UMEÅ UNIVERSITET

FROM KEYSTROKES TO COGNITIVE PROCESSES

ANALYZING MORPHOLOGICAL KNOWLEDGE USING KEYSTROKE LOGGING

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Abstract

The development of keystroke logging programs and their use to study the writing process affords an opportunity to combine keystroke logging together with diagnostic tests to provide further information about the test-taking process beyond the given answers. This exploratory study provides a starting point for the usage of keystroke logging programs when taking diagnostic linguistic tests. Twenty-one Swedish students in upper secondary school took a morphological test in English that assesses morphological knowledge – which recent studies suggest is related to reading and writing development – using the keystroke logging program GenoGraphiX-LOG. Temporal and revision data, as well as GenoGraphiX-LOG's provided statistical and visualization tools, were used to investigate the cognitive processes of the participants in relation to morphological knowledge. Haye's model of the writing process and the Morphological Pathways Framework (MPF) was used to ground the analysis in current cognitive theory. The results reveal that higher-level processes such as evaluation and planning can be seen with the help of keystroke logging, as well as the integration of morphological information and spelling. The current analytical and visualization tools provided by GenoGraphiX-LOG require further development to streamline their usage together with diagnostic linguistic tests.

Keywords: keystroke logging, cognitive processes, morphology, writing processes

Sammanfattning

Utvecklingen av program för registreringen av tangenttryckningar och deras användning inom forskning om skrivprocesser bidrar ytterligare information om provtagningsprocessen utöver provsvaren. Denna explorativa studie ger en startpunkt för användningen av program för tangenttryckningsregistrering tillsammans med diagnostiska lingvistiska prov. Tjugoen svenska elever i andra året på gymnasiet utförde ett morfologiskt prov på engelska som utvärderar morfologisk kunskap – vilket relaterar till läs- och skrivutvecklingen enligt nya studier – med hjälp av programmet GenoGraphiX-LOG. Temporal och revideringsdata användes, tillsammans med programmets verktyg för statistisk redovisning och visualisering, för att undersöka deltagarnas kognitiva processer i relation till deras morfologiska kunskap. Hayes modell av skrivprocessen och Morphological Pathways Framework (MPF) användes för att förankra analysen i aktuell kognitiv teori. Resultaten visar att högre processer såsom evaluering och planering kan synliggöras med hjälp av registrering av tangenttryckningar. De nuvarande analytiska och visualiseringsverktygen i GenoGraphiX-LOG behöver utvecklas vidare för att effektivisera dess användning med diagnostiska lingvistiska prov.

Nyckelord: tangenttryckningsregistrering, kognitiva processer, morfologi, skrivprocesser

From Keystrokes to Cognitive Processes: Analyzing Morphological Knowledge Using Keystroke Logging

The rapid development of technology and its use within education increases the ways in which to investigate the writing process of students. With this development, it is now possible to digitize the test-taking process and use programs to extract more data, as well as data that was previously inaccessible. An example of such a development is keystroke logging programs. The use of keystroke logging programs as a pedagogic tool has included, among other things, the identification of learners with writing difficulties, the monitoring of literacy development and awareness of their own linguistic performance through reflection and discussion of the writing process (Lindgren & Sullivan, 2019). A further possible use for such technology is the utilization of keystroke logging programs during linguistic diagnostic tests. By registering individual keystrokes during a diagnostic test one can utilize data from the test-taking process itself, including each keystroke the participant undertook, revisions of answers and temporal data, such as how long it took to answer a question and pauses in the writing process. If successfully applied, the test administrator would no longer be bound to mere test results (as is the case with pen and paper) but could use the data from the process to identify participants' difficulties. This data could shine further light on what cognitive challenges the participants are faced with. Such diagnostic tests, usually taken with pen and paper, could be specifically designed to be logged with a keystroke logger to optimize what data can be extracted with the program and facilitate diagnosis.

The purpose of this exploratory study was therefore to investigate (i) the feasibility of using keystroke logging programs in conjunction with diagnostic tests to produce further information about the test taking process than what is provided by a test taken with pen and paper and (ii) what the provided data can tell us about morphological knowledge according to contemporary cognitive theory. The current study is therefore meant to provide a starting point for future research and use of keystroke logging for diagnostic tests. A morphological test was developed based on extracted tasks from the computer-adaptive language assessment game Monster, P.I (Goodwin et al., 2022). This English morphological test was taken by Swedish upper secondary school students in a keystroke logging environment in the program GenoGraphiX-LOG (Caporossi et al., 2023). The keystroke logging program is specifically designed for use by teachers and researchers and includes a multitude of tools for analyzing the writing process by visually representing the data. A part of answering the question of how keystroke logging can be used involves how to best represent the data from a linguistic test since the visualization provided by programs such as GenoGraphiX-LOG is mainly designed for the purpose of evaluating the writing process from longer text productions. To gain a better understanding of the cognitive processes that are engaged when writing and manipulating morphemes, Hayes' (2012) model of the writing process as well as Levesque et al.'s (2021) Morphological Pathways Framework was used to inform the analysis of the keystroke logging data.

Keystroke logging and Cognitive Processing

The use of keystroke logging in writing research has focused on a multitude of areas, including writing development, spelling, writing strategies, and the general underlying cognitive processes of writing itself (Leijten & Van Waes, 2013). When analyzing the cognitive process of writing with keystroke loggers, the main focus is usually writing rate and fluency, which connects to the main types of data recorded by the logging programs: revision and temporal data (Leijten & Van Waes, 2013). Such data can reveal the level of cognitive effort expended during writing as indexed by the length and number of pauses during the writing process. For one, pauses in speech are seen as markers of cognitive effort (Leijten & Van Waes, 2013), so it would be groundless to not ascribe it to writing as well, as previously mentioned. Furthermore, previous research has shown that as the cognitive demand of the task surpasses the writer's working memory capacity the writing rate decreases, leading to increased pauses and mistakes (Conijn et al., 2019; Wengelin, 2006). Relatedly, linguistic units can be identified from pause length between keystrokes, which tend to be longer at morphological and word boundaries, and shorter between sentences than between paragraphs (Wengelin, 2006; Weingarten, 2005). Therefore, it seems that certain pauses connect to underlying cognitive processing concerning lexical representations of speech as well as to higher-level cognitive processes during writing. When it comes to revision data however, as Faigley and Witte (1981) points out, it seems to relate to surface level and meaning changes – changes that preserve meaning or correct grammar, and revisions that add new or alters information in the text. In order to interpret such data and analyze the test taking process – the first purpose of the current study – cognitive models of the writing process were considered.

