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Central Masking: Fact or Artifact?

Alison L. McQueen
State University of New York College at Potsdam

James G. Terhune
State University of New York College at Potsdam

Fourteen people with normal hearing participated in a study that used signal detection theory to examine central auditory masking. Participants were tested in a sound-attenuating chamber. Absolute thresholds for stimuli (1000 Hz pure-tone, white noise masker at 40 dB SL) were established: first for the tone, then for the tone in combination with the masker in the contralateral ear. A mean threshold increase (3.8 dB) demonstrated central masking. Contrary to prediction, a paired-samples t-test revealed significant shifts in participant sensitivity (d') [t (10) = 4.46, p < .001], suggesting that participants' sensitivity to the tone decreased in the masking condition. These findings provide support for the theory that central masking is an auditory processing phenomenon.

Keywords: central masking, signal detection theory, auditory processing research, listener bias, receiver operating characteristic

Central masking is an auditory processing phenomenon that has been studied extensively (e.g., Blegvad & Terkeldsen, 1966; Greenberg & Larkin, 1968; Hawkins & Stevens, 1950; Las, Stern, & Nelken, 2004; Schlauch & Hafter, 1991; Zwislocki, 1972). This phenomenon occurs when two stimuli are presented binaurally through well-insulated headphones: A test signal sounds in one ear while a masker sounds in the opposite ear. Although no direct interference between the stimuli occurs, a person's perceptual threshold for the test signal increases and the signal becomes more difficult to detect.

Many experimenters have examined this phenomenon and have posited its occurrence within the neural networks of our brains, rather than at the periphery of the head (Laucius & Young, 1972; Zwislocki, Damianopoulos, Buining, & Glantz, 1967). Some authors have suggested that central masking might occur at specific locations within the brain during auditory processing: the efferent fibers of the cochlea, the eighth cranial nerve, or the auditory cortex (Hirsh, 1948; Neuert, Verhey, & Winter, 2004; Scharf, Magnan, & Chays, 1997; Smith, Turner, & Henson, 2000). Where exactly this phenomenon occurs is currently unknown.

In an early monaural masking experiment, Hawkins and Stevens (1950) examined participants' changes in thresholds for monaurally masked pure-tone signals using white noise (a wide-band masker that contains all known frequencies). Auditory maskers can be single sound frequencies or a group of frequencies presented simultaneously within a controlled range. Wide-band maskers are often used in auditory masking experiments, and when a masker is referred to as wide-band, it simply means that it comprises a very wide range of sound frequencies. For example, a wide-band masker may include all known frequencies between and including 100 Hz to 3,000 Hz (Swets, Green, & Tanner, 1961). Results from the Hawkins and Stevens study revealed an increase in participants' thresholds for the pure-tone signals as the intensity of the white-noise masker increased. That is, participants reported that they were unable to hear the signals well when they were simultaneously presented with the masker. These results demonstrate auditory masking, but they offer limited contributions to the understanding of central masking because both stimuli were presented to only one ear.

Monaural masking effects, like those produced by Hawkins and Stevens (1950), may be attributed to interference between the stimuli within the ear, but central masking is thought to occur during auditory processing when sound information travels beyond the ears and is processed within our vast neural networks (Smith et al., 2000). As such, to effectively examine central masking within an experimental paradigm, controlled binaural stimulation is required.

Seminal studies examined the role of binaural stimulation in central masking (Hirsh, 1948). Hirsh, for example, examined monaural and binaural masking in three experimental conditions. In all conditions, the signal and masker were presented via insulated headphones. Each participant was provided with a manual attenuator to adjust the intensity of pure-tone test signal during masking. In the first condition, Hirsh compared differences in participant threshold shift for a 200 Hz signal masked monaurally and subsequently binaurally by 59.1 dB SPL (Sound Pressure Level; a measure of sound intensity relative to 10 -16 watts/cm2) of white noise. Participants reported a greater threshold shift for the 200 Hz signal during monaural masking. These findings provide support for the hypothesis that participants find test signals more difficult to detect during monaural masking than during binaural masking. However, participants also reported small threshold shifts in the binaural masking condition, which suggests that some interference between the stimuli occurred beyond the ear during auditory processing.

