# Effects of Divided Attention and Operating Room Noise on Perception of Pulse Oximeter Pitch Changes

## *A Laboratory Study*

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## ABSTRACT

**Background:** Anesthesiology requires performing visually oriented procedures while monitoring auditory information about a patient's vital signs. A concern in operating room environments is the amount of competing information and the effects that divided attention has on patient monitoring, such as detecting auditory changes in arterial oxygen saturation via pulse oximetry.

**Methods:** The authors measured the impact of visual attentional load and auditory background noise on the ability of anesthesia residents to monitor the pulse oximeter auditory display in a laboratory setting. Accuracies and response times were recorded reflecting anesthesiologists' abilities to detect changes in oxygen saturation across three levels of visual attention in quiet and with noise.

### What We Know about This Topic

- Competing information and divided attention may diminish ability of anesthesia clinicians to detect subtle changes in monitor values

### What This Article Tells Us That Is New

- In a laboratory study, the investigators measured accuracy and response times of anesthesiologists detecting a reduction in a simulated oxygen saturation signal across three levels of visual attention in quiet and with noise
- There was up to a 17% reduction in the ability to accurately detect a reduction in saturation from 99 to 98%, suggesting that background noise may impair the performance of anesthesia professionals

**Results:** Results show that visual attentional load substantially affects the ability to detect changes in oxygen saturation concentrations conveyed by auditory cues signaling 99 and 98% saturation. These effects are compounded by auditory noise, up to a 17% decline in performance. These deficits are seen in the ability to accurately detect a change in oxygen saturation and in speed of response.

**Conclusions:** Most anesthesia accidents are initiated by small errors that cascade into serious events. Lack of monitor vigilance and inattention are two of the more commonly cited factors. Reducing such errors is thus a priority for improving patient safety. Specifically, efforts to reduce distractors and decrease background noise should be considered during induction and emergence, periods of especially high risk, when anesthesiologists has to attend to many tasks and are thus susceptible to error.

A NESTHESIOLOGY is a discipline of medicine that requires intense vigilance, multi-tasking ability, good aural perception and communication skills, as well as critical decision-making. Anesthesiologists are required to balance a multitude of tasks while working in the operating room, with a primary focus on the health and well-being of the patient. These tasks are carried out in a complex environment that is rich in sensory information, some of it critical to the anesthesiologist's tasks while others are either irrelevant or distracting. As one example of the challenges in such a setting, previous research has found the audible noise concentration in the operating room to average 77 dB,[1] with episodes that can often eclipse 100 dB.[2] Not surprisingly,

this concentration of noise has been shown to have a detrimental impact on anesthesiologists' ability to perform cognitive tasks.[1,2] In addition to noise, the competing attentional demands of the operating room environment may also detrimentally impact anesthesiologists' performance. However, operating room performance has been previously linked to changes in attentional load mediated by, among other factors, task complexity[3] and workload.[4,5]

The pulse oximeter is perhaps the most important monitor anesthesiologists use, providing information on arterial oxygen saturation, heart rate, and rhythm. When focusing visual and haptic attention on a surgical case, anesthesiologists are often expected to rely on their auditory perception of this monitor to detect changes in these physiologic parameters, requiring the detection of an auditory signal within the previously described background noise and with competing attentional demands. Also, anesthesiologists are under pressure from surgical colleagues to set monitors and alarms to a minimum volume despite the presence of loud background noise and music. Consequently, the volume of the pulse oximeter is often relatively low, presenting the anesthesiologist with a classic signal-in-noise challenge.

Surprisingly, there is a paucity of work on examining the perceptual expertise of anesthesiologists at perceiving changes in pulse oximetry pitch, and, perhaps more importantly, how background noise and attentional load impact pulse oximeter monitoring. This lack of study is particularly startling given that inattention and lack of monitor vigilance are commonly cited factors implicated during critical incidents in anesthesia.[6–9] Coupled with this, previous research has shown that the majority of anesthesia-related accidents are not the product of a single catastrophic error, but instead are derivative of a number of small errors, such as not detecting a change in oxygen saturation, that cascade into a serious event.[10] The current study addresses this gap in the literature by investigating the impact of attentional load and auditory noise, as well as the interaction between these factors, on the ability of a cohort of resident anesthesiologists to detect changes in oxygen saturation with pulse oximetry.

