Tracking the Serial Advantage in the Naming Rate of Multiple over Isolated Stimulus Displays

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Abstract

The serial advantage, defined as the gain in naming rate in the serial over the discrete task of the same content, was examined between grades and types of content in English and Greek. 720 English- and Greek-speaking children from Grades 1, 3, and 5 were tested in rapid naming and reading tasks of different content, including digits, objects, dice, number words, and words. Each type of content was presented in two presentation formats: multiple stimulus displays (i.e., serial naming) and isolated stimulus displays (i.e., discrete naming). Serial tasks yielded faster naming rates—irrespective of task content—in both languages. However, content-specific characteristics influenced the trajectory of the serial advantage between grades. Improvement in the serial advantage between grades was found to be greatest for word reading, which started off similar to object naming in Grade 1, but ended up similar to digit or dice naming by Grade 5. In addition, growth in serial advantage was found to be associated with growth in discrete naming rate only in grade level analysis. For individuals, greater serial advantage was found to rely on processing skills specific to serial naming rather than on differences in the rate of naming isolated items. Our findings suggest that group level findings may not generalize to individuals, and although practice and familiarity with the content on the naming/reading task may impact the development of serial advantage, isolated item identification processes contribute little to individual differences in the gain in serial naming rates.

Keywords: cross-linguistic, discrete naming, naming rate, rapid automatized naming, serial naming, word reading

Tracking the Serial Advantage in the Naming Rate of Multiple over Isolated Stimulus Displays

Rapid automatized naming (RAN) refers to the ability of an individual to name rapidly and accurately a matrix of a small set of familiar stimuli, such as letters, digits, objects, or colors (Kirby, Georgiou, Martinussen, & Parrila, 2010). Previous studies have shown that multiple stimulus displays (as in RAN tasks) yield faster naming rates compared to isolated stimulus displays (as in discrete naming tasks), at least among typically-developing children (Zoccolotti et al., 2013) or adults (Jones, Branigan, & Kelly, 2009). This has been termed *serial advantage* (see Altani, Georgiou, et al., 2017). To date, the serial advantage has been documented with alphanumeric (e.g., digits), nonalphanumeric (e.g., colors), and/or orthographic stimuli (words), mainly among older children (see Zoccolotti et al., 2013; Zoccolotti, De Luca, & Spinelli, 2015) or individuals with dyslexia (e.g., Gasperini, Brizzolara, Cristofani, Casalini, & Chilosi, 2014). The serial advantage is a conceptually useful tool in thinking about why serial naming is faster than discrete naming: As illustrated in Figure 1, it transparently corresponds to the degree of temporal overlap (i.e., parallelism) in the processing of successive stimuli, which is only possible in serial naming due to the simultaneous presentation of all the stimuli.

It remains unknown how the serial advantage develops across different grade levels (including younger and older children), different naming materials, and different languages. A few previous studies have reported an asymmetry in the improvement of performance in serial over discrete naming tasks—with serial naming showing a steeper growth—across elementary school grades (Logan, Schatschneider, & Wagner, 2011; Protopapas, Altani, & Georgiou, 2013; Protopapas, Katopodi, Altani, & Georgiou, 2018). If serial naming improves more than discrete naming, another way to state the same fact is that the serial advantage increases in higher grades. From this perspective we can then examine the conditions and correlates of relative growth, expressed as a difference between formats. Thus, our study focuses on quantifying the serial advantage (expressed as the concurrent difference between serial and discrete naming rate) and identifying the factors that are associated with its growth. In particular, we examine the serial advantage in naming digits, dice, number words, objects, and words in a group of Grade 1, 3, and 5 Greek- and English-speaking children.

Although it is well established that RAN is a strong predictor of reading (Kirby et al., 2010; Araújo, Reis, Petersson, & Faísca, 2015) and reading difficulties (Araújo & Faísca, 2019), researchers also concur that their relationship varies as a function of the presentation format of the reading and naming tasks (e.g., de Jong, 2011; Protopapas et al., 2013). For example, word list reading fluency correlates more strongly with serial naming (RAN) than with discrete naming (e.g., Altani, Protopapas, & Georgiou, 2017; de Jong, 2011). This format-specific association seems to apply across various naming tasks. That is, among older children or skilled readers, naming tasks of different content, but same presentation format, correlate more strongly with each other (i.e., serial with serial and discrete with discrete) than naming tasks of the same content, but of different presentation format (Protopapas et al., 2013, 2018).

In contrast, associations between serial- and discrete-trial versions of the same content are not necessarily stable across grades. For example, naming multiple word displays and naming isolated words are strongly associated among beginning readers, but only moderately so among advanced readers (Protopapas et al., 2013). In fact, the association between serial and discrete naming of either words or digits has been reported to decrease with increasing skill (Altani, Protopapas, & Georgiou, 2018). These findings suggest that when a certain proficiency level is achieved, individual differences in serial naming are in part independent from individual differences in discrete naming of the same material (see also Bowey, McGuigan, & Ruschena, 2005). This evidence has led researchers to argue that there might be a distinct skill specific to the sequential processing component of the serial naming tasks (i.e., RAN), which is crucial for the development of fluent performance in multiple stimulus naming beyond the efficiency of naming the same stimuli in isolation.

It has also been claimed that not only the standard RAN tasks, but also word list reading (and presumably text reading) can be viewed as a serial rapid naming task, in the sense that both word recognition of individually-presented words and processing of sequences of multiple items need to become efficient for the successful reading of word lists or text (which is how reading fluency is typically assessed; see Altani, Protopapas, Katopodi, & Georgiou, 2019; Protopapas et al., 2018; Zoccolotti, De Luca, Marinelli, & Spinelli, 2014).[1] This view originates from the idea that individuals need to be able to process multiple stimulus displays (words or other symbols) efficiently performing both parallel and sequential processes. This coordination of multiple elements and processes both in parallel and serially has been termed *cascaded processing* (Protopapas et al., 2013) and is supported by evidence from eye movement studies with oral word reading or digit naming, showing that eyes are ahead of the voice, yet under very tight control (Gordon & Hoedemaker, 2016; Laubrock & Kliegl, 2015). Hence, different processing stages of adjacent words or symbols within a sequence may occur both in parallel and sequentially, resulting in a partial temporal overlap. This also implies that the processing stages of each stimulus within a sequence of a serial naming task are not executed in a strictly serial manner but can overlap in time for successive stimuli, so that the processing of the next stimulus can begin before the processing and production of the previous one is completed. In accordance with the logic illustrated in Figure 1, this overlap corresponds to the serial advantage observed

[1] In some psychometric batteries (e.g., The Process Assessment of The Learner; Berninger, 2007) RAN is even assessed with word naming.

with word stimuli, that is, to the faster performance in reading word lists compared to reading the same words in isolation (for nonbeginner readers; Protopapas et al., 2018; Zoccolotti et al., 2013, 2015). Thus, from this perspective, the study of the serial advantage, its origins and correlates, in comparison between word reading and symbol naming tasks, aims to help us understand the development of reading fluency over and above isolated word reading efficiency (cf. Altani et al., 2019).

The theoretical connection between the observed serial advantage and the aforementioned format-specific associations in naming tasks is far from straightforward. The fact that performance is correlated across serial naming tasks, regardless of content, and that serial naming is faster than discrete naming can be thought to originate in cascaded (i.e., temporally overlapped) processing of successive stimuli (see Gordon & Hoedemaker, 2016; Protopapas et al., 2018; see also Henry, van Dyke, & Kuperman, 2018; Kuperman, Van Dyke, & Henry, 2016). Cascaded processing efficiency is thought to constitute a distinct skill domain, which develops somewhat independently from discrete naming skills and governs performance in serial tasks. Nevertheless, serial and discrete naming tasks are correlated, obscuring the nature of the observed serial advantage, which is meant to express their difference rather than their common elements. In particular, the extent to which individual differences in the serial advantage in naming tasks might depend primarily on individual differences in the discrete or the serial dimension of the naming task remains unknown.

On the other hand, despite their format, naming tasks can be further divided into different categories based on their content, for example, into alphanumeric (digits, letters) and nonalphanumeric (objects, colors) naming tasks (Araújo et al., 2015). This distinction is supported by evidence showing that: (a) alphanumeric and nonalphanumeric tasks load on different factors (Donker, Kroesbergen, Slot, van Viersen, & de Bree, 2016; Rodríguez, van den Boer, Jiménez, & de Jong, 2015; van den Bos, Zijlstra, & Spelberg, 2002); (b) alphanumeric naming tasks correlate more strongly with reading tasks than nonalphanumeric naming tasks (Araújo et al., 2015); and (c) naming multiple stimulus displays is generally faster for alphanumeric than for nonalphanumeric material, at least in elementary school grades (Albuquerque & Simões, 2010; Bowey et al., 2005; van den Bos et al., 2002). It has thus been argued that the alphanumeric and nonalphanumeric stimuli differ not only in the time they are learned, but also in the nature of the sets from which they are derived (see Kirby et al., 2010). Protopapas et al. (2018) also claimed that differences between kinds of stimuli impact the degree of efficient sequential processing in multiple stimulus displays during RAN-type tasks, based on the level of individual processing efficiency and their contextual availability.

In a similar vein, when examining 10-year-old children with dyslexia vs. controls, Pan et al. (2013) found no significant differences between the groups in serial naming of number words depicted as dice surfaces. Instead, significant differences were detected between the groups during naming of the same number words depicted as digits. This suggests that—although the phonological representations were the same—dice were processed differently from digits, in a way that the former required semantic access prior to lexical retrieval, a property shared with nonalphanumeric stimuli such as objects (Jones, Branigan, Hatzidaki, & Obregón, 2010; Liu & Georgiou, 2017); whereas digit naming could proceed via direct (arbitrary) mapping from visual to phonological codes (Roelofs, 2006), a property that alphanumeric stimuli share with (reading of) familiar words. In other words, naming task content patterns into different types that are hypothesized to be differentially processed with implications for serial naming efficiency that may impact the development and magnitude of the serial advantage. Thus, in the present study we included alphanumeric, nonalphanumeric, and orthographic stimuli and anticipated that the trajectory of the serial advantage across grades would be influenced by the task content.

In summary, previous evidence shows that task content and task format matter as to how naming and reading tasks are carried out. Yet, only recently was it pointed out that because of their differential processing requirements, serial- and discrete-trial naming tasks across grades offer a potential model for tracking multi-element vs. single-element processes in reading throughout development (de Jong, 2011; Protopapas et al., 2013, 2018). In particular, word list reading fluency can be modeled as a serial naming task to the extent it is dominated by the common processes of visual recognition, phonological mapping via lexical access, and articulatory planning and execution, rather than by an effort in sublexical graphophonemic decoding. That is, as soon as words are read “by sight”, effectively treated as single items rather than complex sequences, going through a list of words and reading them aloud is very similar to going through a list of digits and naming them (see van den Bos, Zijlstra, & van den Broeck, 2003). As fluency emerges, the transfer of burden from intra-item (or intra-word) to inter-item (or inter-word) processing should be evident in the development of a serial advantage in word reading, in parallel with the overall development of the serial advantage across naming tasks indexing efficient sequential processing skill.

The Present Study

We aimed to examine the development of serial advantage, expressing the gain in naming rate when comparing multiple vs. isolated stimulus presentation, across five different kinds of naming material (digits, objects, dice, number words, and words) and three grade levels (Grades 1, 3, and 5). Serial advantage is defined as the benefit in performance during the serial-trial version of the task compared to the corresponding discrete-trial format. In the context of the present study, serial advantage refers to the difference between the serial and discrete naming rate of the same task content, as measured in items per second, that is, number of elements per unit time.

More specifically, we had two main objectives. First, we aimed to examine differences in serial advantage between different grades and different types of content. We specifically hypothesized that serial advantage would increase significantly in higher grades, confirming the asymmetry in the increase of the serial naming rate compared to the discrete naming rate across material types. Additionally, we examined the interaction between grade and task content to examine whether content-specific characteristics influence the trajectory of the serial advantage. If the serial advantage is content-specific, then we should observe different trajectories across grades for different naming materials. Otherwise, similar trajectories of serial advantage development should be observed across naming tasks irrespective of their content.