In 1980, Hayes and Flower introduced their influential cognitive model of the writing process. As new research was conducted, the model has been steadily updated and revised to best describe the complex cognitive process that is writing. Hayes' (2012) model of writing contains three levels: (i) the control level, (ii) the process level, and (iii) the resource level. Within the process level, four specific writing processes are identified: the *proposer* that essentially decides what is to be conveyed through text, which includes high-level processes for planning and reflection, the *translator* where the plans from the proposer are translated into natural language, the *transcriber* that produces the final output, and the *evaluator* (and *revisor* in previous iterations of the model) that monitors and evaluates text upon production. Keystroke logging as a method is well suited to penetrate the process level; especially when considering it as a part of the process level by the virtue of being a transcribing technology, that directly interacts with the transcriber and the proposer. Furthermore, as Leijten and Van Waes (2013) contend, Keystroke logging seems to be able to penetrate not only the process level, but also the resource level. This is because pause burst length (the number of keystrokes between two pauses exceeding a previously defined threshold) is affected by linguistic skill and working memory capacity, as studies show (Hayes & Chenoweth, 2006). Connecting data from keystroke logging is usually done by dividing the text according to the location of pauses and these pauses can reflect certain processes in the second level of Hayes' model. For example, a burst of keystrokes that ends with a pause greater than 2 seconds is called a P-burst and is thought to reflect the linguistic output possible in one planning episode; whereas a burst interrupted by a revision, called an R-burst, reflects the termination of the planned output (Galbraith & Baaijen, 2019). Pauses greater than 2 seconds – cognitive pauses – are said to reflect the planning phases of the proposer when the translator has finished processing the previous plans. The rationale behind the two second demarcation is that pauses above two seconds are probably not a consequence of activities such as looking for a key on the keyboard; rather, it is thought to reflect higher-level processes regarding the content of the text.

Aligning cognitive processes to units of analysis of keystrokes is not a straightforward matter. As Galbraith and Baaijen (2019) points out, the objects of analysis (such as pauses and revisions) in keystroke logging may reflect several different cognitive processes – pauses could reflect planning, reflection, or re-reading; revisions may reflect an attempt to modify content, but also an automatic correction of errors. This is what Galbraith and Baaijen (2019) refer to as the *problem of alignment*. This problem must be kept in mind when analyzing and interpreting results from keystroke logging. Especially when the keystroke logging method is unaided by other methods that help distinguish cognitive processes from each other. If, for example, an eye tracker is used simultaneously with a keystroke logger, it will help disentangle what the writer is doing – if the writer is looking at the keyboard during a pause, it might indicate that the writer is looking for the correct key rather than reflecting on the content of the text. Since such aids were not used in the current study, the problem of alignment should be kept in mind, i.e., the inferred relationships between temporal and revision data to specific cognitive processes during writing is not definitive.

Cognitive Aspects of Morphology

To fulfill the first purpose of the study – to find out the feasibility of using keystroke logging together with diagnostic tests – a diagnostic test was administered. This test was a morphological test which aims to assess the *morphological knowledge* of the recipient – which leads us to the second purpose – to see if the data from the keystroke logger can tell us something about morphological knowledge from a cognitive perspective. In linguistics, morphology is the study of words and their composition, and a morpheme is defined as the smallest meaning retaining linguistic unit. For example, the multimorphemic word *morphology* contains two morphemes: *morpho-* that stems from the Greek word *morphē* meaning "shape or form" and *-logy*, stemming from the Greek suffix *-logia* meaning "theory, science," etc. (Online Etymology Dictionary). Most people are probably not familiar with linguistic morphology or morphemes, but they are constantly (more or less consciously) manipulated in speech and writing, which becomes especially clear when regarding inflectional morphology – e.g., changing the tense of a verb such as *walk* into *walked*. In recent years, it has become increasingly clear that morphological proficiency is predictive of literacy. Research shows that the ability to utilize and understand morphological structures is a predictor for reading comprehension in several languages (Goodwin et al., 2022; Levesque, 2017). Furthermore, children have an easier time spelling multimorphemic words such as *turning*, than monomorphemic words such as *turnip* (Treiman et al., 1994; Deacon & Bryant, 2006), and it is also easier to provide definitions of multimorphemic words as one can derive meaning from the constituent morphemes (Anglin, 1993), e.g. it is possible to derive the meaning of *turning* by knowing the meaning of the root word *turn*, but it is not possible to derive the meaning of *turnip* by knowing the meaning of *turn* since to *turn* something is not part of the meaning of the word *turnip*. This evidence suggests that morphology plays a more important role in language development and literacy than previously thought.

A study by Goodwin et al. (2022) investigated the impact of different linguistic skills on adolescent reading comprehension. They used a computer-adaptive language assessment game called Monster, P.I; where participants answered questions relating to different linguistic skills, morphology, vocabulary, and syntax the results of which was compared to their reading comprehension. Goodwin et al. (2022) found that each area of skill played an important role in reading comprehension, but that vocabulary and morphological awareness played an especially important role. This result suggests that morphology (and vocabulary) plays a greater role in word-to-text integration than previously thought. Because of the success of Goodwin et al. (2022), the morphological part of the language assessment game Monster, PI was used to develop the linguistic diagnostic test which the participants of the current study performed.

The growing evidence of the importance of morphology on literacy development, as exemplified in Goodwin et al. (2022), has therefore led researchers to reevaluate the role of morphology within models of reading comprehension and the role of morphology. One such reevaluation is seen with Levesque et al.'s (2021) Morphological Pathways Framework (MPF), which outlines the cognitive system as consisting of multiple knowledge sources interacting in relation to morphology to support the reading and writing process. An example of two skills which was measured in Monster, PI and by the current study's morphological test that MPF explicates is morphological decoding and analysis. According to MPF, the morphological skills *morphological decoding* and *morphological analysis* serve as pathways between different linguistic systems and processes. For example, morphological decoding is the ability to use morphological information when spelling, providing a pathway between the orthographic system (which is used for spelling) and word identification processes. Morphological analysis, however, is the ability to use the semantic meaning of morphemes and provides a pathway from *morphological awareness* – the ability to identify and manipulate morphemes – to lexical representations in the word identification processes. The data provided by the keystroke logger was analyzed with MPF in mind since it situates the morphological skills that were tested by the morphological test within a cognitive framework. This was done to facilitate the second purpose of the current study – i.e., to investigate what the keystroke logging data can tell us about morphological knowledge according to current cognitive theory.

Method

Participants

The participants consisted of one English class of 21 students from the second year of Swedish upper secondary school. When taking the test, the participants were asked if they had a different first language (L1) other than Swedish of which there were two students, one English and the other Arabic. Data regarding their gender or age (other than being in their second year of upper secondary school) was not collected.

