability of spelling was small in the first grade (33%), compared to later ages (58-70%), with a larger influence of the common environment (28%). Heritability of the educational achievement test was also large (74%) with a small influence of the common environment (8%). The heritability of children’s educational achievement in The Netherlands is surprisingly comparable to other countries despite major differences in educational systems and teaching methods.

INTRODUCTION

Children differ in their ability to learn the subject material that is taught at school; some master basic skills, such as reading and arithmetic, and pick up knowledge about science, history and biology much faster than their peers. Low educational achievement is associated with continued low achievement, school dropout and delinquency (Moilanen, Shaw & Maxwell, 2010). General cognitive ability is the most important predictor of educational achievement (Deary et al., 2007) and explains about half of the variation (Frey & Detterman, 2004). Most research towards educational achievement of children has focused on environmental factors, such as socioeconomic status (SES) of the parents and school characteristics, and on differences between groups of children, for example boys and girls (OECD, 2010). However, even children attending the same school and taught by the same teacher differ greatly in their performance at school. It may be less relevant to look at group differences when differences within a group are much larger. Causes for individual differences do not necessarily have to be the same as for average differences between groups. The main reason for mean differences in educational achievement between boys and
girls might be environmental whereas the cause for differences in performance between individual children may be largely genetic in nature.

Genetic research can address questions about the causes of individual differences among children and disentangle the extent to which these differences in educational achievement between children are explained by their genes or by the environment (Boomsma, 2013; Plomin et al., 2008). One of the most often used designs in behavior genetics is the twin study, which is based on the difference in genetic relatedness between identical or monozygotic (MZ) and fraternal or dizygotic (DZ) twin pairs. MZ twins develop from the same fertilized zygote and are genetically (nearly) identical while DZ twins develop from separate eggs and share, like non-twin siblings, approximately 50 per cent of their segregating genes. When MZ twins are more similar for a certain phenotype than DZ twins this constitutes evidence for the influence of genetic effects. The environment can be distinguished in the common environment, such as SES of the parents, which is shared between MZ as well as DZ twins, and make them more similar, and the unique environment (including measurement error), which is not shared between twins. When DZ twins are similar to the same extent as MZ twins the common environment has an influence on a phenotype. When MZ twins are dissimilar this indicates that unique environmental effects contribute to individual differences in a phenotype.

Numerous studies have demonstrated that genetic effects have a substantial influence on differences between children in general cognitive ability. It is well established that the heritability of general cognitive ability increases from approximately 40 to 65 per cent from childhood into adulthood (Haworth et al., 2010). Children, when they grow up, can more and more select their own environments based on their genetic make-up and this may be one explanation for this increase (Molenaar et al., 2013). General cognitive ability is often seen as an aptitude while reading, mathematics and spelling are taught at school and perceived as the outcome of education. Hence, it seems reasonable to expect that heritability of educational achievement is lower than the heritability of general cognitive ability. However, a recent study has shown that the opposite was true for primary school children in the United Kingdom (UK). Literacy and numeracy were significantly more heritable than general cognitive ability at ages 7 and 9, but no longer at age 12 (Kovas et al., 2013). The authors propose that the equal opportunities in the relatively homogenous education environment provided in Western societies acts to reduce environmental variation, making differences in educational achievement between children to a greater extent due to genetic differences.

Twin studies have mainly focused on the educational domain reading and, more recently, mathematics, while less is known about the heritability of other
educational domains, such as, spelling, reading comprehension and science. Most studies used teacher assessments or tests that had been administered by the researchers through the internet, telephone or during a home-visit while only some used standardized tests administered at school. Heritability of educational achievement in reading is moderate to high with modest common environmental effects (Byrne et al., 2013; Harlaar et al., 2012; Hart et al., 2013; Kovas et al., 2013) and the same is true for mathematics (Harlaar et al., 2012; Kovas et al., 2013). The twin studies towards educational achievement primarily included English speaking children from the USA and the UK. Studies from other countries with different educational systems and languages are scarce (Byrne et al., 2009; Chow et al., 2011). Previous research has established that languages differ in the complexity of their orthography and it is demonstrated that learning to read is more difficult in English than in other languages (Caravolas et al., 2013; Seymour, Aro & Erskine, 2003). The relationship between the printed words and phonemes in spoken words is least consistent in English. On the other hand, the number naming system is more consistent in English than it is in other languages which could positively influence learning to count and calculate compared to other countries (Göbel et al., 2014).

