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Article

The impact of environmental noise on the cognitive functions and mental workload of high school students

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SUMMARY

Research shows that environmental noise has significant negative impacts on the cognitive processes of young children. Past research has focused on young children or adults and has looked primarily at higher noise levels (>70 dBA). This study covers a gap in literature by observing 70 teenagers from an upstate New York high school who completed tests of select cognitive processes in one of five background noise conditions: 30 dBA of aircraft noise, 30 dBA of construction noise, 60 dBA of aircraft noise, 60 dBA of construction noise, or quiet (i.e., no additional noise). Outcome measures included task accuracy and the workload experienced while completing the task as measured by the NASA Task Load Index (NASA-TLX). We hypothesized that the level and type of background noise would impact both task accuracy and NASA-TLX ratings. Linear regression for task accuracy revealed statistically insignificant ($p>0.05$) effects of the three noise levels and two noise types. However, noise levels impacted NASA-TLX ratings ($p<0.05$). Results suggest that the students experiencing 30 or 60 dBA of background noise recruited more attentional resources to reach the same level of accuracy as their peers who completed the tasks in quiet. Educators should be aware of this discrepancy between mental demand and cognitive task accuracy to understand a significant cognitive strain stems from noise levels not defined as "harmful" (<70 dBA for <8 hours as suggested by the CDC). Future research should study a longitudinal version of this experiment, as there may be amplified mental workload strain over time.

INTRODUCTION

Schools in urban environments, particularly larger buildings like high schools, are surrounded by regular construction, highway, and road construction schedules. Airports have the highest density in urban areas, and aircraft noise is, therefore, a rapidly growing factor in noise pollution for schools in urban areas (1-5). The World Health Organization (WHO) has identified environmental noise as a public health problem, as environmental noise contributes to cardiovascular disease, sleep disturbance, tinnitus, annoyance, and cognitive impairment in children (6). Environmental noise not only interferes with young children's ability to understand target speech, but it also impairs their learning and memory (7). Importantly, the same environmental noise often impacts adults to a lesser degree and some forms of background noise do not impact adults at all (7-10). Therefore, administrators and teachers would benefit from being more aware of the potential impacts of background noise on children as they are less unlikely to struggle with background noise to the same extent as their students.

The cognitive skills of memory recollection (the ability to remember specific information) and attentional control (awareness of a certain stimulus in the environment) are both negatively impacted by irrelevant background noise. For example, when asked to remember sequences of numbers, words, or even pictures for a few seconds, both children and adults often recall fewer items in the presence of background noise (7, 10). However, adults tend to be impacted only by background noises with highly variable acoustic properties (i.e., volume, tempo, pitch). For example, adults may be impacted by cafeteria chatter containing periodic alarms from restaurant equipment but not the cafeteria chatter alone (10). In contrast, elementary school-age children are impacted by background noises as simple as the continuous repetition of a single, meaningless syllable (9). Background noise impacts serial recall because it both captures attention and disrupts a strategy known as rehearsal (11). Rehearsal – a form of private speech – is the repetition of the to-be-remembered item's verbal label. For example, when seeing pictures of an apple, a flower, and a bird, a child might say "apple, flower, bird, apple, flower, bird." Not only does attentional control develop throughout childhood and adolescence, but engaging rehearsal requires more attentional resources for children than adults (7, 12). Consequently, more emphasis has been placed on the effect of irrelevant background noise diverting attentional resources during rehearsal processes, therefore limiting serial recall abilities (7). Importantly, if background noise disrupts children's rehearsal, it may also disrupt private speech that supports a wide range of executive functioning and reading comprehension tasks.