Instruments and Materials

GenoGraphiX-Log

The morphological test was taken using the keystroke logging software GenoGraphiX-log (GGXlog). The project was developed by Caporossi et al. (2023) in collaboration between HEC Montréal, University of Turku, ITEM and GERAD and is focused on data visualization of keystroke data. The program is intended for use by students, teachers, and researchers which provided a good fit for the purpose of this exploratory study. The program offers multiple writing contexts, such as free writing, where the user is provided with a blank window in which to freely write; translation, where the user is provided one window for a non-alterable and uploaded source text and a window for writing; and editing translation, which is the same as translation except that one uploads a text into the writing window for editing. In all these writing contexts, the user begins a session by pressing record and then commences writing in the program. During a writing session, GGXlog registers keystrokes, records temporal data and collects and stores the data in a log file. This data can then be displayed in spreadsheets and uploaded into other statistical software. The program also offers visualization of the data into multiple different tables and graphs.

Morphological Knowledge

To measure morphological knowledge, a linguistic test was developed using questions extracted from the computer-adaptive language assessment game Monster, P.I (Goodwin et al., 2022). This test measured four linguistic skills: (i) *Morphological Awareness*, (ii) *Morphological-Syntactic Knowledge*, (iii) *Morphological-Semantic Knowledge*, and (iv) *Morphological-Orthographic Knowledge*. The skills were assessed by two or more tasks consisting of 10 questions each and all referred to distinctive morphological linguistic abilities:

(i) *Morphological Awareness* refers to the ability to identify morphemes, which was tested in two of the test's tasks: Odd Man Out and Meaning Puzzles. In Odd Man

Out, the participants were provided with three words that shared a similar part. In two of these words, the similar part was the same morpheme (i.e., they shared the same meaning), and the participants were asked to identify and write the word that did not share a morpheme. In the task Meaning Puzzles, the participants were asked to choose the alternative that could help the participants to figure out the meaning of a target word – i.e., the word that shared a morpheme with the target word.

(ii) *Morphological-Syntactic Knowledge* is the ability to identify or produce the correct word and suffix that will complete a provided incomplete sentence. This skill is what the tasks Real Word Suffix and Making it Fit captured. In Real Word Suffix the participants were provided with a sentence that was missing a word, together with four alternatives with the same base word but different suffixes. The participants were supposed to choose the word that fit within and completed the sentence. In Making it Fit the participants were again provided with an incomplete sentence, but instead of four alternatives, the participants were given the base word that was supposed to be inflected and derived such that it fit within the sentence.

(iii) *Morphological-Semantic Knowledge* is an awareness of how morphemes provide semantic meaning (previously denoted as morphological analysis). The task that tested this skill was the Word Detectives task, where the participants were asked to identify the meaning of a morphologically complex word by using the meaning of the morphemes that constituted the word and the context provided together with the target word.

(iv) *Morphological-Orthographic knowledge* (or often called morphological decoding) is knowledge of how morphemes convey information about spelling. This was tested with a single task, where a word was read aloud, together with a sentence using that word, the word of which was then spelled by the participants.

Table 1

Morphological skill or task with an example.

Skill and Task	Example question
Morphological Awareness	
Odd Man Out	Which word shares the same part but has a different meaning? [mushroom*, bedroom, classroom]
Meaning Puzzles	Write the word that could help you figure out the meaning of MOVEMENT. [men, mover*, over, meant]
Morphological-Syntactic Knowledge	
Real Word Suffix	John wants to make a good ______ on his date. [impressive, impression*, impressionable, impressively]
Making it Fit	The cook wanted them to share the last piece of pie, but it was too small to be _____ (divide) into two pieces. [divided*]
Morphological-Semantic Knowledge	
Word Detectives	People were FEARLESS even as the big storm approached. The people could be descried as [A. brave*, B. tired, C. sad, D. scared]
Morphological-Orthographic Knowledge	
Morphological Spelling	(The words and sentences were not seen, only read aloud) [nondiscriminatory*] – we must endeavor to make the justice system *nondiscriminatory*.

Note. The linguistic skill is written in the left column in italics, whereas the task/tasks designed to measure the skill is written beneath the skill in standard bold text. The alternatives and answers are bracketed beneath the example item and the correct answer is marked by *.

The questions that constituted the tasks were extracted from Monster, P.I and marginally altered to fit a keystroke logging environment. All the multiple-choice tasks – Odd Man Out, Meaning Puzzles, Real Word Suffix, and Word Detectives – were altered such that the participants chose the answer by typing the answer, or letter (A-D) corresponding to the answer (as was the case in Word Detectives), instead of clicking the alternative. And in the Morphological spelling task, the words were read once and again within a sentence instead of being a repeatable recording (see table 1 for examples and appendix for the full test).

Procedure

The task was carried out over the duration of an English class (85 min). The students were first given a brief explanation of the purpose of the study, morphology, as well as how providing data would be both anonymous and voluntary. Then the students were instructed on how to download and take the test using GGXlog. The test was taken in the following order: (1) Morphological Spelling, (2) Real Word Suffix, (3) Making it Fit, (4) Meaning Puzzles, (5) Odd Man Out, and (6) Word Detectives. The test started with the morphological spelling task since words needed to be read aloud. Afterwards, the students proceeded at their own pace within the time limit. Each test required the student to upload the task document (including the 10 questions and instructions) and an answer sheet, which consisted of 10 empty, numbered rows on which to write the answers. To begin writing, the students clicked the record button which made it possible to write the answers. When the participants were finished, they raised their hand and were asked to consent to the use of their data for research purposes. If consent was given, the data was collected (consent was also given in GGXlog, before starting the test; however, they were still allowed to take the test if they disagreed).

Analysis

The analysis was conducted by collecting general data on key values such as number of cognitive pauses and revisions from the participant's sessions. No statistical models were used to analyze the general data provided by the participants because of the exploratory nature of this study; instead, the data was presented and visualized to present its primary characteristics. Based on the general results, a specific participant was chosen to allow for a more in-depth individual analysis of that participant's cognitive processes in relation to morphological knowledge. For the in-depth analysis, the statistical and data visualization tools of GGXlog were used.

Ethical Considerations

No personal data was collected other than their first language (L1), and the participants were informed about the purpose of the study before participating. To ensure full anonymity, the participant's data-file was given a coded name attributed to the participant and participants were informed that participating was fully optional and anonymous. Written consent was collected via a checkbox in the keystroke logging program, as well as verbally when approached to collect their data at the completion of the test. All of the students performed the test and consented to their data being used in the study.

Results and Discussion

The Results and Discussion section is split into two main parts: one where the quantitative data for the entire group of students is presented, and another where an individual analysis of one participant's cognitive processes in relation to morphological knowledge is presented. The quantitative study is split into a separate results and discussion section, and the individual analysis is presented in an integrated results and discussion section.