The question is whether the same pattern of estimates of the relative contribution of genetic and environmental effects to the variation in educational achievement exists in the Netherlands. (Calvin et al., 2012) found genetic effects to be an important cause of variation in educational achievement in the educational domains language (43-74%) and arithmetic (36-73%) at age 8, 10 and 12 in Dutch primary school children. However, they used a population cohort without information on zygosity and estimated the resemblance between monozygotic and dizygotic from the proportion of same-sex and opposite-sex twin pairs, but this method is much less powerful than a design in which zygosity is known.

In the Dutch educational system, the majority of primary schools use a pupil monitoring system that includes standardized tests assessing educational achievement (Cito, 2014a; Vlug, 1997). Tests are available for all grades and all important educational domains. The tests are independent of teaching methods and can be used to monitor a child’s educational development in comparison to peers and across grades and educational domains. Tests measuring arithmetic, reading, reading comprehension and spelling are, according to an inventory amongst teachers, the most informative with regard to the educational development of children (Polderman et al., 2011). A standardized educational achievement test is available for the last grade, measuring what a child has learned during all primary school years (Cito, 2002). Together, these data provide a unique opportunity to give an overview of the heritability of
educational achievement in different educational domains across primary school grades. Very few studies examined differences between boys and girls in the heritability of educational achievement, probably due to the small sample sizes. Quantitative gender differences are present if one gender is affected to a greater extent by the same genetic or environmental effects. Qualitative gender differences exist when different genetic or environmental effects have an influence on boys and girls. The aim of the current study is to identify the impact of genes and the environment on arithmetic, reading, reading comprehension and spelling in primary school in a large cohort of Dutch twins and to explore possible gender differences.

METHODS

PARTICIPANTS

The Netherlands Twin Register (NTR), established around 1987 by the Department of Biological Psychology at the VU University Amsterdam, registers approximately 40 per cent of all multiple births in the Netherlands. The parents of the twins receive a survey about the development of their children every two years up until the twins are 12 years old. Details about selection and response rates are described elsewhere (Bartels et al., 2007; Boomsma et al., 2002; Boomsma et al., 2006; van Beijsterveldt et al., 2013). Since 1999, at age 7, 9 and 12, when the twins attend primary school, parents are asked for their consent to approach the teacher(s) of their children. The survey sent to the primary school teachers consists of questions about behavioral and emotional problems, functioning at school and educational achievement. In addition, teachers are requested to provide information on results of the pupil monitoring tests. Results on a standardized educational achievement test, which is administered in the last grade of primary school, were also obtained from the teachers (Cito, 2002). Later, because results become available near the end of the last school year, parents were asked to report the scores of their children on this test.

Data on one of the pupil monitoring tests and/or the educational achievement test were available for 16234 children. We excluded children who had a disease or handicap that interfered severely with daily functioning (N=90) or attended specialized education (N=79), in the Dutch education system special schools are available for children who need extra care due to learning problems, physical and/or mental disabilities or a behavioral disorder, resulting in data for 7228 complete and 1609 incomplete twin pairs. One of the main reasons for incomplete data is that twins attend different classes or schools and only one of the teachers returned the survey.
The study included data of 2818 twin pairs of opposite sex. For same-sex twin pairs, the determination of zygosity status was based on blood or DNA polymorphisms (N=1363) or on parental report of items on resemblance in appearance and confusion of the twins by parents and others (N=4586). This last method can establish zygosity with an accuracy of approximately 93 per cent (Rietveld et al., 2000). Twin pairs for which zygosity was unavailable were excluded from the analyses (N=70). Data on the educational achievement test were available for the majority of these twin pairs (1113 MZm, 1132 DZm, 1338 MZf, 1149 DZf and 2288 DOS) and results for at least one of the pupil monitoring tests were available for approximately one third of the twin pairs (504 MZm, 465 DZm, 554 MZf, 428 DZf and 841 DOS).