The studies discussed above have focused on elementary-grade students and adults. However, there is less data on the noise disruption high school students experience and the specific cognitive functions affected. Standards for noise levels in classrooms only reference expectations for unoccupied classrooms. According to the American National Standards Institute, when no students or teachers are present, ambient noise levels should remain under 35 decibels (dBA) – approximately the sound level of a soft whisper; however, occupied K-12 classrooms regularly reach 50-65 dBA during the school day (13). These noise levels are not deemed a safety hazard, but they may be sufficient to disrupt learning. Indeed, higher average daily sound levels within classrooms were correlated with lower math scores

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on state-wide, standardized tests (14). The same study observed no significant correlation between noise levels and reading scores on the same standardized tests; however, these correlations reflect relationships between academic performance and average noise levels experienced during daily learning rather than noise levels at the time of testing. Therefore, it remains unclear how low-level environmental background noise may acutely affect high school students' performance on cognitive tasks such as sustained attention, immediate recollection, and reading comprehension.

Adults' subjective workload, the total cognitive work needed to accomplish a task, has been found to be significantly affected by noise levels at 95 dBA (11). Measured by questionnaires, these assessments demonstrate how individuals must exert an added effort to filter out irrelevant noise as they complete a task, even when accuracy on cognitive tasks do not differ significantly. Less information is available on the effects of noise on the workload of younger children or teenagers. Background noise at lower levels should also be addressed, as levels below 95 dBA may also have an adverse effect on cognitive workload. If background noise impacts cognitive performance or makes carrying out cognitive tasks feel more challenging, then students may be less productive in school. To further our understanding of the relationship between low-level environmental background noise and cognition, we tested the effect of noise pollution on high school students' performance when completing common school-like tasks.

Teenagers (aged 14 to 17 years) attending a high school in upstate New York completed tasks measuring sustained attention, recollection, and reading comprehension either in quiet or in the presence of environmental background noise. Additionally, they completed self-report measures gauging workload based on mental demand, physical demand, temporal demand, performance, effort, and frustration. We hypothesized that task accuracy will be lower, and workload will be higher when students complete cognitive tasks in the presence of background noise than when completing tasks in quiet. Results showed that increasing noise level significantly impacted cognitive load across all cognitive tasks, but did not significantly impact accuracy. This suggests that students experiencing higher noise levels recruited more attentional resources to reach the same level of accuracy as students who completed the tasks in quiet.

RESULTS

Tasks involving specific cognitive functions utilized in high-school classroom environments were selected to indicate the impact of low-level background noise on academic performance and cognitive load. Participants included 70 students (14-17 years old) who completed three cognitive tasks: (1) The Toulouse-Piéron task assesses sustained attention; students were given three unique items to circle and instructed to circle any items identical to these targets (2) The Word-to-Picture assesses recollection; students were asked to study symbols corresponding to given words and to draw the correct corresponding symbol when shown a given word (3) The Reading Comprehension task assesses a variety of cognitive functions such as visual processing and working memory and consists of a shortened version of standardized English comprehension tests distributed based on grade level. These tasks are often used to measure academic ability, and experiments were designed to test students similarly to in-school tests but with environmental background noise at controlled sound levels. Multiple linear regression was used to test if noise levels (quiet, 30 dBA, 60 dBA) and noise types (aircraft, construction) significantly predicted outcomes on these three tasks. With these models, we either predicted the error rates for each task or the raw NASA-Task Load Index (NASA-TLX), which measures perceived workload. In all analyses, the fitted regression model was:

Outcome (error rate or NASA-TLX) ~
*Noise Levels*Noise Type*

Testing sustained attention with the Toulouse-Piéron

The Toulouse-Piéron task is a cancelation-style sustained attention task administered with pen and paper. Although noise type significantly predicted errors ($\beta = 0.09$, $p = 0.03$), the overall regression for error rate was not statistically significant ($R^2 = 0.17$, $F(37, 4) = 1.85$, $p = 0.14$) as the effect of noise type on errors was small (**Figure 1**). However, the overall regression for perceived workload measured by NASA-TLX was statistically significant (**Figure 2**, R2 = 0.82, $F(37, 4) = 41.98$, $p < 0.01$). Noise level significantly predicted NASA-TLX ($\beta = 1.81$, $p < 0.01$), but there was no main effect of noise type (**Figure 2**, $\beta = -0.42$, $p = 0.14$). Tukey post-hoc tests, corrected for multiple comparisons, confirmed that the impact of all three noise levels differed (all p-values < 0.01). High school students performing the task with 60 dBA of background noise reported greater workload (Mean = 2.79, SD = 0.41) than students with 30 dBA of background noise (Mean = 1.39; SD = 0.49). Both groups reported greater workload than students with no background noise (Mean = 0.75; SD = 0.61). These results suggest that students reported a significantly higher cognitive load under higher levels of both aircraft and construction noise, even though they reached the same level of accuracy as students without background noise.

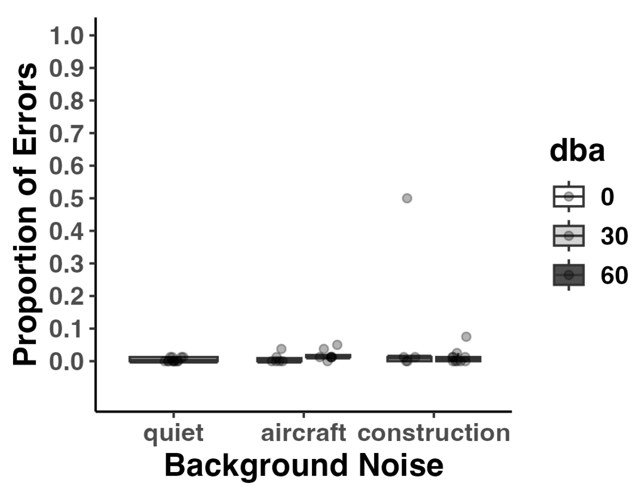

Figure 1: Noise had no effect on sustained attention accuracy. Boxplots of error rates (proportion of misses + false alarms) on the Toulouse-Piéron Task of Sustained Attention are similar across noise conditions. High school students completed the Toulouse-Piéron under 30 or 60 dBA of aircraft or construction noise or in quiet. Multiple linear regression, p = 0.14.

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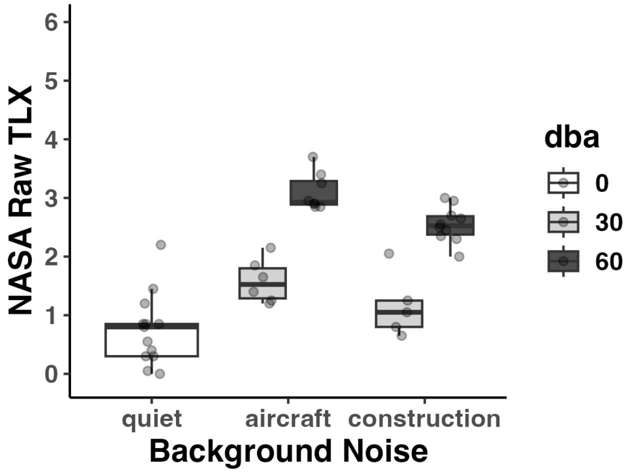

Figure 2: Workload during sustained attention task was greater in background noise. Boxplots of raw NASA-TLX scores on the Toulouse-Piéron Task of Sustained Attention by noise condition. High school students completed the Toulouse-Piéron under 30 or 60 dBA of aircraft or construction noise or in quiet. Multiple linear regression, $p < 0.01$.