Quantitative Results

The results showed a relatively high variance, where total test scores ranged from 15-52 points out of a maximum of 60 – with an average of approximately 37.43 points and a standard deviation of approximately 9.43 (See table 2). The Morphological Spelling task, which measured *morphological-orthographic knowledge*, was the most difficult task with a 5-point average. Next in order of difficulty was Meaning Puzzles which measured *morphological awareness* with a mean of 5.81 points, and Word Detectives which measured *morphological-semantic knowledge* with 5.95 points. Then came Odd Man Out, which also measured *morphological awareness*, with a 6.38 score average. Lastly, Making it Fit and Real Word Suffix had a mean score of 7.10 and 7.19 respectively, making them the two easiest tasks – both of which measured *morphological-syntactic knowledge*. In addition to being the most difficult task, Morphological spelling was also the task with the most variability in score, and second most when it came to variation in revisions. It was the only task where a participant received a score of 0 out of 10, while the most successful participant received a score of 9. The minimum and maximum scores stayed relatively consistent, with one small outlier in the Real Word Suffix task – the task with the least amount of variation and where no participant received a score below 4 points.

The cognitive pause data showed less variation with a relatively high mean at 104.81 with a standard deviation of 11.81. The mean cognitive pauses and revisions between tasks followed a similar pattern: when pauses increased, revisions did as well (see figure 1). Not displayed, however, is any relation between the score and the pauses and revisions – the data showed no relationship between reflection about and revisions of answers and the result across the tasks. The Morphological Spelling task received the greatest mean of cognitive pauses as well as revisions at 22.29 and 23.62 respectively. This pattern continued in Meaning Puzzles as well, with a mean of 16.62 cognitive pauses and 12.43 revisions but breaks with the last two tasks Word Detectives and Odd Man Out. The task that took the most amount of time was the Morphological Spelling task; however, this value did not reflect the performance of the participants since the words that the students spelled were read up at a fixed pace and the session recordings did not start as soon as the first word was read. Furthermore, the time spent on each task did not align perfectly with when each student began with each task; rather, what it signified was the amount of time the window for writing was open. They could, for example, press record and start reading the instructions and then write their answers or read the instructions before pressing record. The revision data showed a high variance. Not surprisingly, the Odd Man Out task had the least amount of variance (4.81) and received a low mean of 4.81. Not strange, considering that this task was multiple choice and only required writing a letter (A-D) for the chosen alternative, unlike the other multiple-choice tasks Real Word Suffix, Word Detectives, and Meaning Puzzles which all required writing down the word alternative. However, the highest variance was displayed by the Real Word Suffix task, the task which had the highest average score and revisions, and second most cognitive pauses.

Table 2

Approximate (rounded to second decimal) mean (M), standard deviation (SD), minimum and maximum (Max. and Min.) values for test score, cognitive pauses, and revisions across the morphological test.

Variables	*M*	*SD*	*Min.*	*Max.*
Score	37.43	9.43	15	52
Cognitive Pauses	104.81	11.82	84	127
Revisions	77.86	56.21	11	278

Table 3

Displayed are the approximate (rounded to second decimal) mean (M), standard deviation (SD), maximum and minimum values (Max. and Min.) for test score, cognitive pauses, and revisions in each task.

Skill	Score				Cognitive Pauses				Revisions			
	M	*SD*	*Min.*	*Max.*	*M*	*SD*	*Min.*	*Max.*	*M*	*SD*	*Min.*	*Max.*
Odd Man Out	6.38	2.08	1	10	13.52	2.81	9	19	5.19	4.81	0	17
Meaning Puzzles	5.81	2.28	1	10	16.62	4.46	11	27	12.43	13.21	0	44
Real Word Suffix	7.19	1.50	4	9	19.90	3.82	14	31	17.67	21.04	0	98
Making it Fit	7.10	2.16	1	10	18.29	3.94	12	25	13.86	12.30	1	42
Word Detectives	5.95	1.99	2	9	14.19	3.65	8	25	5.10	11.67	0	55
Morphological Spelling	5.00	2.39	0	9	22.29	3.69	15	27	23.62	16.93	3	68

Looking at each participant there was an outlier when it comes to number of revisions: participant number nine (see figure 2) with a total of 278 revisions, 134 revisions higher than the participant with the second most revisions (participant thirteen with 144). Looking at the data for each individual person, this participant had an unusually high number of revisions in each task; however, one was the result of a misunderstanding of the instructions in the Odd Man Out task – instead of writing a letter corresponding to the answer, the participant typed the answer out in full. If we exclude the revisions from that task, participant nine had a total number of 223 – still the highest number. The participant stayed at the mean of both cognitive pauses and total score despite the unusual number of revisions.

Figure 1

Mean number of cognitive pauses, revisions, and score across each task in performed order.

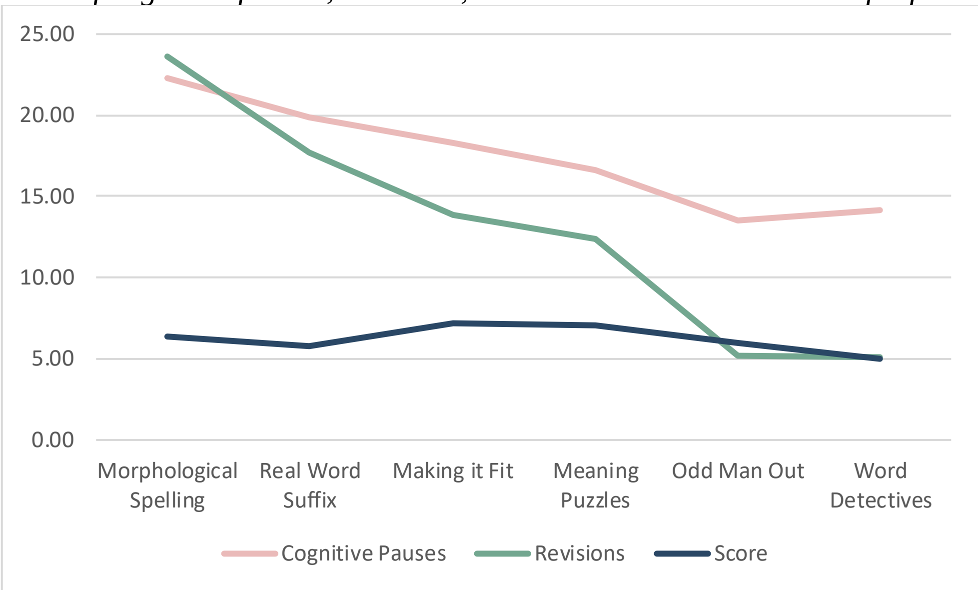
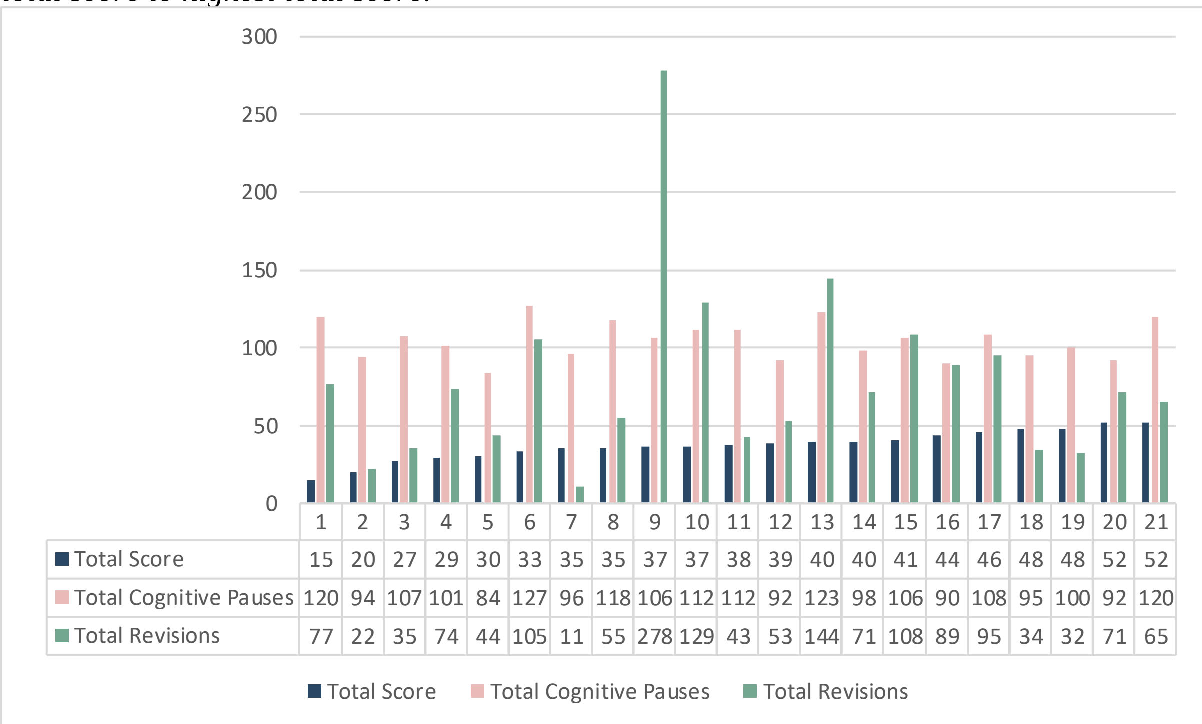