**MEASUREMENTS**

The pupil monitoring system consists of tests to assess the educational achievement of a child in multiple educational domains (Cito, 2014a). The number of correct responses is converted in an ability score and these ability scores can be compared between grades to monitor a child’s development in comparison to peers and over time. Each test score is converted into an ability score with a measurement technique on the basis of item-response theory to ensure that the development in ability scores is on a single scale (Vlug, 1997).

The arithmetic test (grade 1 to 6) consists of a part in which children have to solve simple math problems within a short time period and a part with more complex math problems without a time limit. The test assesses general knowledge of mathematics and arithmetic and comprises written computational problems of addition, subtraction, multiplication and division and problems on the notion of measurements, time and money, and knowledge about fractions, ratios and percentages.

The reading test (grade 1 to 6) measures word decoding skills by counting the total number of individual words a child can correctly read aloud in 1 minute. The test consists of three levels of increasing difficulty and complexity. The first level includes words that are pronounced exactly as they are spelled, the second level includes also other monosyllabic words and the third level includes two or more syllabic words. This study uses the most difficult level of the test which is almost never administered in the first grade.

The reading comprehension test (grade 3 to 6) includes a large variety of different text types and genres with two different types of multiple choice questions. The test consists of a part in which a child has to read a number of short texts and answer questions related to the text and a part with parts of the text left blank that need to be filled out. The test tries to assess different components of reading processing by questions regarding both the facts and
events described in the texts as well as by questions about the purpose of the writer and the intended readership of the texts.

The spelling test (grade 1 to 6) measures both active, writing down the words, and passive, recognizing spelling errors, spelling. Active spelling is measured with a dictation by the teacher where a sentence is read aloud and a child has to write down a specific word from this sentence. Passive spelling is measured with multiple choice questions where a student has to choose the sentence in which the bolded word is spelled incorrectly.

The educational achievement test measures what a child has learned during all primary school grades (Cito, 2002). The results of this test are often used, besides the advice of the teacher, to determine the level of secondary education suitable for a child. The test consists of multiple choice items in four different educational domains, namely Arithmetic, Language, Study Skills and Science and Social Studies. All scores on the scales are standardized to percentile scores to correct for differences in the number of items across the years. The first three test scales are combined into a Total Score, which is standardized on a scale from 500 and 550. The Arithmetic scale includes items on numbers and operations, ratios, fractions and percentages, and measurements, geometry, time and money. The Language scale includes items on writing, spelling, reading comprehension and vocabulary. The Study Skills scale includes items on handling of study texts, handling of information, reading diagrams, tables and graphs and map reading. The Science and Social Studies scale includes items on geography, history and biology.

**STATISTICAL ANALYSES**

Models were fitted to the raw data in the R (R Core Team, 2014) package OpenMx Version 3.0.3 (Boker S.M. et al., 2012; Boker S.M. et al., 2011) with maximum likelihood estimation. The correlations between the MZ and DZ twins were estimated, separately for each gender, to evaluate the relative influence of genetic and environmental effects on educational achievement. A model that freely estimated all parameters, i.e. means, variances and covariances, separately for the different zygosity-by-gender groups, was fitted to the data (saturated model). Norms and questions have been updated regularly for the tests for arithmetic, reading comprehension and spelling, resulting in different means and variances across versions. To correct for these differences, means and variances were estimated separately across different versions. Mean and variance differences between boys and girls were tested in the saturated model (Purcell, 2002).