Testing recollection with the matching word-to-picture task

The word-to-picture task assesses recollection of four word-to-shape associations over a timespan of two minutes. The overall regression of error rates on the word-to-picture task was not statistically significant (**Figure 3,** R2 = 0.20, F (39, 4) = 2.38, p = 0.07). The overall regression for perceived workload was statistically significant (**Figure 4,** R2 = 0.57, F (39, 4) = 12.71, p < 0.01). Noise level significantly predicted NASA-TLX (β = 2.24, p < 0.01), but there was no effect of noise type (**Figure 4,** β = -0.41, p = 0.33). Tukey post-hoc tests, corrected for multiple comparisons, showed that 30 and 60 dBA sound levels were different from 0 dBA (p < 0.01) but not from each other (p = 0.10). High school students performing the task with 60 dBA of background noise (Mean = 2.81, SD = 0.55) and students in 30 dBA of background noise (Mean = 2.25; SD = 0.50) reported greater workload than students with no background noise (Mean = 1.11; SD = 1.01). Again, mental workload was significantly higher for students under 60 dBA of background noise compared to students under 30 dBA when testing recollection, but there was no significant difference between those same students' performance on the task.

Testing reading comprehension using PSAT/SAT practice tests

The reading comprehension task was sourced from publicly available PSAT/SAT practice tests. Again, the overall regression of error rates on the reading comprehension task was not statistically significant (**Figure 5,** R2 = 0.11, F (43, 4) = 1.34, p = 0.27). The overall regression for workload was statistically significant (**Figure 6,** R2 = 0.54, F (43, 4) = 12.47, p < 0.01). Noise level significantly predicted NASA-TLX (β = 2.27, p < 0.01), but there was no effect of noise type (**Figure 6**, β = -0.42, p = 0.32). Tukey post-hoc tests, corrected for multiple comparisons, confirmed that all three noise levels differed from one another (all p-values < 0.01). High school students performing the task with 60 dBA of background noise reported a greater workload (Mean = 2.88, SD = 0.66) than students in 30 dBA of background noise (Mean = 2.12; SD = 0.65) who reported greater workload than students with no background noise (Mean = 1.32; SD = 0.76). In other words, we observed a similar trend for high school student's performance during reading comprehension as was observed during sustained attention and recollection -- students report significantly increasing mental workload as noise level increases despite the type of background noise presented but do equally as well on the task.

DISCUSSION

In the present study, the effects of environmental noise on sustained attention, recollection, and reading comprehension were examined in a high school setting for 70 students aged 14-17. This research expands upon previous research that had found significant differences in young children's cognitive performance in the presence of various kinds of irrelevant auditory stimuli and recent research indicating that the average daily noise levels in high school classrooms are related to performance on end-of-year standardized math tests (8, 13, 14).

Noise level had a statistically significant effect on the perceived mental workload of all three tasks, indicating that students at 0, 30, and 60 dBA reported increasingly higher levels of mental demand because of the increased noise level. The statistically significant increases in workload due to noise level are consistent with prior studies that found significant effects of increased noise exposure (85 to 95 dBA) on mental workload in adults (14). In this study, teenagers reported similar increases in workload at even lower noise levels (30 to 60 dBA). However, no corresponding significant effects of accuracy were observed, indicating that there was no difference in how well students performed based on the noise level they were exposed to (independent of noise type). It is possible that our failure to observe an effect on task accuracy was due to the restricted ranges in task scores and/or general task difficulty. For example, the reading

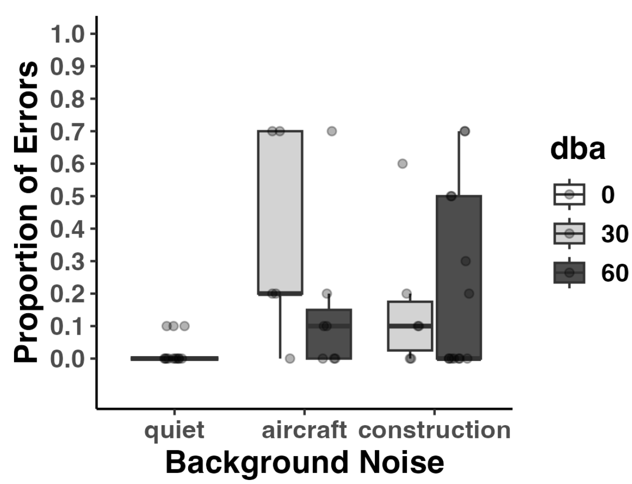

Figure 3: Noise had no effect on recollection accuracy. Boxplots of error rates (the proportion of questions answered wrong) on the Word-to-Picture Task of Recollection across noise conditions. High school students completed the Word-to-Picture task under 30 or 60 dBA of aircraft or construction noise or in quiet. Multiple linear regression, $p = 0.07$.