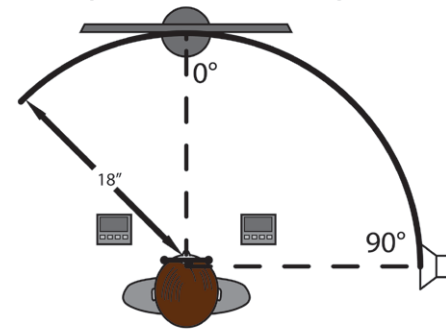## Materials and Methods

### Participants

Participants included 33 resident anesthesiologists (19 male, mean age = 30 ± 3 yr old) who were paid to participate. All recruitment and experimental procedures were approved by the Vanderbilt University Institutional Review Board (Nashville, TN).

### Stimuli

All stimuli throughout the study were presented using MATLAB (MATHWORKS Inc., Natick, MA) software with the Psychophysics Toolbox extensions,[11,12] on a Dell computer (Dell Inc., Round Rock, TX). Visual stimuli consisted of individual letters presented in the central visual field in rapid serial visual presentation at a rate of 10 Hz (100 ms

per presentation). This included 25 capital letters (excluding "Y" for purposes of disambiguating vowels and consonants in the attentional tasks) presented in either red or white. They were presented on a Samsung Sync Master 2233RZ 120 Hz monitor (Samsung Group, Seoul, South Korea) 0.45 m in front of the participant (fig. 1A). Letters were presented in



**Fig. 1.** Methods. *A* shows the experimental setup, with visual tasks presented directly in front of the anesthesiologist while the auditory pulse oximetry stimuli are presented at 90° to the right. *B* shows frequencies measured were fit with an exponential function to derive the frequencies associated with each level of arterial oxygen saturation. *C and D* show the visual tasks for the medium and high-attentional load conditions, respectively. The visual task for the low attentional task was simple fixation and therefore is not depicted.

Geneva, 96-point font, and were approximately $2.2 \times 2.5$ cm in size (although width varied slightly between letters).

Auditory stimuli were presented via mounted speaker 0.45 m from the participants and at 90° angle from the participants' heads on their right side (fig. 1A). Auditory stimuli consisted of 100 ms, sine-wave gated pure tone beeps at frequencies matching the 99% (648 Hz) and 98% (630 Hz) blood-oxygenation saturation concentrations on a Philips patient monitor (Model MP70; Koninklijke Philips Electronics N.V., Amsterdam, Netherlands) at a rate of 75 beats per min. Previous research has shown that majority of individuals are able to detect such a change.[13] To determine the fundamental pitch of these concentrations, sound wavelengths produced by a Fluke Biomedical Index 2MF SpO Simulator (Fluke Biomedical, Everett, WA) at oxygen saturations ranging from 40 to 100% were measured with a Hameg 507 oscilloscope (HAMEG Instruments GmbH, Mainhausen, Germany). Empirically measured sound frequencies were then fitted with an exponential function, which was subsequently used to interpolate frequency values for the appropriate saturation concentrations. This exponential function,

$$Frequency = 37.128e^{0.0289x} \, (saturation) \qquad (1)$$

where *frequency* represents the sound frequency and $x$ the concentration of oxygen saturation, fit the measured sound frequencies significantly well ($R^2 = 0.99$; fig. 1B). All auditory beeps were presented as pure tones, at 80 dB sound pressure level, corresponding to the default QRS volume setting of 2 on the Philips patient monitor, and confirmed as a common level of usage with participants. It should be noted here that different models of pulse oximeters use distinct sound pressure concentrations as well as distinct harmonics to signal changes.[14] Duration and timing of all visual and auditory stimuli were confirmed using a Hameg 507 oscilloscope with a photovoltaic cell and microphone.

Background noise was included in half of the conditions. It consisted of prerecorded operating room noise during cardiac surgery without pulse oximetry beeps. This was played with an average dB sound pressure level, concentration of 67 (ranging from 58 to 86 dB SPL) via a Sony MZ-R700 mini disc recorder (Park Ridge, NJ) through an Optimus SA-155 stereo amplifier and Optimus XTS-3 speakers (Optimus Acoustics, Bloemfontein, South Africa). Background noise included sounds of conversations, movement of operating room personnel, and movement of surgical instruments, but specifically excluded alarms. It should also be noted here that this background noise differs from that in the real operating room in that resident participants were not required to interact with signals in the background noise, such as a request from the surgeon.

### Procedure

Participants completed six tasks in a $3 \times 2$ design. The first factor, attentional load, was varied through three visual tasks

presented in the central visual field that are commonly used in studies of attentional effects,[15–17] and the second factor, noise concentration, was varied although the presence or absence of prerecorded operating room background noise. For each task, participants were seated inside an unlit WhisperRoom™ (Model SE 2000; Whisper Room Inc, Morristown, TN) with their forehead placed against a Headspot (University of Houston College of Optometry, Houston, TX) forehead rest locked in place, with a chinrest and chair height adjusted individually to the forehead rest. Participants were asked to fixate towards a fixation cross at all times, and were monitored by close circuit infrared cameras throughout the experiment to ensure compliance.