Second, we sought to examine how the correlation between naming tasks of the same content, but of different format, might be associated with their corresponding serial advantage and, subsequently, whether the serial advantage is mainly determined by individual differences in the discrete or the serial component of the naming task. Specifically, we hypothesized that if serial advantage depends on the increasing naming rate of individual stimuli (displayed in isolation), then we should observe a positive association between serial advantage and discrete naming rate across grades. Alternatively, if the serial advantage is determined by a distinct skill concerning sequential processing of multiple stimulus displays, then we should observe a stronger association between serial advantage and serial naming rate.

Finally, we sought to examine these research questions in two languages differing in the level of orthographic transparency (English being opaque and Greek being relatively transparent;

Seymour, Aro, & Erskine, 2003). If similar patterns of results are observed in these two languages, then we can reasonably assume that findings concerning the development of the serial advantage in word and symbol naming generalize to alphabetic orthographies and cannot be attributed to language specific aspects related to the consistency of the orthography.

As a terminological clarification, the terms *serial naming* and *discrete naming* are used in this article to refer to tasks in the respective format, regardless of the type of material to be named or read aloud. In other words, they also refer to tasks of reading (aloud) words in lists (serial word reading) or in isolation (discrete word reading). In this context, serial word reading—a measure of word list reading fluency—is conceived of as a special kind of serial naming task, and discrete word reading as a special kind of discrete naming task, in which individual items consist of letter strings (and each string occurs only once). We will henceforth use the terms “word naming” and “word reading” interchangeably to refer to the (serial and discrete) tasks of reading aloud unconnected words.

Methods

Participants

Our participants were 720 children attending Grades, 1, 3, and 5, from two different sites: Canada and Greece. A sample of 409 English-speaking children was recruited in Edmonton (Alberta), and a sample of 311 Greek-speaking children in Athens.[2] Age and gender information in each grade and site are presented in Table 1. All participants were native speakers of their respective language and were recruited from public schools typically serving middle-class families. Both parental and school consent was obtained in each research site prior to testing.

[2] The same English and Greek datasets (or subsamples) have been used in previous studies (Altani et al., 2017a, 2018, 2019; Protopapas et al., 2018) to address different research questions with different analyses.

Protocol approval was also obtained for each site prior to testing.

Materials

Ten tasks were administered: Five naming tasks of different content presented in two formats, namely serial (multiple stimulus displays) and discrete (isolated stimulus displays). Materials consisted of three types of stimuli: alphanumeric, nonalphanumeric, and orthographic stimuli (see Figure 2). Alphanumeric stimuli included four digits (2, 3, 5, 6). Nonalphanumeric stimuli included four images of objects and four images of dice. Orthographic stimuli consisted of four number words and two sets of 36 high-frequency, short words. We used the same four words across the conditions of digit, dice, and number word naming. Object words and all words included in the word reading tasks were matched with the four number words in psycholinguistic variables (e.g., syllabic structure, word-length, frequency, and number of phonemes) to minimize differences in naming requirements (lexical access and articulatory planning) as a potential confounding variable across conditions (see Table S1 in Supplementary Material). Because of the matching requirements, dictated by the number words in each language, and the restriction to the range 1–6 for the dice, all English stimuli were monosyllabic whereas all Greek stimuli were bisyllabic. Object images were derived from a corpus of black-and-white drawings from the Center for Research in Language & International Picture-Naming Project (see Székely et al., 2004), including validated items from various sources with norms across a range of languages (see Bates et al., 2003; Székely et al., 2002), as well as from a subset of stimuli included in the standardized RAN/RAS battery (Form B; Wolf & Denckla, 2005).

Procedure and Apparatus

Each of the naming and reading tasks consisted of 36 items and was administered in two presentation formats: in a serial-trial and a discrete-trial format (see Figure 3). In the serial format, all stimuli were presented simultaneously on a computer screen, in a grid format of 4 rows × 9 items. Participants were asked to name (or read aloud), as fast and as accurately as possible, all presented stimuli starting from the first item on the top left corner and working row-by-row until the last item of the grid. The total naming time until the completion of the entire task was recorded. In the discrete format, stimuli were presented one-by-one, in the middle of the screen. Participants were asked to name (or read aloud), as fast and as accurately as possible, each stimulus—as soon as the item appeared on the screen. The total response time for each item was recorded, including onset latency and articulation, in order to match the serial naming data. The appearance of the next stimulus was controlled by the experimenter via pressing a key, following a complete response of the stimulus. Prior to testing, familiarity with the specific items and the discrete vs. serial trial procedure was ensured. During testing, four practice items preceded each trial (for both formats) to ensure compliance with the demands of the task and familiarity with the intended names of the stimuli. The order of the trials was pseudorandomly determined, the same for all participants, with the restriction that the same item could not appear in consecutive trials (in the discrete format) or adjacent positions (in the serial format). All ten tasks were administered to all participants in individually randomized order.

Participants were seated in front of a 15.4 inches computer laptop screen. The experimental software DMDX (Forster & Forster, 2003) was used for stimulus presentation and response recording. Vocal responses were recorded via a headset microphone (Logitech USB H340 or Sennheiser PC131). Each participant was tested individually in a private and quiet room provided by the school, during school hours, either by the first or the third author, or by trained assistants. Individual testing took approximately 30 to 50 minutes depending on the participant's grade level. Data collection took place during the last trimester of the academic year (April to

June). A consistent protocol was followed across sites.

Results

Data Extraction and Preparation

Response times and accuracy were determined off-line using Check Vocal (Protopapas, 2007). For serial tasks, response time consisted of the completion time of the entire task, including articulation duration and any intermediate pauses. Both correct and incorrect responses were included. For discrete tasks, response time consisted of both onset latency and articulation duration. Thus, both serial and discrete trials included the time required for response preparation and response execution. Finally, response times were transformed into a scale of “item per second” by inversion. Specifically, for discrete tasks, we averaged naming rate over the correctly named items to compute a mean response for each person and task; while, for serial tasks, we divided the serial rate by 36 (the number of items presented in each of the serial trials) to acquire comparable scales across serial and discrete trials. Hence, all of the following results refer to *rate* (i.e., number of stimuli named or read per second). This transformation was made in order to better approximate a normal distribution (see Supplementary Figures S3 and S4), resulting in an interpretable ratio scale of measurement with meaningful parametric indices of central tendency and dispersion (i.e., mean and standard deviation, respectively).

All statistical analyses were performed using R version 3.4.1 (R Development Core Team, 2017). First, we inspected the proportion of errors in discrete tasks to examine the level of accuracy in naming each type of stimuli (see Figures S1-S2 in Supplementary Material). Participants with error rate higher than 30% in two or more naming tasks (English: 56 children in Grade 1; [3] Greek: 3 children in Grade 1, 5 children in Grade 3, and 2 children in Grade 5) were

[3] A minimum level of 70% correct in word reading/word naming has been reported as a reliable

excluded from subsequent analyses. Additionally, a small number of individual data points were removed, associated with outliers based on the examination of quantile-quantile (Q-Q) plots per task and grade, or with low accuracy on individual tasks (English: 1 data point in Grade 1, and 5 in Grade 3; Greek: 4 data points in Grade 1, and 4 in Grade 5). Descriptive statistics for the final dataset are reported in Table 2. Examination of Q-Q plots (Figures S3-S4) and Anderson-Darling (Table S2) tests indicated good approximation to the normal distribution, with at most minor deviations.

Serial Advantage for Each Task

Serial advantage refers to the rate difference between the two different formats, that is, the serial naming rate minus the discrete naming rate for each content type. *Serial naming rate* is the performance, expressed as number of items named per second, when items are presented simultaneously, in a grid format; *discrete naming rate* is the mean performance, expressed as number of items named per second, when items are presented individually, in isolation. This difference[4] describes the gain in serial compared to the discrete-trial format per task content, aiming to capture the hypothesized temporal overlap in processes taking place during the serial naming task (see Figure 1). (Descriptive statistics for this new set of variables are available in the Supplementary Material, Table S3.)

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threshold before speed variability can emerge (Altani et al., 2019; Juul et al., 2014). To retain a consistent sample across conditions, all data from first graders in English with more than 30% errors in word naming were removed from subsequent analyses.

[4] Use of difference scores has been criticised on a variety of methodological grounds (e.g., Edwards, 1994, 2001). One important concern relates to their reliability, which is typically lower than that of the original variables. However, it has been recently argued that, even though there are often preferable alternative approaches, such concerns may have been overstated in the general case (especially in group comparisons; Thomas & Zumbo, 2012), and much depends on the actual reliabilities and intercorrelations of the subtracted measures in each particular case (Gollwitzer, Christ, & Lemmer, 2014; Trafimow, 2015). In the present study, we focus on the difference between the two formats because it directly corresponds to the hypothesized overlap.

Group Differences in Serial Advantage

Mean serial advantage per task content and grade is displayed in Figure 4, for both languages. We first performed targeted linear contrasts to examine (a) whether there are significant differences in the serial advantage between successive grades for each type of content, and (b) whether this difference in the serial advantage between grades is further influenced by the task content.

Overall, serial advantage appears to gradually increase across grades in both English and Greek. To examine whether the serial advantage differs significantly between successive grade levels per task content, we performed a set of multiple linear contrasts, using function glht of package multcomp v. 1.4-8 (Hothorn, Bretz, & Westfall, 2008) on a mixed-effects model of the serial advantage, as a dependent variable, with grade level and task content as independent variables (interacting fixed effects), and random effects of task content nested under participants, using function lme of the nlme package v.3.1-131 (Pinheiro, Bates, DebRoy, Sarkar, & R Development Core Team, 2017) with single-step adjustment of *p* values for multiple comparisons. The results (Table 3) showed that serial advantage differed significantly between Grades 1 and 3 for all types of content in both languages. That is, there was a significantly larger gain in children's naming rate in the serial format compared to the corresponding discrete format–irrespective of task content. Serial advantage was also significantly greater in Grade 5 compared to Grade 3, except for object naming in both languages, and for number words and dice in English.

However, the pattern seen in Figure 4 suggests that serial advantage follows different trajectories in different types of content, concerning both their starting point (in Grade 1) and the magnitude of the increase (in successive grades). For example, a substantial serial advantage in digit naming is already evident in Grade 1 in both languages. In contrast, serial advantage in words and objects seems to start off much lower in Grade 1 compared to the other tasks. Yet, this initial smaller serial advantage in words is followed by a steep increase in the following two grades, greatly exceeding the corresponding serial advantage in objects and gradually approaching serial advantage of digit and number word naming in English, or dice naming in Greek. In comparison, serial advantage in object naming continues to lag behind, across grades, compared to the rest of the tasks.

Next, we further examined how the serial advantage develops for different types of material. Hence, a second set of contrasts tested the interaction between grades and task content, using function contrast of package lsmeans v. 2.27-62 (Lenth, 2016) on the same mixed-effects model as above, with the multivariate t (mvt) method of *p* value adjustment for multiple comparisons. That is, we examined whether differences in serial advantage between successive grades were different for different task contents. Serial advantage differences between Grades 1 and 3 were found to be significantly greater for words than for objects (English: $t = 6.582$, $p < .001$; Greek: $t = 6.273$, $p < .001$) or dice (English: $t = 4.638$, $p < .001$; Greek: $t = 4.241$, $p < .001$). The increase between Grades 1 and 3 for number words was also greater compared to that for objects (English: $t = 4.111$, $p < .001$; Greek: $t = 6.861$, $p < .001$) and dice (only in Greek: $t = 4.829$, $p < .001$). In contrast, the different content of the naming tasks did not cause differential development of serial advantage between Grades 3 and 5. All comparisons (task content pairs fully crossed with successive grade pairs) are listed in Supplementary Material (Table S4). Direct statistical comparisons of serial advantage development slopes between languages, for each type of material, are also listed in Supplementary Material (Tables S5 and S6).