Figure 2

Total number of scores, cognitive pauses and revisions for each participant ordered from least total score to highest total score.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Total Score	15	20	27	29	30	33	35	35	37	37	38	39	40	40	41	44	46	48	48	52	52
Total Cognitive Pauses	120	94	107	101	84	127	96	118	106	112	112	92	123	98	106	90	108	95	100	92	120
Total Revisions	77	22	35	74	44	105	11	55	278	129	43	53	144	71	108	89	95	34	32	71	65

The versatility of the keystroke logging data was seen when investigating the fine-grained temporal effects of morphological processing. The logging data in the keystroke logger displays the time between each keystroke. If the most correctly spelled items are identified (*bravery*, *injustice*, and *underdevelopment*) in the Morphological Spelling task within one uninterrupted burst, we can see that there was a higher mean pause time (below 2 seconds, i.e., not cognitive pause time) between morpheme boundaries (see Table 4).[1]

Table 4

Task item, sample size and each keystroke and the time between each keystroke (in milliseconds).

Task item	*Sample*	Keystroke and mean pause time (ms)
bravery	15	b <223> r <162> a <230> v <169> e **<286>** r <168> y
injustice	15	i <136> n **<243>** j <165> u <180> s <194> t <119> i <83> c <85> e
underdevelopment	9	u <123> n <43> d <70> e <109> r **<513>** d <79> e <153> v <130> e <171> l <151> o <232> p **<270>** m <119> e <60> n <57> t

Note. The pauses are represented in milliseconds within angled brackets (< >). The morpheme boundaries are represented by pauses in bold.

When spelling each of these three items, the highest mean pause time always occurred at the morpheme boundary. In *bravery* it occurred between *brave-* and *-ry*; in *injustice* it occurred between *in-* and *-justice*; and in *underdevelopment* it occurred between *under-* and *-development*. Interestingly, for *underdevelopment*, the second highest mean pause time occurred between two morphemes as well: *develop-* and *-ment*.

Quantitative Discussion

Previous studies have shown that as cognitive demand increases, more pauses and errors result (Conijn et al., 2019; Wengelin, 2006). With this in mind, one might expect to see a clear indication of this effect in the data – e.g., as the task's difficulty increases, the number of revisions and cognitive pauses rises. But there seems to be no immediately clear relationship between how easy the tasks were (reflected in the scores), and the amount of high-level processing employed (represented by the cognitive pauses), nor number of revisions (see figure 1). What this might indicate is that the data provided by the keystroke logger is something which is not captured by mere test score results (whether the data is useful is another matter). For example, two students that received a score of 40 and 39 (both around the mean) had a very different number of cognitive pauses and revisions: the former student (with a score of 40) had a total of 123 total cognitive pauses and 144 revisions, while the latter student (with a score of 39) had a total of 92 total cognitive pauses and 53 revisions (see figure 2). Upon reflection, this seems perfectly reasonable. Some might have struggled with the test but ultimately got a good result, while others need not struggle at all; some breezed through the test and got a bad score, perhaps through a lack of motivation or because of unawareness of their limited morphological knowledge. Therefore, if a keystroke logging environment contributes new information above that which is given by the test results, this is one of the possible outcomes.

As an example of the type of information about morphological processing – besides general and high-level cognitive processes – the keystroke logger captures, we can look closely

[1] These three items were the only ones looked at since they are the only words that were consistently spelled correctly without any interruptions. This is necessary since interruptions would make an inference to implicitly used lexical representations difficult. Interruptions are any event which interrupts a burst – i.e., deletions of keystrokes or a cognitive pause. Even though the students wrote words in other tasks, this is the only task in which the morphological aspect was implicit. If analyzed the data from Making it Fit (which also was not a multiple-choice task), it might not preserve validity because the students were provided the standard form of the word, which is preserved in the word's root.

at the keystroke logging data for the Morphological Spelling task. Here we saw that pauses between morpheme boundaries were generally longer than those within morphemes. If we look at the three words in the task that the students had an easier time writing in one burst, without interruptions, we can see longer pauses between morpheme boundaries. This is precisely what has been found in previous studies and has been called the morpheme boundary effect: temporal delays increase when typing letters at the beginning of a morpheme or syllable (Weingarten, 2005; Gagné & Spalding, 2016). Such evidence reinforces models that stress the importance of morphological information in the cognitive process of writing (Gagné et al., 2023). And the logging data from this experiment provides a window into fine-grained information regarding what type of lexical representations are used during the writing process.