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comprehension task only consisted of four questions due to time restrictions. Future research should attempt to have all participants complete tasks with a larger range of scores to determine if lower noise levels (e.g., 30 dBA and 60 dBA) impact error rates at levels that could not be detected here.

Even though no effect on objective accuracy was observed, the difference in workload suggests that students' subjective experience of each task was impacted by noise level. One interpretation of this finding is that students who were exposed to noise drew on attentional resources more to reach the same level of accuracy as those under no noise. Similar explanations have been given for the increased effort and fatigue reported by children and adults with hearing loss who, nonetheless, often perform similarly to their typically-hearing peers on objective measures of speech perception (15). Additionally, since there were six distinct aspects rated in the NASA-TLX questionnaire that made up an overall workload score, future research could also investigate each specific aspect to distinguish where the significant differences were found.

Sources of environmental noise can range from continuous, such as the constant whir of a lawn mower or heating/ventilation system, to highly variable, such as the periodic passing of aircraft or the use of construction equipment within a city neighborhood. Therefore, even if overall levels of presented noise are held constant, the frequency of such noise sources in a realistic learning environment varies and should be considered individually. Construction and aircraft noise were the focus of this research since these are common sources of environmental noise in urban schools. Further, results of past studies investigating the impacts of diverse types of noise (environmental, nonverbal, meaningful/meaningless, etc.) on learning have often conflicted (12, 14). Linear regressions also revealed that noise type did not significantly predict task accuracy for any of the three tasks.

In other words, construction and airplane noise equally impact students' use of sustained attention, recollection, and decoding. However, occupied classrooms are expected to have at least 30 dB of ambient noise. In other words, absolute noise levels experienced by students in the quiet conditions were likely comparable to 30 dBA levels of either aircraft or construction noise. Nonetheless, students reported a difference in workload between 30 dBA of ambient classroom noise compared to 30 dBA of both aircraft and construction. These findings suggest that background environmental noise requires more workload than the same levels of ambient classroom noise. This difference was seen for all three tasks and could be attributed to the familiarity of high schoolers with ambient classroom noise. Teenagers must often complete similar or even more complex assessments in school that test sustained attention, recollection, or reading comprehension. Additionally, there may be other acoustic properties of the aircraft and construction noise relative to ambient classroom noise. For example, the construction noise contained periodic snippets of dialogue which may be disruptive. Moreover, variability has proven difficult to represent in a single metric, limiting statistical comparisons of variability across different sounds files (16).

The tests and questionnaires used in the current study were conducted within a single short session lasting 10 to 20 minutes. During common standardized educational tests, such as the actual SAT, students typically are subjected to multiple hours of the testing. Therefore, results suggest that teenagers were able to more easily filter out common ambient noise – such as the HVAC system -- while completing such tasks than when aircraft or construction were presented as the background stimulus. It should also be considered that, since environmental noise was presented through earphones, the current study could not isolate qualities of background noise such as frequency, variability in loudness, speech content, and even reverberation time, that were present in the quiet condition. Students were also informed of the study's purpose, and therefore participants who were instructed to wear headphones may have reported more mental workload