In sum, serial advantage was found to grow significantly in higher grades, with a few important exceptions (such as object naming in both languages) of no significant change between Grades 3 and 5. Task content affected the magnitude of the increase in serial advantage between Grades 1 and 3. Specifically, tasks with orthographic stimuli (words, number words) yielded greater difference in serial advantage between first and third graders compared to the corresponding change in serial advantage for the nonalphanumeric naming tasks (objects and dice) between the same grades.

Furthermore, we sought to examine whether the serial advantage depends on the increasing rate in discrete naming. If the serial advantage is an expression of more efficient individual stimulus processing, then one might expect its growth to track discrete naming rate. Indeed, when plotted against the mean discrete rate (Figure 5), the group mean serial advantage appeared to increase across grades as a function of mean discrete naming rate. In other words, as children's average rate of naming individually presented stimuli improved, their average serial advantage also increased. However, this group analysis does not imply that the two variables are directly related at the individual participant level. Both averages could simply exhibit a generic maturational effect. In general, group differences do not necessarily reflect similar trends in individual differences (Berry, & Willoughby, 2017; Fisher, Medaglia, & Jeronimus, 2018). Therefore, to find out whether the development of serial advantage depends on the efficiency of discrete or serial naming (or something else), we must turn to analyses of individual differences.

Individual Differences in Serial Advantage

Our second objective was to examine (a) whether differences in the serial advantage are more closely associated with differences in the discrete or the serial dimension of each naming task of the same content, and (b) how the serial-discrete correlation per task content is associated with their corresponding serial advantage.

We were particularly interested in examining whether group findings also apply for individuals. Thus, we investigated the association of within-grade individual differences in serial advantage with those in discrete and serial tasks. Table 4 shows the correlations between serial advantage and the corresponding serial- and discrete-trial format per task content. Results showed that performance in the serial-trial format of each type of content was strongly associated with serial advantage. In contrast, the correlation between serial advantage and the corresponding discrete-trial format of each naming task was very weak, irrespective of the task content. The only exception concerns word naming in Grade 1, in which discrete-trial format and serial advantage were moderately to strongly associated; followed by a relatively weak correlation in Grades 3 and 5. This pattern of results was consistent across languages and task content. Thus, even though the serial advantage in naming rate is defined as the simple difference between serial and discrete naming rates of the same content, thus potentially affected by both formats, individual differences in the serial advantage are in fact dominated by variance in serial naming rate. In other words, the serial advantage in naming rate is primarily a reflection of serial naming rate. This outcome was in fact predictable on the basis of the differences in the variances of the serial vs. discrete tasks (Table 2), a point to which we will return in the discussion.

If the serial advantage is indeed an index of serial naming efficiency beyond discrete naming, reflecting a separable dimension of individual differences concerning serial processing rather than a simple difference between serial and discrete naming that is constant across participants (e.g., reflecting a simple difficulty difference), then average serial advantage should be inversely related to the correlation between serial and discrete naming. That is, serial advantage should reflect the extent to which individual serial naming performance is not predictable by discrete naming performance. To visually illustrate this implication, mean serial advantage was plotted against the corresponding correlation coefficients for the pair of serial-discrete tasks with the same content (Figure 6). A negative relationship is evident, indicating that as mean serial advantage increased across grade levels, the correlation between the serial and corresponding discrete task (of the same content) either decreased or remained stable between successive grades. The only exception was with object naming in Greek, in which both serial advantage and serial-discrete correlation increased across grades, further confirming the qualitative difference in processing objects comparing to the other types of content.

Intercorrelations among all serial and discrete tasks for each grade and language are available in Supplementary Material (Table S7). Also, Supplementary Table S8 provides a summary of the correlations between serial and corresponding discrete naming tasks for each type of content.

Discussion

We examined the development of serial advantage across grade levels and naming tasks of different types of content, including printed words, in two languages (English and Greek). Serial advantage was defined as the gain in naming rate of multiple over isolated stimulus displays—expressed as the numerical difference between serial and discrete naming rate of the same task content. We used a set of naming tasks, including stimuli corresponding to identical or well-matched words, but differing in the way the words were depicted. In line with our expectation, we found an increase in serial advantage at higher grades for all naming tasks, but at different growth rates for different types of content. The serial advantage for printed words, in particular, increased at a higher rate than for other kinds of material. The increase in mean serial advantage for all types of content appeared to track the corresponding increase in discrete stimulus naming rate, when examined at the group level, but turned out to be related to the serial naming rate when examined at the individual differences level.

As an expression of the development of efficient sequence processing, increased serial advantage was associated with a decreased correlation between serial and discrete naming tasks of the same content. This is the first study to directly link the serial advantage during naming/reading with the previously reported format-specific correlations between naming/reading tasks (i.e., tasks of different format are correlated to a lesser degree than tasks of the same format). Importantly, this pattern of findings held across two languages with very different degrees of orthographic consistency, thus demonstrating that the development of serial advantage does not depend on the consistency of orthographic representations (see also Wimmer & Goswami, 1994, reporting a similar level of performance in serial naming of number words and digits among children aged 8 and 9 who learned to read English and German).

Development of Serial Advantage

Our results showed that there is a significant difference in serial advantage between grade levels, further supporting the idea that multiple-stimulus displays facilitate performance in naming tasks among older typically-developing children (Protopapas et al., 2013, 2018; Zoccolotti et al., 2013; 2015) and adults (Jones et al., 2009). This increase between grade levels was significant across types of naming materials, suggesting that children benefited from multiple-stimulus displays in naming tasks regardless of the task content. However, we found content-specific effects in the magnitude of the serial advantage and in the increase in serial advantage between grades, especially between Grades 1 and 3.

More specifically, there was a stable ranking of task content (material types) with respect to serial advantage, across grades. In particular, objects—and, to a lesser degree, dice—lagged behind in the development of serial advantage compared to alphanumeric stimuli (digits) and orthographic stimuli (number words). This finding is consistent with the idea that object naming and generally image naming requires semantic mediation to retrieve the name, in contrast to alphanumeric (e.g., digits) or orthographic stimuli (e.g., words), which permit direct access from visual to phonological forms (Liu & Georgiou, 2017; Pan, Yan, Laubrock, Shu, & Kliegl, 2013; Poulsen & Elbro, 2013; Roelofs, 2006). In our data, serial advantage in dice naming was intermediate between serial digit and object naming. This can be attributed to the specific dice images being not only fixed, but also familiar, presumably better-practiced than objects, and thus permitting partial access to unmediated naming due to repeated prior exposure (cf. Roelofs, 2003, 2006).

At the other end, digits and number words (especially after Grade 1) ranked highest in serial advantage across grades and languages, consistent with the idea of fast, direct mappings between visual and phonological forms for stimuli that are highly familiar and largely predictable due to their status as members of small sets. In particular, past the beginner reader stage, number words exhibited as large a serial advantage as digits because they were 25% predictable in the context of the naming task, since there were only four of them in the task. In contrast, printed word lists exhibited significantly less serial advantage, even though the words were chosen to be comparably familiar, and equally short and pronounceable as the number words, because each word in the list had to be recognized from among an unlimited potential set.

The stable ranking of task content with respect to serial advantage across grades and languages is consistent with the idea that there are important differences in how different types of stimuli are processed, when it comes to serial naming, in the sense that some kinds of processes lend themselves to efficient serial processing whereas other kinds do not. This is not a function of individual stimulus processing rate, because the differences between material types in serial advantage are much greater than the corresponding differences in discrete naming (compare the ranges of values in Table 2). It remains to be elucidated exactly what kinds of mechanisms are involved in the processing of each type of material that facilitate or impede their accessibility to efficient serial processing in multiple stimulus displays (however, see Alario et al., 2004; Levelt, Roelofs, & Meyer, 1999; Roelofs, 2003, for models of isolated object and/or word naming).

At the same time, between-grade differences in serial advantage were greatest for word naming (i.e., reading), especially when compared to objects. Both objects and words can be considered less practiced items, derived from large open sets, compared to the small closed set of numbers from which digits, number words, and dice were sampled. Yet the development of serial advantage between grades differed greatly between printed words and objects, even though they started off at similar levels in Grade 1. In particular, serial advantage in word naming took off by Grade 3 and gradually approached serial advantage of number words and digits, or dice, by Grade 5. Instead, serial advantage for object naming lagged far behind.

Taken together with the otherwise stable ordering of task content, the steep increase in word serial advantage suggests that the processing of printed words undergoes a qualitative change in cognitive processing mechanisms, starting off in some way similar to object naming in Grade 1 but ending up similar to digit or dice naming by Grade 5. This processing change may be related to intra-word processing, that is, processing of the words as complex objects composed of parts (letters, graphemes, or syllables) that must be dealt with individually. This is expected to be the case in Grade 1. In contrast, more advanced readers are expected to read words “by sight” (Ehri, 2005), that is, with their internal constituents processed in parallel (de Jong, 2011; van den Boer, Georgiou, & de Jong, 2016; van den Boer & de Jong, 2015). The serial advantage growth curve corroborates this qualitative leap in word processing, which likely underlies efficient serial word reading, that is, word list reading fluency. Our results can thus be interpreted as consistent with the idea that word list reading fluency arises from a combination of both intra-word processes, which enable word reading by sight, and inter-word processes, which underlie efficient serial naming/reading.

This could also account for the apparently smaller serial advantage for Greek words—in comparison to the other materials. Greek words were bisyllabic, hence composed of more internal elements/constituents, or of a more complex internal structure than the monosyllabic English words. If the steep slope (in English) reflects a complete qualitative shift from intra- to inter-word processing, and words in Greek have more complex internal structure, and therefore more involved intra-word processing, then serial advantage in word naming should be expected to be smaller in Greek than in English relative to digits/dice.

Group Trends versus Individual Differences

Analyses of group average performance appeared to confirm the hypothesis that serial advantage increases as a function of the increase in discrete naming rate. In other words, group differences suggested that performance in discrete naming rate largely determined the corresponding increase in serial advantage between grades. Indeed, the graphs in Figure 5 show an almost perfectly linear relationship across grades between discrete naming rate and serial advantage. The same linear relationship (same slope) seems to hold even for objects, despite their overall lower serial advantage relative to the observed discrete naming rate. However, this image is misleading, because it simply reflects the almost-inevitable outcome that skills increase with age. Thus, anything that exhibits developmental growth can appear to be strongly associated in such a group-level analysis. The important question here is not whether differences in mean serial advantage across grades track corresponding mean differences in discrete (or serial) naming rate but, rather, whether individual differences in serial advantage are consistently associated with individual differences in discrete (or serial) naming rate within age (or grade-level) groups.

As it turns out, individual differences tell a very different story. In particular, we found that serial advantage in naming rate is largely independent from discrete naming rate. In other words, the efficiency with which children within a grade group retrieve and produce the names of individually presented items seems to have limited influence on their serial advantage for these items. In contrast, differences in the serial naming tasks were strongly associated with differences in serial advantage. In other words, the serial advantage seems to be primarily a reflection of serial naming rate, even though by the nature of its calculation one might expect it to depend equally on both serial and discrete naming rate.

Moreover, we found that increase in serial advantage is associated with decrease in the correlation between serial and discrete naming rate. That is, as serial naming rate dissociates from discrete naming rate, the corresponding serial advantage increases. This pattern was evident in both languages, across naming tasks of different content (with the exception of object naming, for which the relationship between serial and discrete naming was unstable or increasing).

The relevance of the serial-discrete correlation can be seen with respect to the processing mechanisms that are responsible for serial naming. In particular, a high correlation between discrete and serial naming indicates that there is not much difference in processing individually presented stimuli and stimuli presented within a matrix of other stimuli. This can be interpreted as processing of the stimuli in the serial task one by one, that is, the serial naming task is effectively a succession of discrete naming trials. This seems to be the case, for example, for word reading in Grade 1 (Figure 6). In contrast, a low correlation between discrete and serial naming indicates that what determines single-item processing efficiency is different from what determines multi-item display processing efficiency. This can be interpreted as involvement of different—or additional—mechanisms in serial naming and reading tasks (as has been suggested by Altani, Georgiou, et al., 2017; Altani, Protopapas, et al., 2017; Protopapas et al., 2013, 2018). This seems to occur, for example, for most naming tasks after Grade 1 and word reading in Grade 5.