Other data from the keystroke logger beyond cognitive pauses and revisions could perhaps provide better insight into the relationship between the cognitive processes and difficulty as reflected in the results of diagnostic tests – burst fluency, for example. Further research into the usage of keystroke loggers with diagnostic tests might prove more successful in establishing such a connection. The program GGXlog does not, at the moment, include any tools for the visualization across individuals or sessions. Instead, the data is provided to be used with other statistical programs. However, if used by teachers it would be helpful to be able to import multiple sessions for analysis and visualization to facilitate comparisons of multiple students.

Individual Results and Discussion

A specific participant's result was analyzed connecting the participant's cognitive processes as represented by the keystroke logging data to their morphological knowledge captured by the morphological test. The selection of a particular participant was made based on performance on the morphological test reflected by their total score, number of cognitive pauses and revisions. Participant fourteen (see figure 2) received a mean score of 40 (slightly above the mean of 37.43 points), a mean of 98 cognitive pauses (5.81 below the mean of 104.81), and 71 revisions (6.86 revisions lower than the mean of 77.86). This was the participant closest to the mean on all three variables and was thus selected to best exhibit what was captured by the keystroke logger.

GGXlog provides a multitude of tools for analyzing and visually representing data. If we start with the first task that the students performed, Morphological Spelling, we can look at the Linear Text notation to view each keystroke, revision, as well as the location and length of cognitive pauses. In the text string we can clearly see the location of R-bursts that resulted from mistyped keys – e.g., the typing of the character *b* instead of *v* in (1).

(1) Brabe<BACKSPACE2>very

Connecting to the Hayes model, this seems to be a result of the evaluator monitoring and interrupting the transcriber, which is generally the case with R-bursts. This is probably the result of the keys for the characters *v* and *b* are beside each other; however, R-bursts occur when correcting certain spelling mistakes resulting from the participants knowledge – rather than a mistyped key – as well, which we can see in the correction of *maintenance* in (2).

(2) Maintene<BACKSPACE>ance

We can see that this R-burst was probably related to linguistic capacities compared to the previous example since it clearly related to the spelling of the suffix *-ance*. The spelling mistake that the participant corrected was made by several other participants, which isn't strange since it is different spellings of the same morpheme – e.g., *maintenance* compared to *insolence* or *difference*. If we look at the participant's notation for *diagnostician* in (3), the same type of mistake was almost made again before a quick correction.

(3) Diagnos<4265>tici<BACKSPACE5>sti<2260>cion<BACKSPACE2>an

Participant fourteen almost wrote "diagnosticion" instead of "diagnostician". Much like *-ance* and *-ence*, the morphemes *-ion* and *-ian* are pronounced the same – e.g., *suspicion* or *coercion* and *physician* or *musician*. What we can see displayed in the latter case (*diagnostician*) seems to be the recognition of the information carried in morphemes – i.e., morphemes with the same pronunciation are generally spelled differently depending on the linguistic meaning it carries. These are the "islands of regularity" (Rastle et al., 2000) morphology provides to orthographic processing. The usage of morphological information for orthographic processing is a clear example of morphological decoding (what this task is meant to measure), which we can see as the orthographic system interacting with the word identification process in the Morphological Pathways Framework (Levesque et al., 2021). However, morphemes do not always come with this type of regularity as was displayed in the former case (*maintenance*) since the spelling of the morpheme in *difference* and *maintenance* do not differentiate meanings carried by different morphemes. This is something which is learned during reading and writing development: that spelling requires the integration across morphological and orthographic patterns (Levesque et al. 2021). In other words, one must learn to utilize orthographic patterns as well as morphological patterns. Here, participant fourteen successfully integrated both patterns, which was sometimes not successful across participants, as was the case with participant three when they wrote "diagnostision".

Continuing, two clear P-bursts is displayed in (3). The first one, "Diagnos", was followed by a four second pause, which was followed by what looks like an evaluation and planning process (thinking about how *-stician* is spelled) that was later followed by another P-burst and later a revisional R-burst. The P-bursts are the more cognitively interesting types of bursts since they seem to be events related to cognition about the content of the test and higher-level evaluative and planning processes rather than reflexive corrections of mistyped keys. As previously mentioned, P-bursts are thought to reflect the capacity of the translator and therefore linguistic capacity, and the relevant metric is sometimes seen as either burst length (number of characters) or fluency (number of characters per minute). However, this is not a direct reflection of linguistic capacity since the translator is limited by the planned message of the proposer (Galbraith & Baaijen, 2019). In this case, it was further limited by the test that was performed, i.e., the task materials within the task environment in Hayes model, which affects the content that is planned by the proposer. In this way, morphological knowledge interacted with the involved cognitive processes (the proposer and translator) and should be reflected in the P-bursts.

GGXlog also contains a Burst and Fluency Analysis. This type of analysis visualizes the distribution of bursts over time throughout the session. The *trimmed mean burst fluency* is displayed in this type of analysis, which was approximately 440 characters per minute for participant fourteen. We can compare this to participants twenty-one and ten with a burst fluency of approximately 463 and 400, and a score of 9 and 3 on the spelling task respectively. Not surprisingly, considering that difficulties with spelling should lead to more and shorter bursts, hence less fluency. This type of analysis is better suited to the writing of longer texts, rather than a diagnostic test with short answers and multiple-choice questions. If the test could be divided such that it visualizes individual questions and their written answers separately, it might prove more useful. The same applies to the Pause Analysis. However, it does provide a more useful overview since it categorizes the cognitive pauses according to where they occur and what type of action the pause is connected to. For example, 16.67% of the total number of participant fourteen's pauses were located within words and probably regard uncertainties about spelling (considering the task). Participant twenty-one, who got a higher score (9 out of 10) in the spelling task, had a within word pause percentage of 4.55.

Moving to the task Making it Fit we can see that participant fourteen struggled in (5) with inflecting the word *provocation* in (4).

(4) He remained calm despite repeated _______ (provoke).

(5) prob<BACKSPACE>vol<BACKSPACE>keation<BACKSPACE6>ation<BACKSPACE5>eing<BACKSPACE3>omg<BACKSPACE3>ing<BACKSPACE4>e<BACKSPACE>ation

The participant went from "provokation" to "provoking", then back to "provokation". First of all, despite having chosen the correct morpheme, the participant failed to correctly derive the word, spelling it with a *k* instead of a *c*. This might be because English is participant fourteen's second language, and *provokation* is the Swedish translation of *provocation* (it could also be because of irregularities in how the root is spelled depending on the derivation). Furthermore, the fact that the participant almost chose the wrong derivation might indicate that they struggle with agreement – the adjective *repeated* cannot describe the verb *provoking* since it would have to be a noun. However, this behavior is not repeated in this task and the participant performed well, with a score of 8 out of 10 (one point above the mean).