In the remaining two conditions, Hirsh (1948) examined binaural masking effects only. In the second condition, he examined threshold shifts for six different test signals. Signals of 100 Hz, 200 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 5000 Hz were masked by white noise. Participants, on average, reported the greatest threshold shifts (5.5 dB, on average) for a 1000 Hz test signal masked binaurally by white noise. In the third condition, Hirsh recorded threshold shifts for a 200 Hz signal masked by various intensities of white noise: 9.1 dB, 29.1 dB, 44.1 dB, and 59.1 dB. Results revealed that threshold shifts increased as the intensity of the masker increased. These findings supported Hirsh's hypothesis that central masking could be demonstrated, even though stimuli were presented to opposite ears through well-insulated headphones. Zwislocki et al. (1967) also used various masker intensities to produce binaural masking effects. The authors utilized pulsed and steady test tones, and found that, on average, participants reported threshold shifts of 3 dB for a 1000 Hz signal masked by white noise at 40 dB. These results provide further evidence that masking effects may occur beyond the initial sound processing stage within the ear.

High-intensity (or "loud") maskers have been found to cause vibrations that travel across the skull (Hirsh, 1948; Rosen & Stock, 1992) and interfere with test signals. Because transcranial vibrations are a potential confounding variable, many experimenters have examined the effect of low-level white noise in central masking (Benton & Sheeley, 1987; Laucius & Young, 1972). Low-level maskers (e.g., 60 dB and lower), such as the ones used by Benton and Sheeley, prevent unwanted vibrations from traveling across the skull, preventing uncontrolled masker interference with the test signal. As such, standard intensity for maskers used in central masking experiments is 40 dB (Benton & Sheeley, 1987; Laucius & Young, 1972; Zwislocki, 1972).

Benton and Sheeley (1987) examined the effects of three low-level maskers on pure-tone thresholds. The three masking conditions included a wide-band masker, a narrow-band masker, and a pure-tone masker. Maskers were presented at 40 dB SL (SL; sensation level, a measure of sound intensity relative to the observer's absolute threshold for that sound). Wide-band maskers' and narrow-band maskers' middle frequencies matched the frequency of the test signal. Pure-tone maskers were identical in frequency to the test signal. Benton and Sheeley used manual audiometry found in clinics that consists of a uniform 5 dB step procedure to determine threshold shifts. This audiometry differs from the experimental standard Bekèsy audiometry, which allows for more exact measurements of threshold shifts. Thresholds were recorded in the three masking conditions for test-tone signals at 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz. Benton and Sheeley found a significant difference in threshold shifts caused by pure-tone maskers: ninety percent of participants experienced a threshold shift of at least 5 dB. The wide-band maskers did not produce statistically significant changes in participants' thresholds for the test signals.

Laucius and Young (1972) examined the effects of various maskers on a test signal. The authors studied threshold shifts reported by 30 participants (six with normal hearing and twenty-four with partial hearing loss) for a 1000 Hz test signal masked by white noise. The authors varied the intensity of the white-noise masker in 20 dB increments, from 0 dB to 100 dB. Participants reported a threshold shift for the test signal when presented with maskers as low as 20 dB. On average, participants reported a 1 dB threshold shift when the 1000 Hz signal was masked with 20 dB of white noise. Participants reported, on average, a 3.5 dB threshold shift for the signal when it was masked by 40 dB of white noise, and a 6.5 dB shift was reported when the signal was masked by 60 dB of white noise. Participants with hearing loss reported threshold shifts for the 1000 Hz signal when the masker was played into their damaged ear. Even though the masker was reportedly inaudible, participants' thresholds for the test signal increased. These results provide evidence of stimuli interfering with each other beyond the ear, perhaps during a later stage of sound processing.

Threshold Measurement. Fechner (1856) provided the three most commonly used methods for measuring thresholds: method of limits, method of constant stimuli, and method of adjustment. Of these, the method of constant stimuli (MOCS) requires the greatest number of trials and it is generally assumed to provide the most accurate measure. Most central masking studies report using one of Fechner's classical paradigms to measure masked and unmasked thresholds.

The problem with these classical methods—in fact, with all measures of threshold—is that they depend on the participant to accurately report whether or not the stimulus has been perceived. This reporting process is subject to bias (Breier, Gray, Klass, Fletcher, & Foorman, 2002; Penner, 1972). Detecting a signal at low intensities makes it extremely difficult to hear (as is the case in threshold measurement) and this often results in participants favoring responses based on subjective decision-making criteria. These criteria can be manipulated in light of perceived rewards and punishments (Greenberg & Larkin, 1968; Hafter & Kaplan 1976; Penner, 1972). This, therefore, calls into question the very concept of a measurable threshold—or, at least, our ability to accurately assess auditory thresholds.