How can we understand then the relationship between serial advantage and serial and discrete naming rates in this context? Let us consider some hypothetical limit cases to help elucidate these relationships. First, assume that there is a constant serial advantage for some reason, that is, serial naming rate is higher than discrete naming rate, but the difference is the same for everyone. This amounts to a constant difference in processing difficulty but no qualitative difference in processing mechanisms between serial and discrete naming. In this case, there is equal variance in discrete and serial naming rate, and a perfect ($r = 1.00$) correlation between them, but there is zero variance in serial advantage and, therefore, no correlation between serial advantage and either serial or discrete naming. In a second case, assume that there is a constant discrete naming rate, that is, everyone names isolated stimulus displays equally fast, but there are individual differences in serial naming rate. Therefore, there will be individual differences in their difference, that is, in serial advantage, which will be perfectly correlated with serial naming rate. The lack of variance in discrete naming rate implies a zero correlation with both serial naming rate and serial advantage. Finally, if we assume the converse, that is, individual differences in discrete naming rate but no differences in serial naming rate, in other words, everyone names multiple-stimulus displays equally fast despite differences in isolated stimulus naming. In this case, there will be zero correlation of serial naming rate with both discrete naming rate and serial advantage, and a perfect correlation between discrete naming rate and serial advantage.

Our findings are mostly in line with the second of these hypothetical scenarios. Correlations between serial advantage and serial naming are greater than 0.80 in most cases, often approaching 1.00, and hover near zero for discrete naming rate, with some exceptions (such as words). Discrete naming rate is not constant, of course. It is, however, less variable than serial naming rate (about a quarter to one tenth of the variance, if we square the standard deviations in Table 2). This pattern of findings, showing that the serial advantage (the difference between serial and discrete naming rate) correlates much more strongly with the serial naming rate (the variable with the greatest variance), is known as the “cow-canary paradox”[5] (Capitani, Laiacona, Brabarotto, & Cossa, 1999). This term refers to the general statistical phenomenon whereby a difference between two variables will always correlate much more strongly with the one variable that has the largest variance, even though it might be intuitively expected to depend on both variables to a similar degree, since it is formed by their simple numerical difference. Simulations with numbers in the range of our measured variables indeed confirm that the observed correlations of serial advantage with serial and discrete naming are in line with the observed variance differences (R script included in the Supplementary Material).

Still, that the observed properties of our difference variable are statistically expected does not suffice to explain the properties themselves. Examining the effect of presentation format from the perspective of the serial advantage serves to highlight the fact that there is greater variability in the serial naming rate, compared to the discrete naming rate. This is puzzling, given

[5] We are grateful to an anonymous reviewer for pointing this out.

that the items are identical in the two formats and the task demands (i.e., naming) are largely overlapping. The observed difference in variance between the serial and discrete naming rates suggests that there must be something unique in the serial format, which contributes greatly to performance on the task. If individual differences in serial task performance are dominated by an additional factor that is not present in the discrete task, so that variance along this additional dimension is present in serial but not discrete naming performance, this can explain the difference in variance among the two formats and the concomitant statistical consequences.

Thus, overall, these findings are in line with previous evidence suggesting that, with increasing proficiency and among well-practiced items, individual differences in serial naming/reading are gradually dissociated from individual differences in discrete naming/reading (Altani et al., 2018; de Jong, 2011; Protopapas et al., 2018). This has been attributed to the emerging dominance of a cascaded processing skill, which concerns the ability to temporally overlap the inter-item processing of multiple stimuli over multiple stages during serial naming and reading tasks. That is, a stimulus is processed while the previous one is uttered, and the next one is viewed (and possibly the one further down previewed) at the same time. This overlap of processing stages among consecutive stimuli must be the origin of the serial advantage, saving time over the serial task because successive stimuli can be processed simultaneously through the different stages in a “cascaded processing” pipeline (refer to Figure 1 for a visual illustration of the temporal overlap in serial naming/reading). In this context, one way to interpret the differential correlation of serial advantage with serial and discrete naming rate is the following: As serial naming/reading becomes increasingly efficient, it matters less how long each stimulus takes to name; instead, what matters most is how soon one can begin to process the next stimulus in the sequence (while processing of the current stimulus is still in progress). A tightly packed pipeline of cascaded processing amounts to a greater serial advantage, regardless of how long it takes for each stimulus to finish. Thus, the cascaded processing hypothesis seems to be consistent with the differential correlation pattern observed for the serial advantage.

Printed words are no exception to this pattern. Beginner readers are limited in their reading rate by how long it takes to read individual words, and thus serial word reading (i.e., word list reading fluency) correlates very strongly with discrete word reading (i.e., individual word reading speed). In contrast, skilled readers are limited in their reading rate by how long after one word has been seen the next word can begin to be processed, regardless of how long individual word processing takes to be completed. To the extent that fluent reading depends on a packed pipeline of cascaded word processing (i.e., the ability to overlap the processing stages across multiple words), this can be seen as the source of the serial advantage in word reading, as well as the explanation for the strong relationship between RAN and reading fluency, which survives control not only for phonological and orthographic processing but also for single word reading speed, across languages (Altani et al. 2017, 2019).

Some limitations of the present study are worth mentioning. First, our study was cross-sectional. Although serial advantage was estimated as the absolute difference between serial and discrete naming rate concurrently (within grade level), an examination of how serial advantage develops across time (between grade levels) would ideally involve a longitudinal design. Second, our study included only alphabetic languages. A future study should replicate these findings in non-alphabetic languages (e.g., Chinese). Finally, our study design does not elucidate the cognitive mechanisms involved in the serial processing of naming tasks of different content, and the cascaded (temporally overlapped) processing hypothesis as a candidate mechanism underlying serial advantage in RAN-type tasks remains speculative. Future studies should investigate this hypothesis using more fine-grained measures, decomposing the complex serial naming and reading tasks.

Conclusions

Our results confirm that multiple stimulus displays facilitate naming and reading rates across stimulus types and languages. However, content-specific characteristics influence the trajectory of serial advantage between grades. We have suggested that practice and familiarity with the task content may influence the development of serial advantage, irrespective of initial difficulty. Notably, we observed a steep increase for serial advantage in printed words (from being similar to objects in Grade 1 to being more similar to digits by Grade 5), suggesting that words undergo a qualitative shift in how they are processed and named.

In addition, growth in serial advantage was found to be associated with growth in discrete naming rate only in group (grade level) analysis. For individuals, greater serial advantage was associated with greater serial naming rate and with a decrease in the correlation between discrete and serial naming rate (with the exception of objects). This has important implications, as findings derived from group differences might not generalize to individuals (see Fisher et al., 2018, for a similar argument). Our findings suggest that individual differences in serial advantage rely on fluency-specific skills of serial naming rather than on differences in the speed of naming individually presented items. Thus, training naming of individual items is not expected to result in transfer of gains to serial naming rates for the same material; and training reading of individual words may have only very limited transfer of gains to oral reading fluency. Future studies should investigate the nature of the cognitive mechanisms involved in naming processes, focusing on the difference between discrete and serial naming and on the prerequisites of efficient serial naming.

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Table 1
Sample Information

	Grade	*N*	Age (*SD*)	Gender (F:M)
Greek				
	1	100	82.8 (3.4)	53:47
	3	103	107.1 (3.5)	53:50
	5	99	130.0 (3.4)	54:45
English				
	1*	101	81.6 (4.2)	50:51
	3	130	105.8 (3.9)	64:66
	5	122	129.7 (4.2)	70:52

Note. F = female; M = male; Mean age is reported in months. Information is reported for the final sample following the cleaning procedure. * The original sample size was 157 children (age = 81.4; *SD* = 4.2; F = 87).

Table 2

Descriptive Statistics for Serial and Discrete Tasks for Each Grade and Language

	Grade 1					Grade 3					Grade 5				
English	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt
Serial Tasks															
Digit	101	1.23	0.30	0.14	−0.05	130	1.69	0.39	0.28	−0.18	122	1.92	0.38	0.29	−0.38
Object	101	0.82	0.18	0.12	−0.55	127	1.09	0.20	0.33	0.40	122	1.26	0.20	0.31	−0.24
Dice	101	0.92	0.26	0.35	0.02	130	1.29	0.32	0.17	−0.55	122	1.53	0.31	0.32	1.07
Number word	101	1.31	0.30	−0.12	−0.54	130	1.77	0.32	−0.10	−0.39	122	1.95	0.35	0.07	−0.72
Word	99	0.93	0.38	0.02	−0.98	130	1.56	0.39	−0.25	−0.34	122	1.80	0.37	0.11	−0.40
Discrete Tasks															
Digit	101	0.84	0.14	0.25	−0.58	130	1.04	0.14	0.06	−0.19	122	1.17	0.13	0.01	0.38
Object	101	0.71	0.10	0.09	0.47	130	0.85	0.10	−0.15	0.30	122	0.95	0.10	−0.05	0.09
Dice	101	0.70	0.14	−0.07	−0.47	129	0.86	0.13	0.16	−0.38	122	1.01	0.13	0.11	−0.02
Number word	101	0.89	0.15	0.28	−0.62	130	1.06	0.15	0.16	0.44	122	1.19	0.14	0.02	−0.14
Word	101	0.72	0.16	0.02	−0.04	129	0.98	0.13	0.09	0.66	122	1.09	0.12	−0.30	−0.03
Greek	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt
Serial Tasks															
Digit	100	1.38	0.27	0.04	−0.43	103	1.91	0.34	−0.17	−0.47	99	2.13	0.38	−0.59	0.47
Object	100	0.74	0.16	0.34	−0.64	103	1.05	0.20	0.33	−0.35	99	1.20	0.23	0.19	0.77
Dice	100	1.12	0.27	0.00	−0.17	103	1.55	0.30	0.01	−0.35	98	1.72	0.34	0.26	0.27
Number word	100	1.24	0.31	−0.02	0.27	103	1.92	0.33	−0.33	−0.08	99	2.16	0.38	−0.33	0.06
Word	98	0.67	0.26	0.52	−0.36	103	1.40	0.40	−0.01	0.02	98	1.67	0.35	−0.14	−0.49
Discrete Tasks															
Digit	100	0.90	0.15	0.29	0.18	103	1.13	0.16	0.39	0.95	99	1.21	0.17	0.23	−0.10
Object	100	0.69	0.10	0.53	0.43	103	0.89	0.13	0.28	0.45	99	0.94	0.13	0.21	−0.10
Dice	100	0.80	0.15	−0.03	−0.02	103	1.00	0.16	0.33	0.10	98	1.06	0.15	0.40	0.07
Number word	100	0.86	0.15	0.08	−0.23	103	1.14	0.17	0.31	0.78	99	1.20	0.18	0.15	−0.44
Word	98	0.60	0.15	0.01	−0.57	103	0.96	0.17	−0.04	0.16	99	1.06	0.16	0.01	−0.50

Note. Skew = skewness; Kurt = kurtosis.