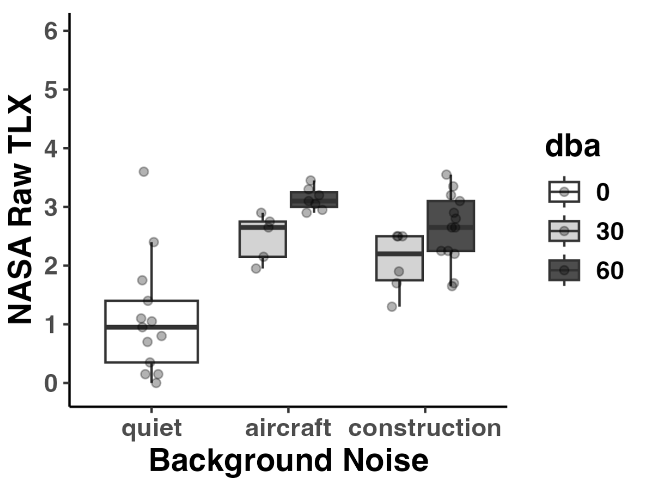

Figure 4: Workload during recollection was greater in background noise. Boxplots of raw NASA-TLX scores on the Word-to-Picture Task of Recollection by noise condition. High school students completed the Word-to-Picture Task under 30 or 60 dBA of aircraft or construction noise or in quiet. Multiple linear regression, $p < 0.01$.

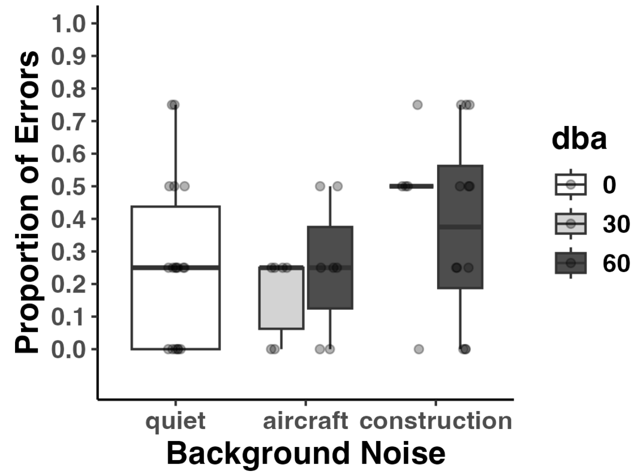

Figure 5: Noise had no effect on reading comprehension accuracy. Boxplots of error rates (the proportion of questions answered wrong) on PSAT or SAT Reading Comprehension by noise condition. High school students read a passage and answered four multiple-choice questions from either the PSAT or SAT as appropriate for their grade level. Each student completed the task under 30 or 60 dBA of aircraft or construction noise or in quiet. Multiple linear regression, $p = 0.27$.

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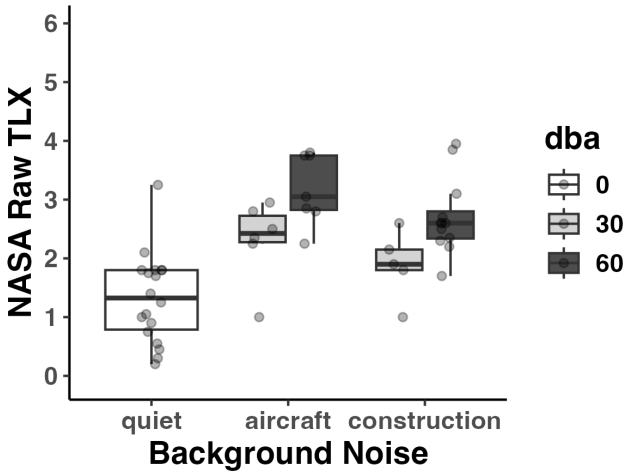

Figure 6: Workload during reading comprehension was greater in background noise. Boxplots of raw NASA-TLX scores on PSAT or SAT reading comprehension task by noise condition. High school students read a passage and answered four multiple-choice questions from either the PSAT or SAT as appropriate for their grade level. Each student completed the task under 30 or 60 dBA of aircraft or construction noise or in quiet. Multiple linear regression, $p < 0.01$.

as a form of response bias. Since participants took the three tests under a single noise and level condition, they also could have adjusted to their designated noise level over the course of testing.