Signal Detection Theory. Signal Detection Theory (SDT) was proposed, in part, as a way to circumvent the problem of response bias inherent in classical techniques (Abdi, 2007; Egan, 1971; Green & Swets, 1966; McNicol, 2005). SDT makes some assumptions about a participant's behavior during a psychophysical experiment. For example, consider the assumptions made about a participant listening for a 1000 Hz tone: (1) the 1000 Hz input "channel" (i.e., the participant's ear) is never completely inactive; there is always a random amount of noise in the channel; (2) the amount of noise present at any given time varies as a Gausian (normal) random variable; (3) adding the 1000 Hz signal at a particular intensity merely increases the activity in the channel by a constant amount, and this constant amount of added activity is called d-prime (d'); (4) d', then, is an objective measure of how sensitive the observer is to a 1000 Hz pure-tone (at a given intensity), and, as such, deserves our attention more than any other measure of threshold; (5) when listening for the 1000 Hz signal, the observer sets a criterion for deciding whether to respond that they have or have not heard the signal. If channel activity exceeds an observer's subjective criterion the observer will report, "Yes, I heard the signal." This criterion can change and be manipulated, as can an observer's bias to report hearing the signal by means of instruction, reward, punishment, or meaningfulness of stimuli (Greenberg & Larkin, 1968; Hafter, Sarampalis, & Loui, 2008; Moray, 1959; Penner, 1972).

Considering these assumptions, a participant will make errors or correct detections about the presence of a 1000 Hz signal presented at an extremely low intensity (Abdi, 2007; Larkin & Greenberg, 1970). Sometimes the participant will report that a test signal is not present when it actually is (a miss), or that the signal is present when it is not (a false alarm). Alternatively, the participant could be correct in two different ways: the participant will report that the signal is present when it is (a hit) or that the signal is not present among noise when it is not (a correct rejection).

The probability of a hit and the probability of a false alarm can be estimated experimentally. Additionally, these estimates can be used to estimate *d′*, thus yielding a bias-free measure of the observer's sensitivity to the test signal. A component of SDT is the probability distributions that depict sound and noise characteristics. The receiver operating characteristic (ROC) curve plotted along a line symbolizing chance performance is used to measure actual signal detection. Points along the ROC curve are determined by the probabilities of hit rate and false-alarm rate for each detection trial. Detection is measured by the participant's sensitivity to the signal (*d*'), and is best described as the measurement of difference between the ROC curve and chance performances for each trial (Moore, Peters, & Glasberg, 1999).

Furthermore, Greenberg and Larkin (1968) explored the variability of participants' behaviors during signal detection experiments. They developed a method to determine whether test-tone detection was attributable to selection behavior. A 1000 Hz test signal was presented to the participants prior to experimental trials, and the participants were instructed that this signal was the target frequency that they should listen for. Greenberg and Larkin observed participants' detection of distracter signals that sounded similar to the 1000 Hz signal, but actually differed from the signal by 100 to 200 Hz (e.g., signals at 800 Hz, 900 Hz, 1100 Hz). It was found that although these distracter signals were very similar in frequency to the test signal, participants reported not hearing them. These findings suggest that the participants' abilities to discern minute differences were honed by the 1000 Hz cue. If cues or remuneration can affect participants' abilities to detect test stimuli, then their selection behaviors and subjective criteria for making decisions are subject to bias.

As such, the current authors call into question previous methods of threshold measurement used in central masking experiments. Did the threshold shifts reported in previous experiments result from participant bias or actual physiological phenomena? We suggest that central masking is not an auditory processing phenomenon and is best attributed to listener bias. We hypothesize that by using SDT to reveal participants' d-primes (*d*') in a binaural masking task, actual threshold shifts will be found to be insignificant in scope, thus demonstrating that central masking is not a processing phenomenon but one that results from participant decision-making behavior.

Method

Participants

Fourteen people (8 women and 6 men) agreed to participate in this study. All participants were from the psychology department (10 students and 4 faculty) at State University of New York at Potsdam. They all reported that they had normal hearing. Participants were not paid for their time, but students within this group were awarded extra-credit points towards a psychology class of their choice. All participants were treated in agreement with the ethical cannon put forth by American Psychological Association.