Table 3

Linear Contrasts Testing Differences in Serial Advantage Between Successive Grades per Task Content

		English			Greek		
Grades	Task Content	Est.	*z*	*p*	Est.	*z*	*p*
G1 vs. G3	Digits	0.272	7.338	<0.001	0.311	8.509	<0.001
G1 vs. G3	Objects	0.126	3.382	0.006	0.121	3.309	0.009
G1 vs. G3	Dice	0.202	5.448	<0.001	0.231	6.332	<0.001
G1 vs. G3	Number words	0.281	7.580	<0.001	0.411	11.271	<0.001
G1 vs. G3	Words	0.377	10.117	<0.001	0.377	10.276	<0.001
G3 vs. G5	Digits	0.098	2.782	0.045	0.130	3.556	0.004
G3 vs. G5	Objects	0.074	2.084	0.250	0.096	2.625	0.070
G3 vs. G5	Dice	0.955	2.703	0.057	0.104	2.828	0.040
G3 vs. G5	Number words	0.049	1.380	0.732	0.173	4.725	<0.001
G3 vs. G5	Words	0.125	3.525	0.004	0.161	4.406	<0.001

Note. Est. = contrast estimate; *p* values are adjusted for multiple comparisons using the "single-step" method; G = grade; Serial advantage = difference between serial and discrete naming rate of the same task content (i.e., Serial naming rate – Discrete naming rate)

Table 4

Correlations Between Serial Advantage and Each Task Format

English	Grade 1		Grade 3		Grade 5	
Serial Advantage	Serial Task	Discrete Task	Serial Task	Discrete Task	Serial Task	Discrete Task
Digits	0.87	0.13	0.92	0.02	0.94	0.07
Objects	0.84	−0.08	0.86	−0.15	0.86	−0.03
Dice	0.82	0.20	0.92	0.25	0.91	0.12
Number words	0.86	0.09	0.89	−0.14	0.92	0.01
Words	0.93	0.57	0.96	0.22	0.94	0.17

Greek	Grade 1		Grade 3		Grade 5	
Serial Advantage	Serial Task	Discrete Task	Serial Task	Discrete Task	Serial Task	Discrete Task
Digits	0.86	−0.11	0.88	0.01	0.86	−0.11
Objects	0.79	−0.30	0.78	−0.17	0.83	0.15
Dice	0.89	0.23	0.83	0.03	0.89	0.06
Number words	0.86	0.09	0.81	−0.04	0.89	0.04
Words	0.85	0.52	0.91	0.30	0.90	0.15

Note. Serial advantage = difference between serial and discrete naming rate of the same task content (i.e., Serial naming rate – Discrete naming rate)

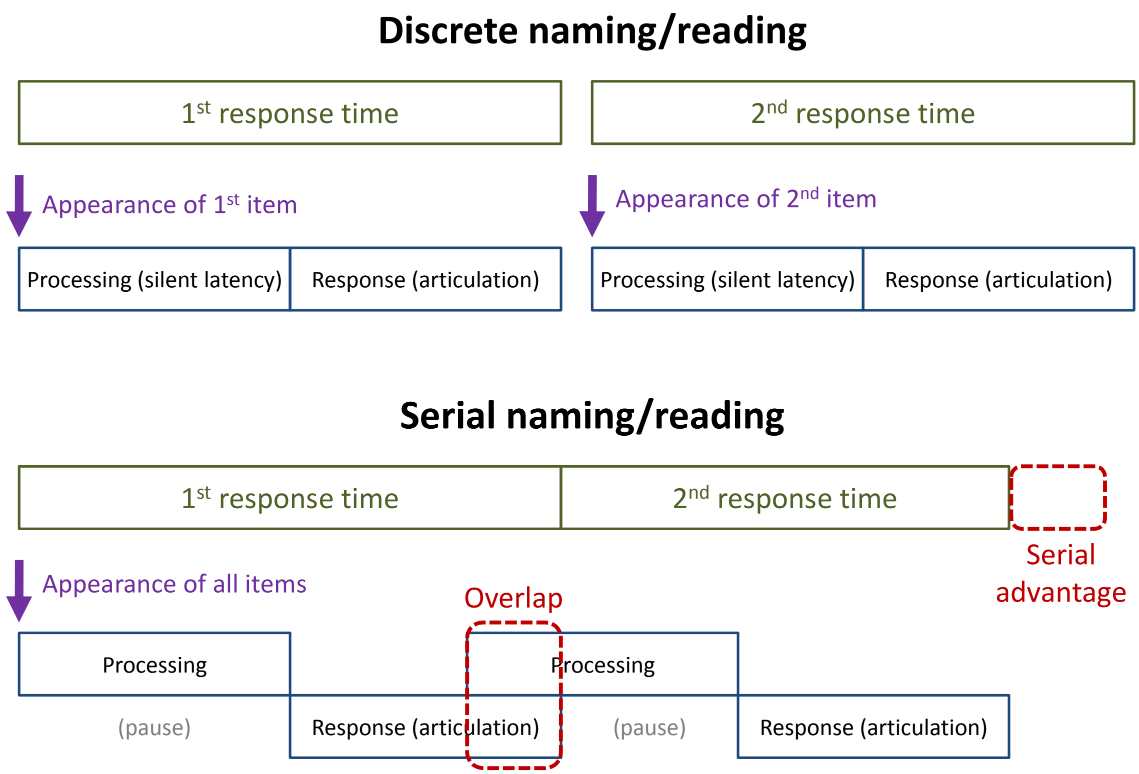


Figure 1. Schematic illustration of the serial advantage. Top: In the discrete format, each stimulus appears after the previous one has been named, therefore each response time includes a complete processing and spoken response cycle, observable as onset latency and articulation time, respectively. Bottom: In the serial format, all stimuli appear simultaneously, so it is possible to begin processing one item while the preceding one is still being articulated. Even though individual stimulus processing and articulation times are equal to those in the discrete formats, the temporal overlap between successive stimuli causes the silent intervals (i.e., pauses) in the response to shrink and the total response time for the task to diminish by an amount of time equal to the overlap. This difference between response times in the two formats is the serial advantage.

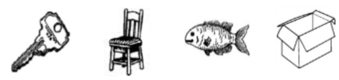
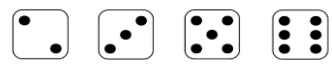
Materials	**English**	**Greek**
Digits	2 3 5 6	2 3 5 6
Objects		
Dice		
Number words	two three five six	δύο τρία πέντε έξι
Words	tea horse bike fox ...	νέο θεία ζούσε όλα ...

Figure 2. Material per task in each language.

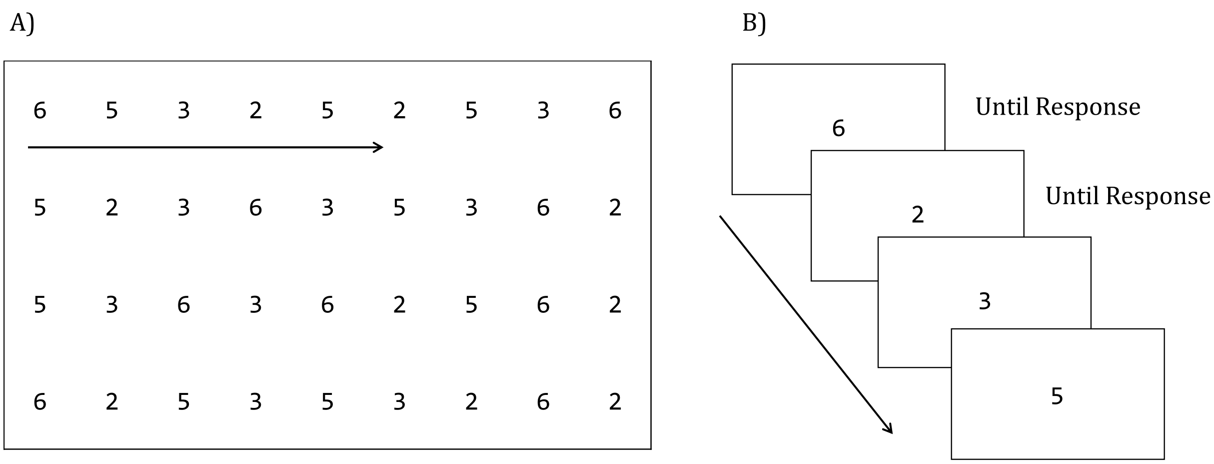


Figure 3. Example of (A) serial-trial vs. (B) discrete-trial format in digit naming.

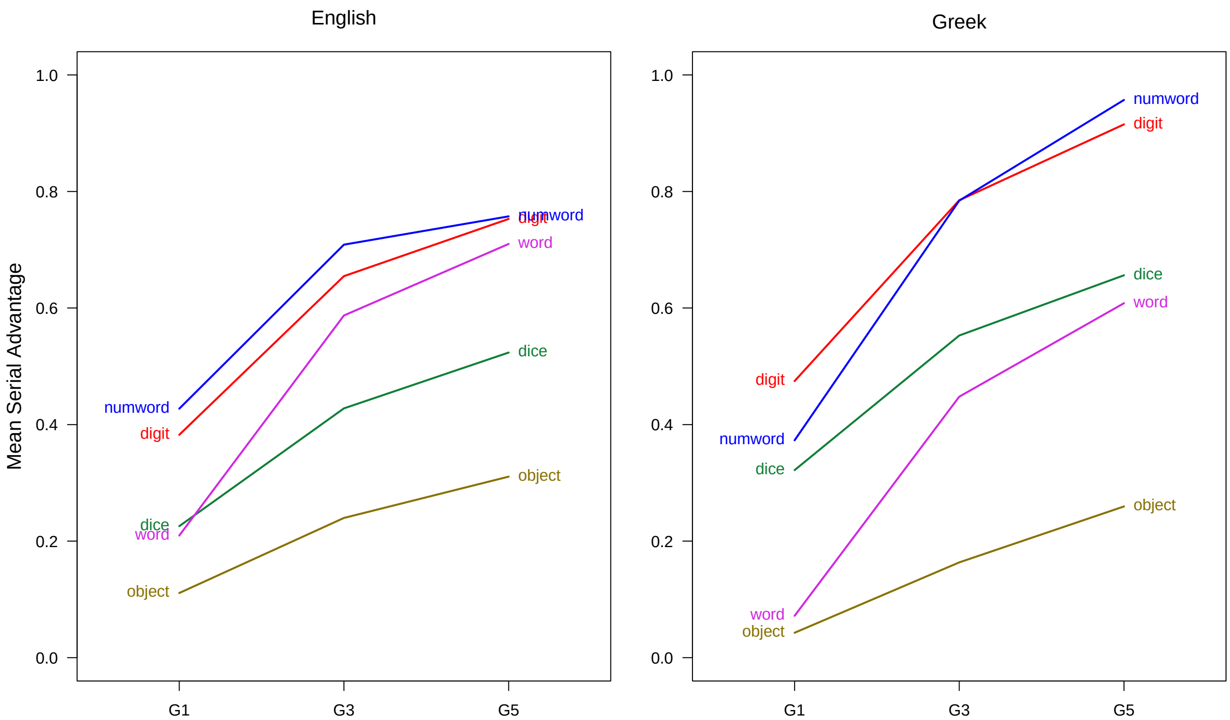


Figure 4. Mean serial advantage per task content and grade in each language.

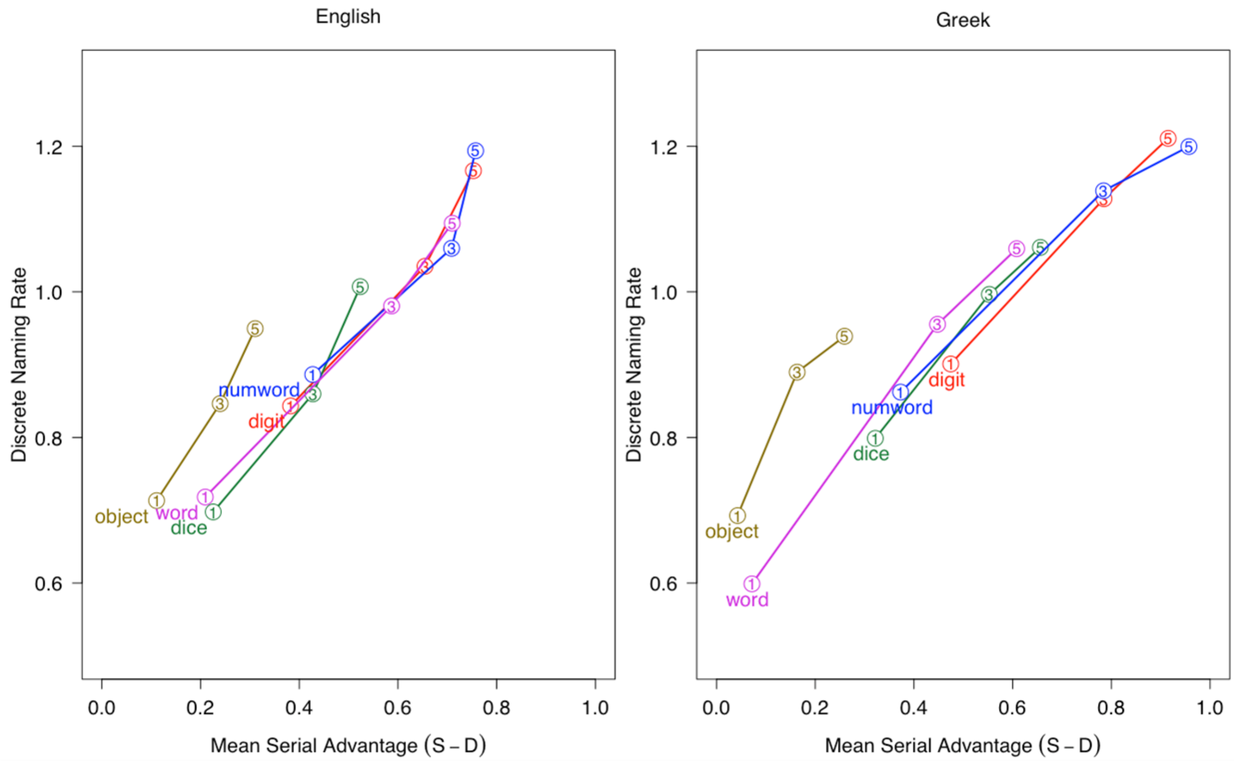


Figure 5. Average performance in discrete naming rate (y-axis) as a function of mean serial advantage (x-axis) per task content and grade in each language.