Our hypothesis of noise level having a significant effect on task accuracy was rejected, conflicting with earlier studies and possibly supporting the claim that teenagers as an age group should not be grouped with elementary students (17). Rather, they are experiencing completely different working conditions and have different cognitive skills and therefore should be researched as an independent subject of study.

Environmental noise is considered one of the major proponents of noise pollution, and earlier studies have clearly shown its effects on neurological processes. However, the current study used noise levels below what is defined to cause noise pollution and still found a significant effect. Consequently, teachers, schools, and society may need to reconsider the approach to noise typically regarded as insignificant. High school educators and administrators should be aware of this discrepancy between mental demand and cognitive task accuracy. Actions to mitigate this effect could include rerouting of aircraft traffic on important testing days as is done in other countries such as Korea, or school-wide renovations to increase windowpane thickness to improve soundproofing efforts. However, even simple environmental modifications – such as installing sound-absorbing panels and carpeting classrooms – could help minimize background noises. The current data suggests that significant cognitive strain stems from noise levels below the 70 dBA threshold. While the moderate noise levels tested in this study may not be recognized by most as harmful in school and work environments, these results highlight the important impacts it can have on cognition.

MATERIALS AND METHODS

Participants

Seventy students, ages 14 to 17 and in grades 9 to 12, were recruited from Eastchester High School (**Table 1**). Science teachers at Eastchester High School provided incentives for extra credit to their students for their voluntary participation. All students responded to a questionnaire that confirmed no prior hearing loss, hypersensitivity to noise, or other related auditory issues. Participants were fully fluent in English, though some were bilingual and spoke a different language at home. As residents of a suburban area, participants have been exposed to little noise disturbance at home in general. In the present study, they were exposed to, at most, 60 dBA of noise. This level did not cause any harm and did not exceed the exposure limit set by the CDC. All collected data and information on participants is strictly confidential. No names or other identifying information have been or will be included in the published data.

Procedure

Study subjects completed testing within a single 20–25-minute visit, in a second-floor classroom at Eastchester High School after school when there was little to no noise disturbance in the hallways. Permission was given by the Institutional Review Board (IRB) which included signed forms from a high school administrator/IRB chair, medical health professional, and educator. All students and their guardian(s) completed a human informed consent form which covered the purpose of the project, expectations for participation, potential risks of study, benefits, and maintenance of confidentiality. All auditory stimuli of either aircraft or construction noise were played through identical stereo jack earphones. Those assigned to the control group (silence) were not given headphones and completed tasks with no significant auditory interference. Instructions for each task were described, and noise was calibrated on each laptop to remain at average levels of 0, 30, and 60 dBA.

Toulouse-Piéron Task Testing Sustained Attention

The Toulouse-Piéron (TP) test assesses sustained attention (18). Sustained attention requires continued focus

	0 dBA	30 dBA		60 dBA		Total
Task		Construction	Aircraft	Construction	Aircraft	
Sustained Attention	13	5	6	10	8	42
Recollection	13	6	5	13	7	44
Reading Comprehension	18	5	6	12	7	48

Table 1: Number of students tested for each combination of task (sustained attention, recollection, reading comprehension), noise level (0dBA, 30dBA, 60dBA), and noise type (aircraft or construction). A-weighted decibel is abbreviated to dBA.

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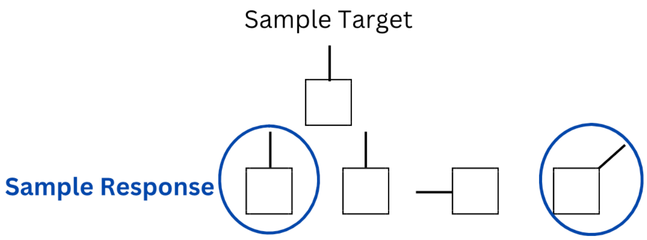