To gain further insight into the causes of individual differences in educational achievement of children in primary school, univariate genetic models were
fitted to the data for each educational domain and grade. The variation in educational achievement was decomposed into variance due to additive genetic effects (A), to common environmental effects (C) and to unique environmental effects (E) (Posthuma et al., 2003). Additive genetic effects are the sum of the effects of all genetic variants influencing educational achievement. Common environmental variance results from environmental effects that are shared by both members of a twin pair. Unique environmental variance results from environmental effects that are not shared by a twin pair. The variance components A, C and E were estimated separately for boys and girls. The variance components are expected to correlate differently for MZ and DZ twin pairs due to the difference in genetic resemblance (Figure 1). Since MZ twin pairs share (nearly) all their genes the correlation between the genetic effects of MZ twin pairs is fixed to 1.0. DZ twin pairs share approximately 50 per cent of their segregating genes and therefore the correlation between the genetic effects of DZ twin pairs is fixed to 0.5. The correlation between the genetic effects is estimated freely for DOS twin pairs as different genetic effects could have an influence on educational achievement in boys and girls. For both MZ, DZ and DOS twin pairs the correlation between the common environmental effects is fixed to 1.0.
**FIGURE 1** Path diagram representing the twin model

![Path diagram]

\[ \begin{align*}
A &= \text{additive genetic effects; C = common environmental effects; E = unique environmental effects; } \\
&= \text{rMZ = correlation between MZ twins; rDZ = correlation between DZ twins; } \\
&= \text{rDOS = correlation between DOS twins; } \\
&= \text{a = coefficient representing the path loading for the additive genetic effects; } \\
&= \text{c = coefficient representing the path loading for the common environmental effects; } \\
&= \text{e = coefficient representing the path loading for the unique environmental effects} \\
&= \text{Note: the coefficients of the path loadings are estimated separately for boys and girls}
\end{align*} \\
&= \text{In the subsequent models, the influence of the gender of the student on the variance components was tested in two ways. First, we tested whether the same genetic effects are important in boys and girls (qualitative gender differences) by fixing the correlation between the genetic effects of DOS twin pairs to be equal to the correlation for DZ twin pairs. Qualitative gender differences will result in a lower genetic correlation between DOS twin pairs. Second, we tested whether the genetic effects had an influence to the same extent in boys and girls (quantitative gender differences) by fitting a model, which incorporates total variance differences, but does not allow the relative contribution of the variance components to be different between boys and girls. Quantitative gender differences will result in unequal variance components between boys and girls. Finally, the significance of the common environmental effects was tested by dropping them from the model. The difference in model fit between the nested}
\]
models was assessed with a log-likelihood ratio test (LRT) which calculates the difference in \(-2\log\text{-}likelihood\) \((-2LL)\) and evaluates this \(\chi^2\)-statistic with the difference in the number of estimated parameters between the models as degrees of freedom. A \(p\)-value smaller than 0.01 was considered significant. Constraints were kept, when a more restrictive model did not significantly decrease the goodness of fit, as a more parsimonious model is preferred.

RESULTS

Table 1 gives the means and standard deviations of scores on the pupil monitoring tests across all grades and the educational achievement test, for boys and girls separately and for the old and the new version of the tests. There were significant gender differences for arithmetic and reading comprehension in most grades. Boys were better at arithmetic and girls performed better on the reading comprehension tests. Gender differences were also present for all scales of the educational achievement test. Boys scored higher on arithmetic, study skills and science and social studies while girls obtained better results for language.

Twin correlations were estimated in the five zygosity-by-gender groups and could be equated between the different versions of the tests (Table 2). All MZ correlations were higher than DZ correlations, suggesting additive genetic effects. Sometimes DZ correlations were larger than half the MZ correlations, suggesting common environmental effects. The genetic model fitting results with the standardized estimates and their 95\% confidence intervals are reported for arithmetic, reading, reading comprehension and spelling across grades and an educational achievement test administered in the last grade of primary school (Table S1). The full model showed small differences between boys and girls in the heritability estimates, but these were not significant for all but one test, spelling in grade 5. The relative contribution of the additive genetic, common environmental and unique environmental effects are displayed for the models estimating all variance components equal for boys and girls while allowing total variance differences (Figure 2).
TABLE 1 Means and standard deviations of the educational achievement test scores