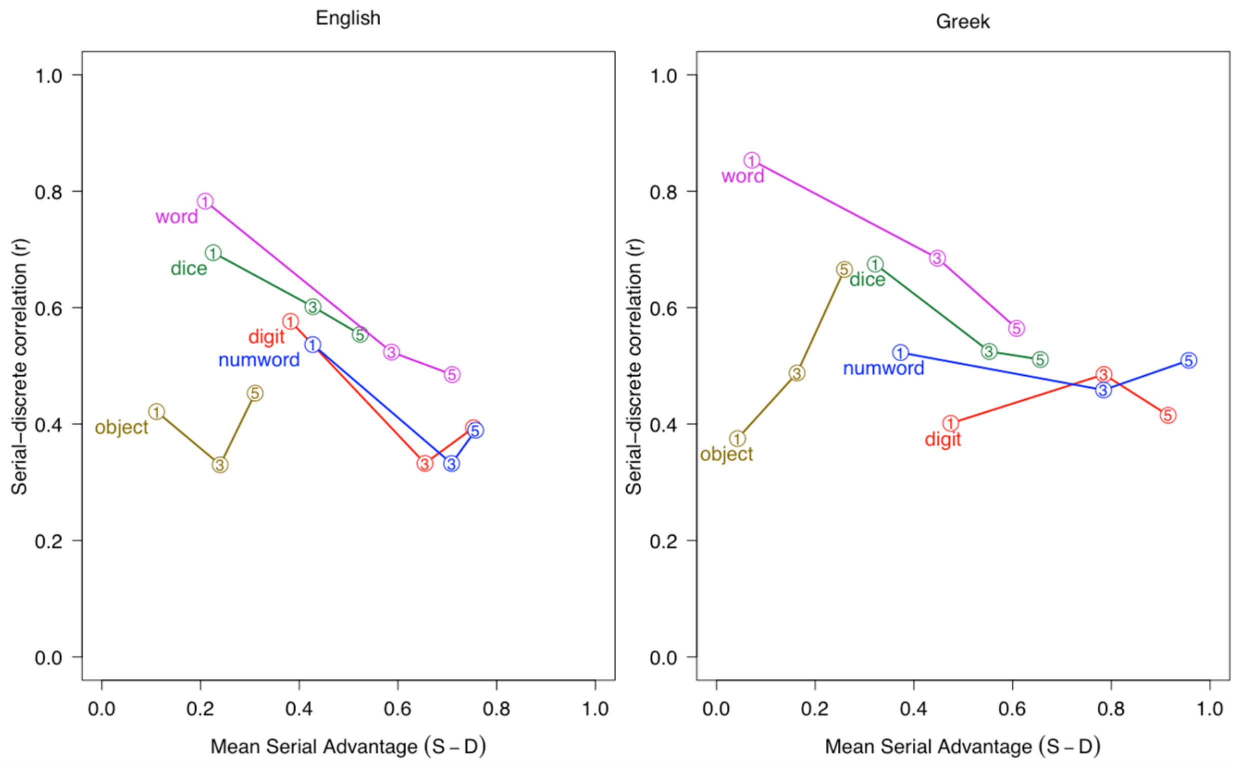


Figure 6. Serial advantage (x-axis) as a function of serial-discrete correlation (Pearson's *r* coefficient; y-axis) per task content and grade in each language.

Tracking the Serial Advantage in the Naming Rate of Multiple over Isolated Stimulus Displays

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Supplementary Material

Table S1

Properties (length and frequency) of the words used in each type of content

	Number words				Word list 1				Word list 2				Object words			
Measure	M	SD	min	max	M	SD	min	max	M	SD	min	max	M	SD	min	max
Greek																
Number of letters	3.8	1.0	3	5	4.1	0.6	3	5	4.1	0.5	3	5	4.2	1.0	3	5
Number of phonemes	3.8	0.5	3	4	3.8	0.4	3	4	3.8	0.4	3	4	3.8	0.5	3	4
Number of syllables	2.0	0.0	2	2	2.0	0.0	2	2	2.0	0.0	2	2	2.0	0.0	2	2
Printed frequency (children)	5.5	0.4	5.1	6.0	5.2	0.5	4.6	6.5	5.3	0.4	4.4	6.1	5.5	0.4	5.1	6.0
Printed frequency (adult)	5.6	0.5	5.2	6.3	5.1	0.7	3.9	6.5	5.0	0.6	3.7	6.0	5.6	0.5	5.2	6.3
English																
Number of letters	3.8	1.0	3	5	3.8	0.7	3	5	3.8	0.7	3	5	3.8	1.0	3	5
Number of phonemes	3.0	0.8	2	4	3.0	0.5	2	4	3.0	0.5	2	4	3.0	0.8	2	4
Number of syllables	1.0	0.0	1	1	1.0	0.0	1	1	1.0	0.0	1	1	1.0	0.0	1	1
Printed frequency (children)	5.6	0.4	5.2	6.0	5.6	0.3	5.2	6.1	5.6	0.3	5.3	6.1	5.7	0.4	5.2	6.0
Printed frequency (adult)	5.7	0.4	5.3	5.8	5.1	0.5	4.1	6.4	5.2	0.5	4.0	6.4	5.6	0.5	5.2	5.8

Note. The same or some of this information has been previously reported in Altani et al. (2017a, 2019), and in Protopapas et al. (2018).

Table S2

Anderson−Darling tests of normality for the data per task format and grade

		Digits		Objects		Dice		Number words		Words	
English	Grade	*A*	*p*	*A*	*p*	*A*	*p*	*A*	*p*	*A*	*p*
Serial	1	0.41	0.34	0.19	0.90	0.22	0.82	0.39	0.38	0.73	0.05
	3	0.29	0.62	0.20	0.88	0.46	0.26	0.27	0.67	0.32	0.54
	5	0.53	0.18	0.46	0.26	0.33	0.51	0.53	0.17	0.44	0.29
Discrete	1	0.71	0.06	0.54	0.17	0.29	0.62	0.77	0.05	0.30	0.57
	3	0.29	0.61	0.27	0.68	0.23	0.79	0.32	0.52	0.49	0.22
	5	0.86	0.03	0.21	0.85	0.24	0.78	0.26	0.71	0.41	0.34
		Digits		Objects		Dice		Number words		Words	
Greek	Grade	*A*	*p*	*A*	*p*	*A*	*p*	*A*	*p*	*A*	*p*
Serial	1	0.30	0.59	0.85	0.03	0.16	0.95	0.74	0.05	0.83	0.03
	3	0.45	0.27	0.42	0.33	0.26	0.70	0.33	0.51	0.40	0.36
	5	0.88	0.02	0.47	0.24	0.46	0.26	0.25	0.74	0.30	0.57
Discrete	1	0.38	0.39	0.48	0.23	0.27	0.68	0.36	0.44	0.23	0.79
	3	1.01	0.01	0.44	0.28	0.33	0.51	0.47	0.25	0.24	0.76
	5	0.41	0.34	0.42	0.32	0.85	0.03	0.60	0.12	0.37	0.42

Table S3

Descriptive statistics for serial advantage in each grade and language

	Grade 1					Grade 3					Grade 5				
English	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt
Serial Advantage															
Digits	101	0.38	0.25	0.07	−0.36	130	0.65	0.36	0.37	0.54	122	0.75	0.35	0.11	−0.64
Objects	101	0.11	0.17	0.46	0.29	127	0.24	0.19	0.36	0.52	122	0.31	0.18	0.43	0.21
Dice	101	0.23	0.19	0.34	0.55	129	0.43	0.26	0.30	−0.20	122	0.52	0.27	0.22	0.04
Number words	101	0.43	0.26	0.17	−0.30	130	0.71	0.31	0.00	−0.48	122	0.76	0.33	−0.04	−0.64
Words	99	0.21	0.27	0.42	−0.39	129	0.59	0.33	−0.04	−0.53	122	0.71	0.33	0.18	−0.23
Greek	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt
Serial Advantage															
Digits	100	0.47	0.25	−0.15	−0.72	103	0.79	0.29	−0.11	−0.01	99	0.92	0.34	−0.74	0.50
Object	100	0.04	0.15	0.38	−0.29	103	0.16	0.18	0.10	−0.56	99	0.26	0.17	0.19	−0.30
Dice	100	0.32	0.20	0.31	0.14	103	0.55	0.26	0.04	−0.28	98	0.66	0.29	0.23	0.03
Number words	100	0.37	0.27	0.14	0.21	103	0.78	0.30	−0.46	0.52	99	0.96	0.33	−0.20	−0.17
Words	97	0.07	0.16	0.84	0.04	103	0.45	0.30	0.24	0.01	98	0.61	0.29	0.01	−0.20

Note. Skew = skewness; Kurt = kurtosis.

Table S4

Linear contrasts testing differences in serial advantage between successive grades and pairs of task content (Grade × Content interaction)

Grades	Task content	English			Greek		
		Est.	*t*	*p*	Est.	*t*	*p*
G1 vs. G3	word vs. dice	–0.176	–4.638	0.000	–0.179	–4.241	0.001
G1 vs. G3	word vs. digit	–0.103	–2.719	0.096	–0.107	–2.529	0.153
G1 vs. G3	word vs. number word	–0.095	–2.492	0.168	0.025	0.589	0.999
G1 vs. G3	word vs. object	–0.250	–6.582	< 0.001	–0.265	–6.273	< 0.001
G1 vs. G3	dice vs. digit	0.073	1.928	0.485	0.072	1.712	0.634
G1 vs. G3	dice vs. number word	0.082	2.156	0.335	0.204	4.829	< 0.001
G1 vs. G3	dice vs. object	–0.074	–1.958	0.465	–0.086	–2.032	0.410
G1 vs. G3	digit vs. numword	0.009	0.228	1.000	0.132	3.117	0.031
G1 vs. G3	digit vs. object	–0.147	–3.884	0.002	–0.158	–3.744	0.003
G1 vs. G3	number word vs. object	–0.156	–4.111	0.001	–0.290	–6.861	< 0.001
G3 vs. G5	word vs. dice	0.028	0.769	0.995	0.033	0.803	0.993
G3 vs. G5	word vs. digit	0.028	0.780	0.994	0.003	0.063	1.000
G3 vs. G5	word vs. number word	0.077	2.147	0.341	–0.024	–0.575	0.999
G3 vs. G5	word vs. object	0.052	1.429	0.821	0.056	1.367	0.848
G3 vs. G5	dice vs. digit	0.000	0.010	1.000	–0.030	–0.741	0.996
G3 vs. G5	dice vs. number word	0.049	1.375	0.849	–0.057	–1.379	0.842
G3 vs. G5	dice vs. object	0.024	0.661	0.998	0.023	0.563	0.999
G3 vs. G5	digit vs. numword	0.049	1.367	0.853	–0.026	–0.639	0.998
G3 vs. G5	digit vs. object	0.023	0.651	0.998	0.053	1.306	0.878
G3 vs. G5	number word vs. object	–0.026	–0.711	0.997	0.080	1.945	0.469

Note. Est. = contrast estimate; *p* values are adjusted for multiple comparisons using the multivariate t (mvt) method; G = grade.