Figure 7: Example of the Toulouse-Piéron Task of Sustained Attention. One example target (top row) and four example items (bottom row) included in the Toulouse-Piéron task. The blue circles indicate sample student responses. The scoring procedure is described below each item. For example, the leftmost item matches the target and was circled, so was a "correct" hit. Similarly, the third item from the left does not match the target and was not circled, so was a "correct" rejection.

over time and is highly essential in the learning environment (19). The Toulouse-Piéron Test was shortened to 80 items arranged in 5 rows of 16 on a single sheet of paper. Each item is a small square with a straight hatch extending in one of 8 directions (**Figure 7**). Three additional target items were depicted at the top of the page. Participants were given 30 seconds per row to circle any items that were identical to the targets at the top of the page. Each participant's error rate was calculated as the number of items circled incorrectly added to the number of items not circled but should have been divided by the total number of items (*i.e.* 80).

Word-to-Picture Task of Recollection

Recollection is a key component for educational development, such as fill-in-the-blank assessments often used within the educational curriculum (20). The word-to-picture task was administered using PowerPoint. The first slide depicted a triangle, a square, a circle, and a diamond corresponding to the words "Cat," "Sat," "Bat," and "Mat," respectively. This learning slide was shown for 20 seconds. Then, one of the four words was shown with all four symbols below it and participants were asked to draw the symbol corresponding to the given word. This step was repeated a total of 10 times, and students had 10 seconds per slide/item to provide an answer.

Standardized Reading Comprehension Task

Participants were administered a shortened version of a standardized English comprehension test based on their grade: grade 9 students were given the PSAT 8/9, grade 10 students were given the PSAT 10, grade 11 students were given the PSAT, and grade 12 students were given the SAT (21). Regardless of the specific test, students were given 10 minutes to read a passage and answer four corresponding questions.

NASA-TLX Questionnaire

Immediately after each testing session, students were asked to complete a short questionnaire to assess the mental workload (MWL) experienced by the participant while performing that task. Mental, physical, temporal demand, amount of effort, and frustration level were rated from "very low" to "very high". In addition, the students rated the level of success they believed they had reached (from perfect to failure). Participants rated these six scales on a 20-point scale. Each rating was converted to decimal format and aggregated to get an overall score of subjective workloads on a 6-point scale. Based on a review of 550 studies of various fields in which NASA-TLX was used, scientists in the auditory field have established alpha reliability coefficients relating to different age groups: 0.65 with young adults and 0.54 for both younger and older adults (22,23).

Descriptive Pre-Study Survey

A self-reported survey was administered to each participant through google forms before in-person participation. This assessed age, grade, type of home (house or apartment), number of people/bedrooms, native language, language used most at home, long-standing illnesses, and known hearing issues. Collected data was used to account for uncontrollable variables that might have influenced individual differences.

Background Noise and Calibration

Construction and aircraft recordings were sourced from the free online sound database "freesound.org". Three recordings were selected and modified to allow for about 8 minutes of aircraft noise: an overhead plane recorded in the countryside, an overhead plane recorded in a suburban area, and near an LAX landing strip (24, 25, 26). The construction noise recording was recorded at a New York City construction site in Manhattan (27). An SPL Pro on the Sound Tools iOS App by Studio Six Digital was used to calibrate the sound levels emitted during testing. It should also be noted that the silence condition in a typical quiet room is about 30 dBA, therefore the participants under "silence" conditions were likely to be exposed to 30 dBA of ambient classroom noise.

Statistical Analyses

Multiple linear regression was conducted using the R program to determine if the two independent variables of decibel level (0 dBA, 30 dBA, 60 dBA) and noise type (aircraft, construction) significantly predicted errors on, and mental workload scores reported for each cognitive task. Tukey post-hoc tests corrected for multiple comparisons, determining specifically where significant differences were present between each pair of group means. A p-value less than the prespecified significance level of 0.05 indicates statistical significance. Boxplot graphs made using the GGPLOT package in RStudio also provided graphical demonstration of the effects and interactions of each factor.

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