Both of the tasks Morphological Spelling and Making it Fit were non-multiple choice, while the four remaining tasks was a form of multiple choice. This means that the type of data one can look for changes since there was a considerable drop in within-word pauses or revisions for multiple choice tasks. This would probably be due to experiencing a lot less cognitive load – the planning processes are altered in that one does not have to come up with possible answers from scratch, the answers do not have to be cognitively maintained, and the amount of orthographic processing needed is decreased since the correct spelling is already provided. It is considerably more difficult to extract any useful data from multiple choice questions with the provided analytical and visualization tools. What can be looked at instead are changes in answers and the order in which answers were given. In the task Real Word Suffix for instance, we can see that participant fourteen skipped over two questions and returned to provide the answers at a later point in time. To skip over questions that one finds difficult is not an unusual strategy, and keystroke logging data captures the use of such strategies that would otherwise be inaccessible, allowing us to get a clearer picture of what tasks the participants struggled with. In this case, participant fourteen got a score of 8 out of 10, one error of which occurred in one of the two skipped questions. The same strategy was applied in the Odd Man Out task. In line with the group level analysis, participant fourteen had an easier time with the morphological-syntactic tasks Real Word Suffix and Making it Fit. In the task Meaning Puzzles, the participant got their lowest score of 4 out of 10. Interestingly, there is no real indication of a struggle in the keystroke logging data, showing an average amount of cognitive pauses for the task (17 compared to the mean of 16.62) and a low number of deletions (6) compared to the mean (12.43). This result is difficult to interpret but it seems to indicate an absence of indecisiveness. Whether or not we can see an explicit thought process within the keystroke logging data seems, again, to be dependent on the person and, as far as the current findings indicate, not connected to performance and the participant's morphological knowledge.

Concluding Remarks

The purpose of this exploratory study was to investigate (i) the feasibility of using keystroke logging programs in conjunction with diagnostic tests to produce further information about the test taking process and (ii) what the provided data can tell us about morphological knowledge according to contemporary cognitive theory. Implied by these purposes is the goal of providing a starting point for the use of keystroke loggers when taking diagnostic linguistic tests. The keystroke logger provides multiple avenues for analysis using statistical data which can be extracted from the sessions, as well as tools for analyzing the individual sessions and visually representing the data. As such, a part of providing the starting point is to assess the aptitude of the tools for diagnostic linguistic tests. As of this point, the current visualizations are more suited for longer-form writing sessions, and this is precisely what keystroke loggers have thus far been used for. Because of the format that is required for the logging sessions, it is not easy to design a diagnostic test with short-form answers. If one were able to design a test with a keystroke logger such that each question is presented in its own window and questions are marked in the visualization, then connecting the keystroke data to the content of the diagnostic test would be clearer. As of now, there is no way to demarcate the questions in, for example, Pause Analysis or Burst and Fluency other than noting when the participant started each question for each of the tasks and then compare it to the Pause Analysis and Burst and Fluency analysis.

Further research is needed to determine how diagnostic linguistic tests should be designed when combined with keystroke loggers, but multiple-choice answers should probably be limited such that choosing an alternative is made in one keystroke (as was done with the Odd Man Out task), as opposed to writing the alternative word letter by letter. This will streamline the analytical process and remove superfluous data – i.e., mistyped keys when answering. This will make the visualization for the multiple-choice questions more useful as well since such datapoints are not pertinent. For example, mistyped keys will show up in the Pause Analysis categorized as deletions, but if multiple choice answers are made by typing a specific letter (A-D, as was the case with the Meaning Puzzles task) it is more likely that the deletion was a change of answer.

When it comes to the use of investigating the individual cognitive processes, we can see clear examples of cognitive processes relating to morphological knowledge, but these are mostly confined to the individual performance of participants. We can see the island of regularity in action, as well as the successful integration of morphological patterns with orthographic patterns in the Morphological Spelling task. Evaluative and planning processes were displayed in the data throughout the tasks revealing uncertainty and reflection. What kind of pauses and bursts that relate to the content of the morphological test was demarcated by noting where they occur and what type of action follows the event in question. Therefore, keystroke logging seems to be able to provide a better understanding of morphological processes in diagnostic testing environments. This information would not be accessible in a diagnostic test with a pen and paper format, which shows positive prospects for the use of keystroke loggers together with diagnostic tests. However, a lot more research needs to be done to streamline its use and effectiveness.

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Appendix

Morphological Test

This appendix consists of the morphological test, including the test forms for each of the six tasks arranged in the performed order, that was taken by the participants. The test consists of one document for each task, including instructions and the questions.

Task 1: Morphological Spelling

A total of 10 words will be read aloud first as an individual word, then in a sentence. Write down each word on the correct row.

1. Bravery - he received a medal for bravery.

2. Injustice - the law is part of an effort to correct injustice.

3. Underdevelopment - the baby was born with an underdevelopment.

4. Nondiscriminatory - we must endeavour to make the justice system non-discriminatory.

5. Asymmetrical - Victorian architecture is known for asymmetrical shapes.

6. Diagnostician - a diagnostician specializes in medical diagnosis.

7. Maintenance - bridges require a lot of maintenance.

8. Acknowledgement - I applied for five jobs, but only got three acknowledgements.

9. Likelihood - in all likelihood, everything will go to plan.

10. Odorous - odorous cheeses should be tightly wrapped.

Task 2: Real Word Suffix

You will see a number of sentences that are missing a word. You have four different words that share the same root (the main part of the word) but have a different suffix - that is, the words end in different ways. Your task is to write down the word that best fits within the sentence.

Let us look at an example:

1. John wants to make a good ______ on his date.

    impressive
    impression
    impressionable
    impressively

The first word doesn't seem to be right since "to make a good impressive" does not sound correct. We cannot have an adjective describing another adjective in this way. However, "to make a good impression" does sound right - the adjective "good" can describe the noun "impression". Therefore, the answer is "1. impression".

The real task begins here!

1. The success of the entire military ______ depended on the training of the soldiers.

    operative
    operational
    operation
    operationalize

2. Although the fire was extinguished, the remaining smoke in the air strongly reduced ______.

    visibility
    visible
    visualize
    visibly

3. The new ______ of the bird species had a longer beak and smaller wings than most of the other kinds of birds in its family.

    variously
    variant
    varied
    variable

4. The political candidate promised an ______ distribution of resources for all voters.

    equality
    equally
    equalization
    equitable

5. The construction of the grand cathedral was completed thanks to the ______ of the royal family.

    beneficiential
    beneficial
    benefit
    beneficence

6. Some plants ooze a certain kind of ______ gel when they are damaged, which protects the wound from further injury.

    mucilagize
    mucilage

mucilaginous
mucilant

7. The ______ of the discussion kept it moving along smoothly, encouraging others to speak up and avoiding getting stuck.

facilitate
facile
facility
facilitator

8. Carefully ______ the results from even simple experiments helps students develop habits of scientific thinking.

analytical
analyzing
analysis
analyze

9. To act ______ means to donate from your personal wealth, no matter how much money you have.

philanthropic
philanthropically
philanthropist
philanthropy

10. Cleaning out the refrigerator of the months of leftovers helped her understand the biological process of ______.

putrid
putrefy
putridity
putrefaction

Task 3: Making it Fit

You will see a number of sentences with an important missing word. You will be given a clue word that is written in its uninflected form. This means that you will have to change the word's form to make it fit in the sentence.