Table S5

Results of a mixed-effects model with serial advantage as the dependent variable and grade, content, and language as independent variables

Effect	*df*	*F*	*p*
Task content	4	656.09	< .001
Grade	2	184.16	< .001
Language	1	2.88	.090
Task Content × Grade	8	23.30	< .001
Task Content × Language	4	55.66	< .001
Grade × Language	2	2.13	.120
Task Content × Grade × Language	8	3.31	< .001

Note. fixed effects : Task Content, Grade, Language (fully interacting); random effects : task content nested under participants.

Table S6

Results of mixed-effects models (interaction term only) with serial advantage as the dependent variable and grade and language as independent variables

Task Content	Grades	*β*	*t*	*p*
word	G1 vs G3	0.002	0.03	.977
dice	G1 vs G3	−0.029	−0.64	.522
digit	G1 vs G3	−0.038	−0.66	.511
number word	G1 vs G3	−0.130	−2.36	.019
object	G1 vs G3	0.008	0.24	.812
word	G3 vs G5	−0.038	−0.63	.529
dice	G3 vs G5	−0.007	−0.15	.883
digit	G3 vs G5	−0.032	−0.50	.620
number word	G3 vs G5	−0.124	−2.09	.037
object	G3 vs G5	−0.025	−0.73	.468

Note. Each row displays the results for the interaction term (Grade × Language) of a single model. Separate models were fitted for each task content and for each grade pair (G1–G3 or G3–G5), as a follow-up to the statistically significant three-way interaction obtained in the omnibus model (Table S5). The effects displayed here concern difference between languages in the differences in serial advantage between successive grades, that is between-languages differences in the slope of serial advantage across grades (refer to Figure 4 in the main article for illustration).

Table S7

Correlation coefficients (Pearson's r) among all tasks for each grade and language

G1			1.sDig	2.sObj	3.sDic	4.sNwrd	5.sWrd	6.dDig	7.dObj	8.dDic	9.dNwrd	10.dWrd
1	serial	Digit		0.27	0.60	0.54	0.53	0.40	0.38	0.47	0.44	0.49
2	serial	Object	0.42		0.36	0.34	0.40	0.20	0.38	0.24	0.25	0.23
3	serial	Dice	0.67	0.51		0.45	0.41	0.54	0.55	0.67	0.48	0.47
4	serial	Number word	0.60	0.50	0.50		0.77	0.33	0.32	0.35	0.52	0.71
5	serial	Word	0.29	0.34	0.18	0.59		0.32	0.32	0.38	0.51	0.85
6	discrete	Digit	0.58	0.24	0.45	0.48	0.25		0.65	0.77	0.74	0.53
7	discrete	Object	0.48	0.42	0.50	0.39	0.10	0.66		0.73	0.65	0.49
8	discrete	Dice	0.62	0.38	0.69	0.45	0.19	0.67	0.67		0.77	0.59
9	discrete	Number word	0.46	0.35	0.46	0.54	0.37	0.73	0.62	0.71		0.73
10	discrete	Word	0.37	0.24	0.20	0.64	0.78	0.51	0.34	0.37	0.63	

G3			1.sDig	2.sObj	3.sDic	4.sNwrd	5.sWrd	6.dDig	7.dObj	8.dDic	9.dNwrd	10.dWrd
1	serial	Digit		0.61	0.68	0.81	0.62	0.49	0.47	0.50	0.41	0.60
2	serial	Object	0.64		0.56	0.58	0.49	0.38	0.49	0.38	0.40	0.50
3	serial	Dice	0.71	0.70		0.59	0.57	0.44	0.44	0.52	0.41	0.56
4	serial	Number word	0.67	0.50	0.52		0.75	0.52	0.48	0.45	0.46	0.65
5	serial	Word	0.56	0.42	0.36	0.67		0.48	0.41	0.38	0.42	0.69
6	discrete	Digit	0.33	0.16	0.26	0.40	0.26		0.80	0.83	0.85	0.82
7	discrete	Object	0.23	0.33	0.27	0.30	0.14	0.62		0.80	0.82	0.77
8	discrete	Dice	0.41	0.49	0.60	0.30	0.20	0.59	0.61		0.85	0.78
9	discrete	Number word	0.25	0.16	0.13	0.33	0.31	0.76	0.64	0.54		0.84
10	discrete	Word	0.18	0.11	0.11	0.45	0.52	0.65	0.42	0.40	0.69	

G5			1.sDig	2.sObj	3.sDic	4.sNwrd	5.sWrd	6.dDig	7.dObj	8.dDic	9.dNmwrd	10.dWrd
1	serial	Digit		0.54	0.68	0.82	0.65	0.42	0.57	0.54	0.49	0.45
2	serial	Object	0.53		0.67	0.47	0.48	0.35	0.67	0.51	0.41	0.31
3	serial	Dice	0.70	0.60		0.60	0.52	0.25	0.50	0.51	0.35	0.20
4	serial	Number word	0.74	0.54	0.59		0.77	0.42	0.52	0.48	0.51	0.51

5	serial	Word	0.61	0.39	0.44	0.68		0.42	0.50	0.41	0.54	0.56
6	discrete	Digit	0.39	0.11	0.31	0.44	0.34		0.70	0.77	0.86	0.78
7	discrete	Object	0.45	0.45	0.46	0.46	0.27	0.65		0.76	0.74	0.68
8	discrete	Dice	0.51	0.31	0.55	0.51	0.40	0.79	0.78		0.77	0.68
9	discrete	Number word	0.28	0.09	0.28	0.39	0.37	0.85	0.59	0.73		0.83
10	discrete	Word	0.42	0.25	0.38	0.49	0.49	0.78	0.64	0.75	0.85	

Note. Correlation coefficients for English, below the diagonal; correlation coefficients for Greek, above the diagonal; s = serial; d = discrete. Correlations in Greek have been previously reported in Protopapas et al. (2018).

Table S8

Correlation coefficients (Pearson's r) between the serial and the discrete version of each task across grades and languages

		Digits	Objects	Dice	Number words	Words
English						
	G1	.58	.42	.69	.54	.78
	G3	.33	.33	.60	.33	.52
	G5	.39	.45	.55	.39	.49
Greek						
	G1	.40	.38	.67	.52	.85
	G3	.49	.49	.52	.46	.69
	G5	.42	.67	.51	.51	.56

Note. G = grade.

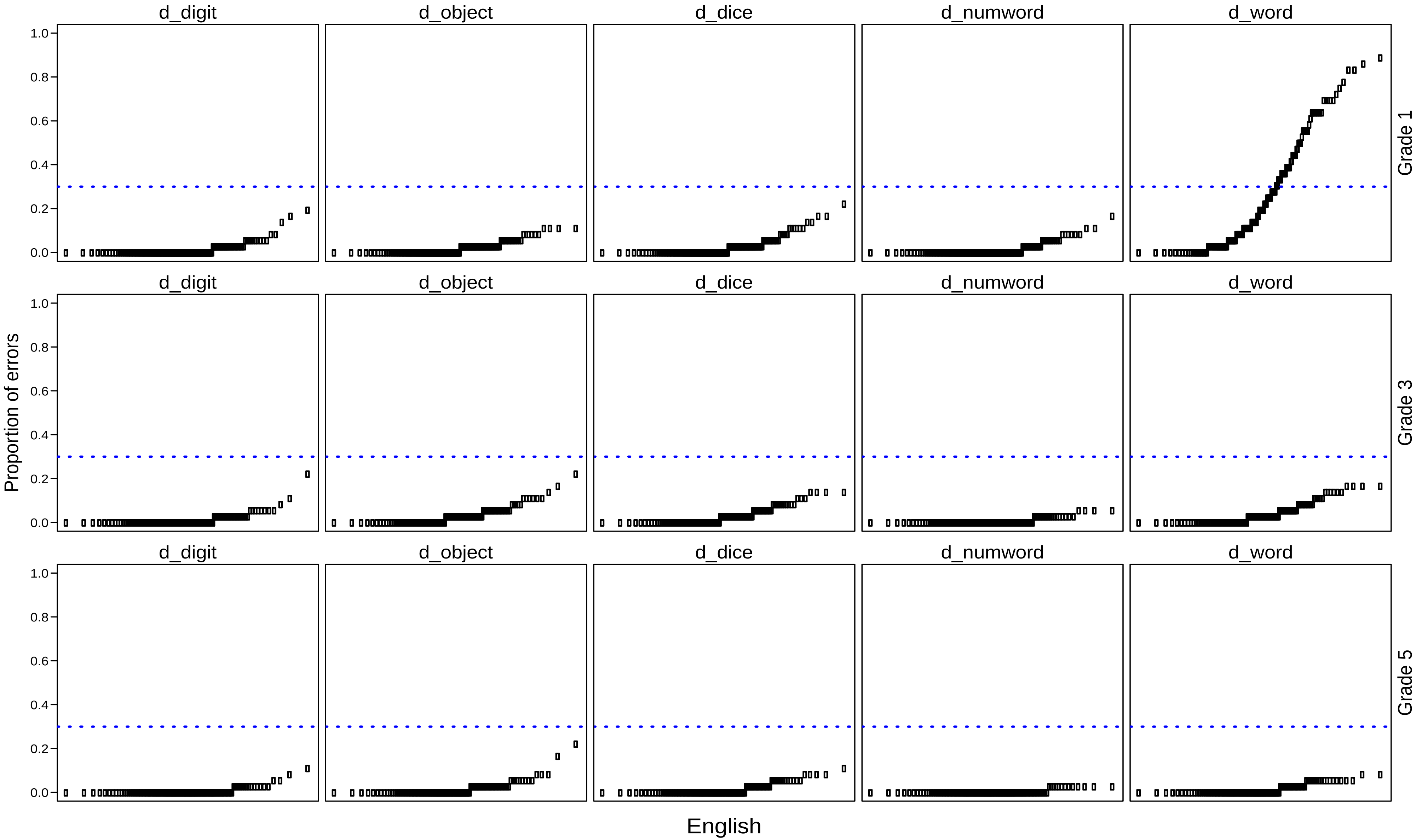

Figure S1. Proportion of errors per task content (discrete format) in each grade in English.