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TABLE 2 Twin correlations for arithmetic, reading, reading comprehension, spelling and educational achievement

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MZm = monozygotic male twin pairs; MZf = monozygotic female twin pairs; DZm = dizygotic male twin pairs; DZf = dizygotic female twin pairs; DOS = dizygotic of opposite sex twin pairs; N= number of (in)complete twin pairs
FIGURE 2 The relative contribution of the genetic, common environmental and unique environmental effects for arithmetic (A), reading (B), reading comprehension (C), spelling (D) and educational achievement (E).
Genetic effects were the most important contributor to individual differences in educational achievement in arithmetic (60-74%), reading (72-82%) and reading comprehension (54-63%) and for most grades in spelling (33-70%). Common environmental effects had a negligible influence on arithmetic (0-8%), reading (0-7%) and reading comprehension (2-12%) and a slightly larger influence on spelling (0-29%). Unique environmental effects explained the remaining variance in arithmetic (26-34%), reading (11-29%), reading comprehension (32-35%) and spelling (30-39%). Genes were also the largest contributor to the variation in the educational achievement test (74%). The heritability differed somewhat between the educational domains measured with this test, i.e. arithmetic (68%), language (67%), study skills (60%) and science and social studies (56%). The common environmental effects were also small for the total score (8%), arithmetic (5%), language (10%), study skills (6%) and science and social studies (21%). Unique environmental effects explained the remaining variance (18-34%).

DISCUSSION

The current study presents the heritability of educational achievement in several educational domains across primary school grades 1 to 6, corresponding to ages 6 to 12, in a large, representative cohort from The Netherlands. The influence of the genetic and environmental effects was systematically examined for the educational domains arithmetic, reading, reading comprehension and spelling. The extent to which genes influenced differences in educational achievement was large and relatively stable across all grades for arithmetic (60-74%), reading (72-82%) and reading comprehension (54-63%). Similar heritability estimates were obtained at all ages despite large differences in content across grades. In contrast, the heritability of spelling was smaller in the first grade (33%) compared to later ages (58-70%). Heritability of the educational achievement test in the last grade was high, higher than estimated in a partly overlapping, but considerably smaller, sample (74 vs 57%) while the influence of the common environment was slightly lower (8 vs 27%) (Bartels et al., 2002). There was a noteworthy difference between the heritability of the specific domains included in the educational achievement test. Science and social studies, i.e. geography, history and biology, showed somewhat lower heritability estimates and a larger influence of the common environment compared to arithmetic and language. This is also observed in earlier research towards science performance which too is not one of the core educational domains, e.g. writing, reading and mathematics (Haworth et al., 2008).
Traditional mean gender differences in educational achievement were observed with boys scoring better on numeracy and girls performing better at some of the literacy subjects (Cito, 2014b; OECD, 2010). There was no consistent indication for the presence of quantitative gender differences, meaning that the extent to which genes and the environment influence educational achievement is similar across gender. Qualitative gender differences were also not present which means that the genes that have an influence on educational achievement are the same for boys and girls. The absence of gender differences in the heritability of educational achievement is in line with other studies that estimated the magnitude of the effects for genes and the environment separately for boys and girls (Harlaar et al., 2005).

The twin method assumes that MZ twins are more similar in educational achievement than DZ twins because of their larger genetic resemblance and not because MZ twins are treated more alike, by for example teachers, than DZ twins or experience more similar environments. This equal environment assumption is potentially violated if this similarity in treatment and environment relates to a similarity in a phenotype. Research has shown that the equal environment assumption holds for, amongst others, general cognitive ability and educational achievement (Evans & Martin, 2000; Loehlin, 1989). To be able to generalize the outcome of twin studies to the general population, the twin method further assumes that twins are representative of the general population for the phenotype of interest. Twins do differ from singletons in striking ways with regard to birth conditions. Twins are born, on average, 3-4 weeks prematurely and have approximately 1 kg lower birth weights (Martin et al., 2010). These differences dissipate fairly early on, however, and, already in childhood, twins and singletons have very similar scores for body size (Estourgie-van Burk et al., 2010) and, more relevantly, for general cognitive ability (Webbink et al., 2008) and educational achievement (Cohen et al., 2002; de Zeeuw et al., 2012).