Materials

All participants were tested individually in an external-sound attenuating Industrial Acoustics Sound Isolation Chamber (IAC). All stimuli were presented through well-insulated, studio circumaural headphones (AKG, Model # 271). Signals (1000 Hz sinusoid) were generated with a Hewlett Packard oscillator (HP precision oscillator, Model # 202C). Signals were produced at 0.6 mV (RMS) and passed through a Hewlett Packard Model 4437A precision decade attenuator. Sound waves were viewed with an oscilloscope (Hitachi oscilloscope, Model # V-1050F) to ensure integrity of the tone wave used for the test signal. White noise was generated using a Grason-Stadler white noise generator (Model # 90113). Noise and signals were turned on and off by two programmable tone switches (Kresgie Hearing Research Institute, University of Michigan). The tone switches were adjusted to provide an onset rise-time envelope in which the peak amplitude of the stimulus increased (rise time = 600 ms). Stimuli, when present, were 600 ms in duration. Intensities for the noise and test signal were controlled using a manual attenuator (HP Attenuator, Model # 4437A). Data collection and experimental control ran through a programmable digital logic system.

During the trials, participants communicated with the researchers (one female and one male) by means of a hand-held device that was wired to the wall of the IAC. On the device was a button that was to be pressed if the participant detected the test-tone stimulus. A panel of lights was wired into the IAC. The panel box measured 10 in. x 3.5 in. x 5 in., and the green and red lights were each 1 in. in diameter. The experimenters controlled the lights via a digital logic system that was programmed by James G. Terhune, a psychology professor at SUNY Potsdam. A green light was illuminated to signal the start of each threshold trial and a red light was illuminated to signal the start of each test-trial. Overhead fluorescent lights were turned off to prevent sound interference with the test stimuli. A General Electric nightlight was used to light the IAC during testing.

Procedure

Participants were tested individually in sessions that ranged in duration from 75 min to 105 min. On the specified testing day, the experimenters guided participants to the IAC chamber and familiarized them with equipment inside (i.e., headphones, button on hand-held device, panel of lights, chair), then asked participants to remove any earrings and demonstrated the proper way to wear the headphones. The experimenters explained that the study was an attempt to examine the participant's ability to hear a 1000 Hz pure-tone, which would be presented alone and subsequently in the presence of a white-noise masker. Participants were told that the study would have six phases and a 15-minute break would be mandatory after the fourth phase.

The experimenters explained that on a panel in the IAC, a green light would signal the start of each threshold trial and a red light would signal the start of all other trials. Lights would be extinguished at the end of each trial, and although the trials would be short in duration (3 s), they would be numerous.

Each participant was instructed to press a button on the hand-held device if the tone was heard and to do nothing if no tone was heard. The experimenters explained that when the 1000 Hz tone was present, it would always play through the right side of the headphones and when the white noise was present, it would always play through the left side of the headphones. These conditions would remain constant even if the stimuli were presented simultaneously. After all instructions were given, the experimenters instructed the participant to sit comfortably in the IAC chamber with the door closed for 10 minutes, which allowed the effects of ambient sounds to subside.

The first and second phases of the study were used to obtain the participant's approximate thresholds for the 1000 Hz tone and the white noise. Approximate threshold for the tone was obtained using a modified Bekèsy procedure in which the levels of attenuation were manually adjusted by the experimenter. Attenuation of the tone began at 40 dB and was increased in 10 dB steps until the participant no longer heard the tone. From that point, attenuation was decreased in 5 dB steps until the participant signaled that the tone was again audible. Finally, the experimenters adjusted attenuation levels in increasing and decreasing 1 dB steps, until a final approximate threshold was obtained.

In the second phase, the experimenters obtained the participant's approximate threshold for the wide-band white noise. White noise attenuation began at 50 dB. The order of events was identical to those in the first phase. In the third phase, a MOCS procedure was used to obtain the participant's absolute threshold for the tone. The participant's approximate threshold was assigned to "level 5" on an 11-level programmable attenuator. Levels 1 through 10 decreased or increased attenuation of the participant's approximate threshold in 1 dB steps. For example, if the participant's approximate threshold was 55 dB, level 1 on the programmable attenuator would be 51 dB, whereas level 10 would be 60 dB. There was no tone present on level 11 (which, in turn, generated 10 catch trials). Breier et al., (2002) found that participants with attention-deficit/hyperactivity disorder respond to a significant number of catch trials, which generates a large number of false alarms in experiments such as the present one. A disproportionate number of false alarms indicates that a participant's behavior does not reflect detection and serves to create a potential confounding variable. In this light, participants who responded to several catch trials were excluded form further data analyses (Demany & Semal, 2002).