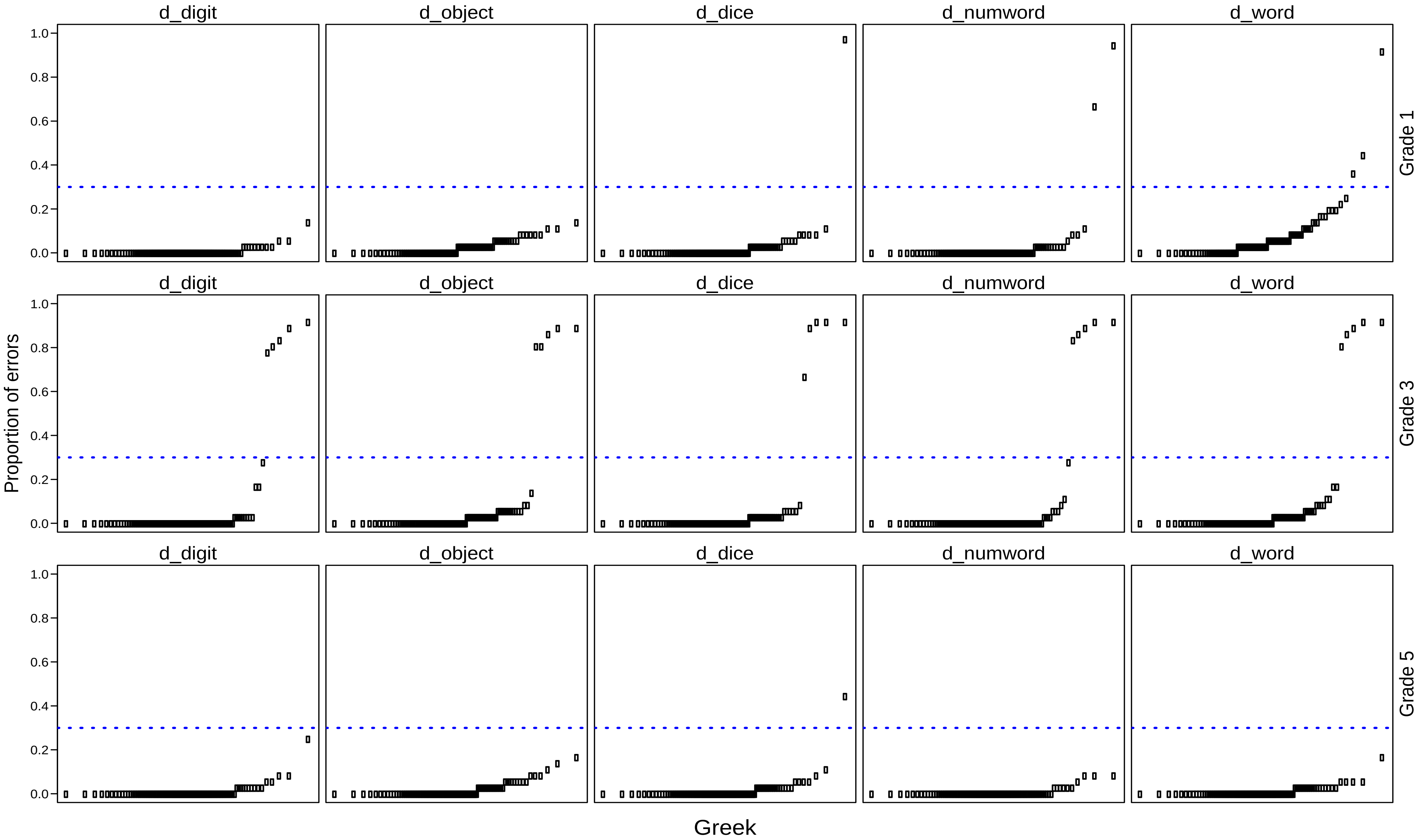

Figure S2. Proportion of errors per task content (discrete format) in each grade in Greek.

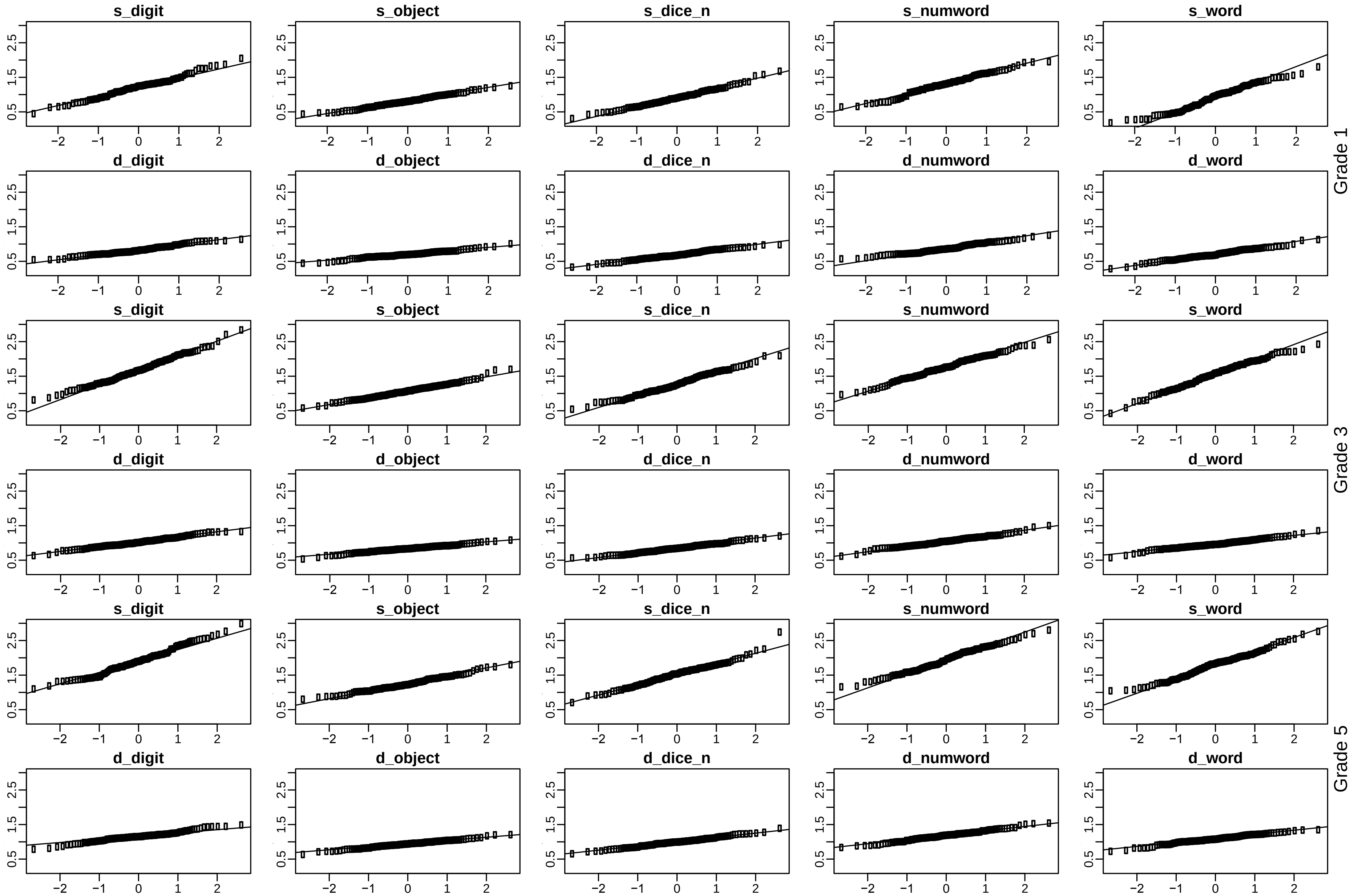

Figure S3. Q-Q plots of data (naming rate in items per second) per task content and task format in each grade in English.

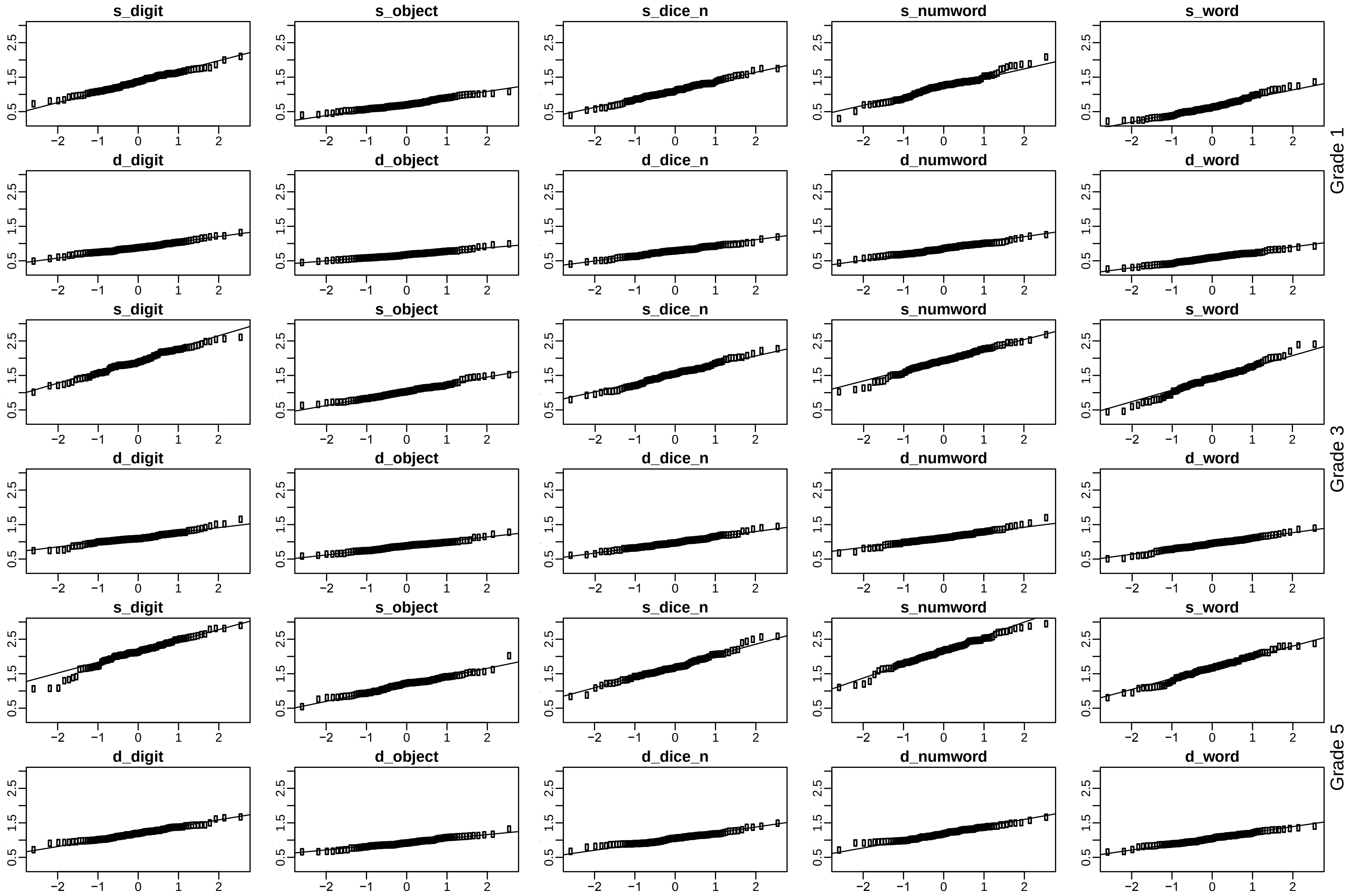

Figure S4. Q-Q plots of data (naming rate in items per second) per task content and task format in each grade in Greek.

R code to simulate the cow-canary paradox with the difference of two correlated variables

```
# Demonstration of the cow-canary "paradox":
#  (that a difference between two variables will correlate much more strongly
#   with the one variable that has the largest variance, almost to the exclusion
#   of the other variable, even though it might be intuitively expected to
#   depend on both variables to a similar degree, since it is formed by their
#   simple numerical difference)
# Capitani, Laiacona, Barbarotto, & Cossa (1999), J Clin Exp Neuropsych 21, 216-28

library(MASS) # for the mvrnorm function

m1  <- 0.80  # mean of the first variable
m2  <- 1.20  # mean of the second variable
s1  <- 0.15  # standard deviation of the first variable
s2  <- 0.30  # standard deviation of the second variable
r12 <- 0.50  # Pearson correlation between the two variables

# Form variance-covariance matrix
cm <- matrix(c(s1^2,r12*s1*s2,r12*s1*s2,s2^2),nrow=2)

k <- 10000                  # number of simulations (samples)
crm <- array(NA,dim=c(k,2)) # set up array of correlation coefficients
vrm <- array(NA,dim=c(k,2)) # set up array of variances / covariances

for (i in 1:k) {
  s <- mvrnorm(100,c(m1,m2),cm)      # draw a random bivariate sample
  d <- apply(s,1,diff)               # calculate difference between two variables
  crm[i,] <- cor(cbind(s,d))[3,1:2]  # calculate and save the correlations of the
                                     # difference with each of the two variables
  s[,1] <- -s[,1]                    # negate var1 to correspond to the difference
  vrm[i,] <- c(var(d),sum(cov(s)))   # calculate the variance of the difference
                                     # and associated variance-covariance matrix
}

apply(crm,2,summary)  # five-point summary of the correlations with each variable
apply(vrm,2,summary)  # five-point summary of the difference variances; equal to
                      # the sum of the variance-covariance matrix, as expected
```