Heritability estimates are always limited to the population in which they have been assessed. The relative contribution of genes and the environment to the variation in educational achievement will be different when either the genetic effects are different or the environmental effects differ, for example, due to differences in SES, national curriculum or educational opportunities. Differences across countries may lead to a relatively larger or smaller role of the environment. The observed heritability estimates for educational achievement in the Netherlands are surprisingly comparable to other countries despite major differences in educational systems and societies. The educational system in The Netherlands is more similar to the one implemented in the UK, both countries have a national curriculum, while the educational system in the USA is more
decentralized. A national curriculum could restrict the variation in school environments leading to an increase in the relative contribution of genes to the variation in educational achievement. Differences in heritability for educational achievement between countries might also be explained by differences in society. Several studies have found that the heritability of general cognitive ability is larger in children from middle and upper class families while environmental effects have a larger influence in children from lower income families (Scarr-Salapatek, 1971; Turkheimer et al., 2003). Children from low SES families more often live in bad neighborhoods and are less likely to attend good quality schools. The inequality in income, educational opportunity and circumstances under which children grow up is larger in the USA and the UK compared to the Netherlands. If SES moderates the heritability of educational achievement as it does that of general cognitive ability, a lower percentage of children from disadvantaged groups will lead to a higher heritability of educational achievement.

The common environment had a minimal influence on educational achievement. Nonetheless, the fact that there was evidence for the existence of influence of the common environmental effects on some of the educational domains, just as for general cognitive ability (Deary, Johnson & Houlihan, 2009), is of interest as it is in contrast with what is observed in many other developmental domains, such as personality or psychopathology (Plomin, Asbury & Dunn, 2001). However, growing up with the same parents, SES, attending the same school and even being taught by the same teacher did not seem to contribute much to individual differences between children in educational achievement. The absence of a main effect of the common environments still leaves open the possibility that the school environment indirectly contributes to such individual differences. The same teacher, classroom and peers may be experienced rather differently by children transforming these shared environmental factors into unique environmental effects. Furthermore, there could still be an influence of the common environment due to gene-environment (GxE) interaction, when heritability depends on, for example, SES of the parents (Kendler & Eaves, 1986).

Which aspects of the learning environment make children different in their ability to learn at school still needs to be determined. Earlier research has suggested that the relationship between a student and a teacher might be one of these factors as it plays an important role in motivating children to perform well at school (Turner et al., 2002). A study design using the differences within monozygotic twin pairs can be used to identify these unique environmental effects which have an impact on educational achievement (Asbury, Dunn & Plomin, 2006). Knowledge of the factors in the classroom, which are
experienced differently by children, that contribute to differences in the educational achievement may provide opportunities to develop interventions in the school environment to realize each child’s learning potential.
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#### 2 ACE: rA\_DOS = rA\_DZ

| Boys | Girls | 8 | 9671.34 | 1174 | 1 | .03 | .861 | .55 [.28-.85] | .28 [.00-.54] | .16 [.12-.23] |
|------|-------|---|---------|------|---|----|----|--------|-------------|------------|-------------|

#### 3 ACE: Boys = Girls

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### Reading Comprehension

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#### 2 ACE: rA\_DOS = rA\_DZ

| Boys | Girls | 11 | 21731.97 | 2720 | 1 | .09 | .768 | .49 [.24-.70] | .15 [.00-.37] | .35 [.29-.43] |
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#### 2 ACE: rA\_DOS = rA\_DZ

| Boys | Girls | 11 | 17165.00 | 2156 | 1 | .02 | .899 | .49 [.25-.75] | .23 [.00-.44] | .28 [.22-.35] |
|------|-------|---|---------|------|---|----|----|--------|-------------|------------|-------------|

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#### 4 AE: Drop C

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