Each attenuation level was presented 10 times in a random series of 110 trials. Each participant received a different series of randomly presented trials. The experimenter recorded the number of detections for each of the 11 levels. Data were used to calculate the level at which the participant heard the tone fifty percent of the time. This level was designated as the participant's absolute threshold.

Participants who responded to several catch trials were thanked for their time and debriefed (e.g., Demany, 1985; Demany & Semal, 2002). It was unlikely that their future behavior in the experiment would accurately reflect whether they had heard the tone or not. Their behavior was a potential confound and was, perhaps, due to the tediousness of the task and difficulties with concentration.

In the fourth phase, the experimenters obtained the participant's absolute threshold for the 1000 Hz tone during masking conditions. The MOCS procedure was repeated exactly as before, but in addition white noise at 40 dB SL was present on every trial. The experimenters recorded the number of detections at each of the 110 trials. The participant's masked threshold was the level at which the participant detected the tone fifty percent of the time.

After completion of the fourth phase, participants were asked to exit the IAC and take a 15-minute break. All participants complied with the directions. During this time, the experimenters plotted the number of participant responses to each of the 11 levels in both the third and fourth phases of the experiment. Threshold curves were calculated to determine whether the participant demonstrated a change in threshold during the two phases. If a threshold shift occurred, it was possible that attenuation adjustments would need to be made during the tone-plus-masker condition of the signal detection phase.

After the 15-minute break, the participant reentered the IAC and the fifth phase of the experiment began. One hundred signal detection trials were randomly presented, in which the tone was present on 50 trials. There was no tone present on the other 50 trials and there was no white noise present for any of the 100 trials. The participant was given 10 practice trials, because the tone was at absolute threshold and, therefore, at a very low level. Participant behavior was recorded as a hit (participant reported "yes" when the tone was present), a miss (participant reported "no" when the tone was present), a false alarm (participant reported "yes" when the tone was not present), or a correct rejection (participant reported "no" when the tone was not present). This information was used to calculate a measure of participant sensitivity (*d´*).

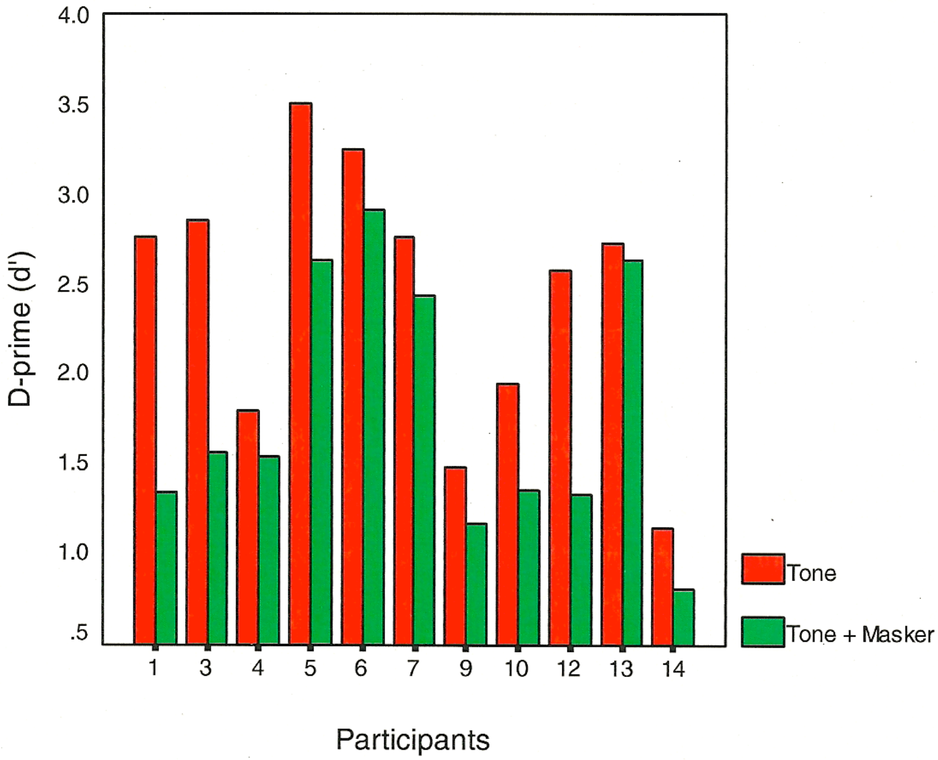
In the sixth phase of the experiment, the signal detection procedure was repeated exactly as in the fifth phase, with the addition of white noise on every trial. Participant behavior was recorded in exactly the same manner, and the data were used to calculate d´.