Write down the correct form of the clue word provided in parentheses such that it fits within the sentence.

Let us look at an example:

1. The cook wanted them to share the last piece of pie, but it was too small to be _____ (divide) into two pieces.

In this example, the clue is "divide" and to fit in the sentence we have to change the form into past tense by adding the suffix -ed. That means that the answer is "1. divided".

The real task begins here!

1. He left the _____ (equip) they needed for the science experiment in his car.

2. He remained calm despite repeated _______ (provoke).

3. A wise __________ (advertise) will get to know the people to whom they are attempting to sell their product.

4. In literature, an allusion is when one text makes _________ (refer) to another, typically well-known, text.

5. Some people argue that the _______ (sense) thing for Rosa Parks to do on her historic bus ride would have been to give up her seat, but instead, Rosa Parks stood up for what was right and started a movement.

6. Charles Schulz is the famous _________ (cartoon) who created such memorable comic strip characters as Charlie Brown and Snoopy.

7. The primary ________ (argue) of the paper was that students should not receive more than two hours of homework each night.

8. The ________ (instruct) of the chemistry course was known to strictly enforce the attendance policy, so it was important to be on time to every class.

9. My teacher says to handle the iPads _______ (care) so they don't break.

10. Pop music is catchy because of its ________ (rhythm) beats and melodic verses.

Task 4: Meaning Puzzles

It is sometimes difficult to figure out the meaning of a word, and it is sometimes necessary to use a part of the word to figure out its meaning or to utilize another word that shares a part with the same meaning. In this task, you will choose the word that can help you figure out the meaning of the capitalized word.

Choose one of the four provided words beneath the question and write it down.

Let us look at an example:

1. Write the word that could help you figure out the meaning of MOVEMENT

men
mover

over
meant

In this example, the answer is "1. mover". We can figure this out because "mover" shares the part "move" with the word "movement". The fact that they share a part with the same meaning tells me that "movement" has to do with the process of something moving.

The real task begins here!

1. Write the word that could help you figure out the meaning of CENTRALITY

cent
entrails
reality
center

2. Write the word that could help you figure out the meaning of ACCUSATORY

accurate
accuse
cushion
custom

3. Write the word that could help you figure out the meaning of MONOTONY

tone
money
notorious
notion

4. Write the word that could help you figure out the meaning of INTERNALIZATION

international
internship
intermarry
internally

5. Write the word that could help you figure out the meaning of IMPOVRISHMENT

improvise
impose
poverty
over

6. Write the word that could help you figure out the meaning of RESPIRATION

pirate

spiral
respite
perspire

7. Write the word that could help you figure out the meaning of EGOCENTRIC

centennial
center
ergonomic
egalitarian

8. Write the word that could help you figure out the meaning of PERIPHERAL

perish
personal
period
perimeter

9. Write the word that could help you figure out the meaning of AUTOCRACY

democratic
auction
authorial
emergency

10. Write the word that could help you figure out the meaning of JUVENILE

convenient
profile
rejuvenate
judicial

Task 5: Odd Man Out

Each question consists of three words; two words are associated, and one is not. Each of the three words have one part in common that consists of the same letters. In two of the words, the part has a similar meaning but in one of them it does not. Your task is to write down the word that has the same part with a different meaning.

Let us look at an example:

1. mushroom bedroom classroom

In this example, we can see that each word shares the part "room". In "bedroom" and "classroom" the part means the same thing: an enclosed area (room) in a building. However, in the word "mushroom" the part "room" does not mean an enclosed area in a building. Therefore, the answer is "1. mushroom".

The real task begins here!

1. lighten listen weaken

2. interior interact interfere

3. illness business lioness

4. desolate solitary solarium

5. doctor vendor labor

6. incontrovertible contagion contradict

7. unstable valuable comfortable

8. sulfide confident infidel

9. irritating irregular irrational

10. annual perennial announce

Task 6: Word Detectives

When reading, one sometimes stumbles upon an unfamiliar word and it's sometimes useful to use different kinds of clues to figure out its meaning. These clues can sometimes be found within the word itself or in the sentence it is in. In this task, you will choose the meaning of the capitalized word within the sentence.

Write down the letter (A, B, C or D) of the capitalized word's meaning on the correct row.

Let us look at an example:

1. People were FEARLESS even as the big storm approached. The people could be descried as

    A. brave
    B. tired
    C. sad
    D. scared

In this example, the word FEARLESS is made up of the parts "fear" and "less". Put together, the word must mean to be without fear, which is what "brave" means. Therefore, the answer must be "1. A." since "brave" corresponds to the letter A.

The real task begins here!

1. The order of the presentations was PREDETERMINED. The presentations were

A. early in the day
B. randomly organized
C. very lengthy
D. decided ahead of time

2. During the Jurassic Period, there was a marked DIVERSIFICATION of animal life. This period saw

A. the death of many animal species
B. animals become more aggressive
C. animals start to live longer
D. an increase in the variety of animals

3. The sponge is UNSATURATED. The sponge

A. cannot be used
B. is falling apart
C. is filled with water
D. can hold more water

4. The two teams had an ADVERSARIAL relationship. The two teams

A. were friendly with one another
B. worked together well
C. fought a lot
D. questioned each other

5. Although rare, MATRIARCHAL societies exist around the world. From Albania to the Congo, numerous communities are traditionally and successfully led by

A. men
B. religious leaders
C. kings
D. women

6. Our system of government makes it difficult for the President to make UNILATERAL decisions. This prevents

A. seeing one side of the issue
B. making quick decisions
C. compromising with others
D. changing opinions

7. An INTERPLANETARY magnetic field was discovered to have an effect on auroras. This magnetic field

A. covered the whole earth
B. extended between planets
C. was strongest around the poles
D. was generated by aircraft

8. Many people considered the point that the politician made to be INDUBITABLE. They thought that what she said was

A. controversial
B. obviously true
C. very important
D. questionable

9. There were new advances in research during World War II leading to the first SUPERSONIC flight. The aircraft traveled

A. faster than a person
B. faster than the sun
C. Faster than the speed of light
D. faster than the speed of sound

10. The current world record holder in the DECATHLON is American athlete Ashton Eaton. In the 2015 World Championships, he scored a total of 9045 points from

A. winning multiple years in a row
B. ten different events
C. the panel of judges
D. running marathons