Participants were then thanked for their time and debriefed. The experimenter briefly explained the phenomenon of central masking and the use of signal detection techniques to examine threshold shifts. The entire experiment was approximately 110 minutes in duration.

Results

Data from 3 participants were excluded, due to frequent abnormal behavioral responses during the MOCS procedure (i.e., responding to catch trials during the initial threshold-measurement procedure). Resulting data generated by the remaining participants (N = 11) demonstrated central masking and revealed, on average, threshold shifts of 3.5 dB. On average, participants also demonstrated a shift in d´ between the two stimulus conditions (mean difference = 0.64, SD = 0.48). Shifts in d´ ranged from 0.095–1.413. A paired samples t-test was done to determine the significance in *d´* shifts. Contrary to what was predicted, this analysis revealed that participants experienced significant shifts in *d´* [t (10) = 4.46, $p < 0.001$]. Please refer to Figure 1 for a graph depicting participants' *d´* values for stimulus conditions.

Figure 1. Measures of participants' sensitivities to stimuli in two experimental conditions



Discussion

Results from this study reveal significant shifts in participants' *d′* values. Contrary to the authors' predictions, results revealed that a listener's sensitivity changed during a central masking experiment. These results provide evidence for the physiological consequences of divided attention in an auditory perception experiment. Although the authors posited that central masking could be attributed to a participant's decision-making behavior and confusion with a difficult experimental task, results demonstrated that sensitivity to an auditory stimulus decreased in the presence of another auditory stimulus for these participants. These findings suggest that one source of sound information may interfere with the processing of another and therefore compromise a person's ability to discern between the two.

The present experiment was not without imitations. One potential confounding variable was the behavioral inhibition factor. We controlled this variable by excluding participants who responded to initial catch trials, a procedure in line with other psychophysical experiments (e.g., Demany, 1985; Demany & Semal, 2002; Hafter et al., 2008). However, the remaining students and faculty members who were unfamiliar with the length and tediousness of psychophysical studies may have been susceptible to fatigue, even though a mandatory 15-minute break was included in the experiment. It is possible that the break further contributed to the participants' fatigue. This, in turn, may have contributed to a misrepresentation of participants' typical reporting behaviors.

Another limitation is the variability in speed at which participants learned how to respond to the stimuli using the hand-held control. Some participants quickly learned what to listen for and how to communicate their responses while others did not. Consequentially, some participants might have not responded to the signal although they had heard it. Past studies used volunteers who had undergone training sessions that familiarized participants with the tasks and tediousness of psychophysical experiments (Laucius & Young, 1972). Future studies should replicate the present procedure with well-trained participants.

By examining participants' absolute thresholds for the 1000 Hz pure-tone within a signal detection paradigm, we were able to remove the influence of decision-making biases from reports of the pure-tone presence when presented with white noise. It is important to note that although potential rewards and punishments may affect the "success" with which a participant reports hearing a tone under difficult listening circumstances (Penner, 1972), it seems as though physiological consequences of divided attention to auditory stimuli is prominent.

The results of the present study may have useful applications when designing learning environments or classrooms. The findings suggest that divided attention is compromised attention. Therefore, learning environments should be free of external distraction and noisy backgrounds. For example, individuals having a conversation in a lecture hall during a class may actually interfere with students' ability to register and process the auditory information being communicated by the instructor. Furthermore, perhaps certain students are more organically inclined to distraction by two auditory stimuli occurring at once than others. Difficulty in concentration then would not stem from correctable behavior. Future experiments might examine the effects of visual distraction on auditory perception, or vice versa. Results from such studies might contribute to the effective design and implementation of optimal classroom and learning environments.

Lastly, these results could be applied to understanding the way attention is divided when people use electronic devices. For example, it is obvious that when one listens to music through ear buds, that person can hear little else. But what about the person walking down the street while talking on a cell phone? The results from the present study suggest that that person is less able to hear other sound information, which may in turn be hazardous to his or her safety.

The findings of this study suggest that central masking is a phenomenon that occurs beyond the ear, during central auditory processing. Future studies should examine potential locations for central masking, thus providing a better understanding of the consequences of binaural stimulation and auditory sound processing.

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