For the first visual task, which we will refer to as the low-attentional load condition, the participant was asked only to fixate towards a constant fixation cross. For the second visual task, which we will refer to as the medium-attentional load condition, participants were presented with a series of single letters in rapid serial visual presentation format, 96% presented in white and 4% in red (fig. 1C). Participants were asked to respond as quickly and accurately as possible via button press with their left hand any time that they saw any red letter (target rate = 4%). Specific letters and colors were presented in pseudorandom order. For the third visual task, which we will refer to as the high-attentional load condition, participants were presented with a series of single letters in rapid serial visual presentation format, 80% presented in white and 20% in red (fig. 1D). Participants were asked to respond via button press with their left hand any time that they saw a red vowel (with vowels making up 5 of 25 letters, excluding y, target rate = 4%). Specific letters and colors were presented in pseudorandom order. A total of 6,000 letter presentations were made for each condition, with 240 targets.

With each of these six tasks, participants were also asked to complete an auditory monitoring task that was identical across conditions. Auditory beeps were presented continually at a rate of 75 beeps per min, with 90% of the beeps (675) presented at the 99% saturation pitch and 10% at the 98% saturation pitch (75), for a total of 750 beeps during each 10-min trial. Participants were asked to respond as quickly and accurately as possible via button press with their right hand every time they heard a 98% saturation-concentration beep. Targets were presented in a pseudorandom order.

Each run began with an instruction screen, after which the participant was asked whether he or she understood the instructions. After indicating they were ready by pressing the spacebar, participants were cued with a timed visual countdown, and the monitoring task began. Half of the way through, at 5 min, participants were offered a break, if needed. On indicating readiness to continue, the second half of the given condition proceeded in the same manner as the first half. The order of the six conditions was randomized across participants. Between conditions, participants were

offered breaks as needed. Total experimental time lasted 60 min not including breaks or instructions.

### Statistical Analysis

For each of the conditions, low, medium, and high, attentional load with and without noise, mean accuracies and response times (RTs) were calculated for the auditory task. Repeated-measures, $3 \times 2$ ANOVAs were run testing for main effects of both attentional load and noise, as well as an interaction between these two factors. Where these ANOVAs were significant ($\alpha = 0.05$), follow-up, pair-wise $t$-tests were conducted.

To assure that the visual attentional load tasks did, in fact, vary in difficulty, mean accuracies and RTs were calculated for the visual task for four of the six conditions, medium and high-attentional load with and without noise (no responses to visual stimuli were made to during the low-attentional load conditions). Repeated-measures, $2 \times 2$ ANOVAs were run testing for main effects of both attentional load and noise as well as an interaction between these two factors. Where these ANOVAs were significant, follow-up, pair-wise $t$-tests were conducted.

## Results

### Auditory Performance

Mean accuracies of individuals' ability to detect changes in pitch associated with changing concentrations of arterial oxygen saturation were calculated for each of six experimental conditions. A $3 \times 2$ ANOVA showed a significant main effect of visual attentional load ($F = 11.90$, $P < 0.01$) and of audible noise level ($F = 56.51$, $P < 0.01$). This analysis also revealed that these effects were additive, showing no significant interaction ($F = 1.29$, $P = 0.28$). Follow-up $t$-tests showed that participants performed with lower accuracies on the high relative to the low-attentional load task, and accuracies were lower in the conditions with noise relative to those without (fig. 2A).

An analysis of mean RTs provided similar findings (fig. 2B). Once again, a $3 \times 2$ ANOVA showing a main effect of both visual attentional load ($F = 123.86$, $P < 0.01$) and of audible noise level ($F = 56.45$, $P < 0.01$), and that these effects were additive, with no significant interaction ($F = 0.27$, $P = 0.77$). Follow-up $t$-tests showed that responses were slower under conditions of higher attentional load and noise. Because RTs were not normally distributed, this pattern of results was also verified in median RT calculations.

### Visual Performance

In an effort to validate that stimulus manipulations indeed had an effect on task difficulty, performance on the visual tasks were also assessed. Mean accuracies were calculated for both the medium and high-visual attentional load conditions, with and without audible noise (fig. 3A). A $2 \times 2$ ANOVA showed a significant main effect of task ($F = 168.46$, $P < 0.01$) and of audible noise level ($F = 7.64$, $P = 0.01$). This analysis revealed no interaction between these
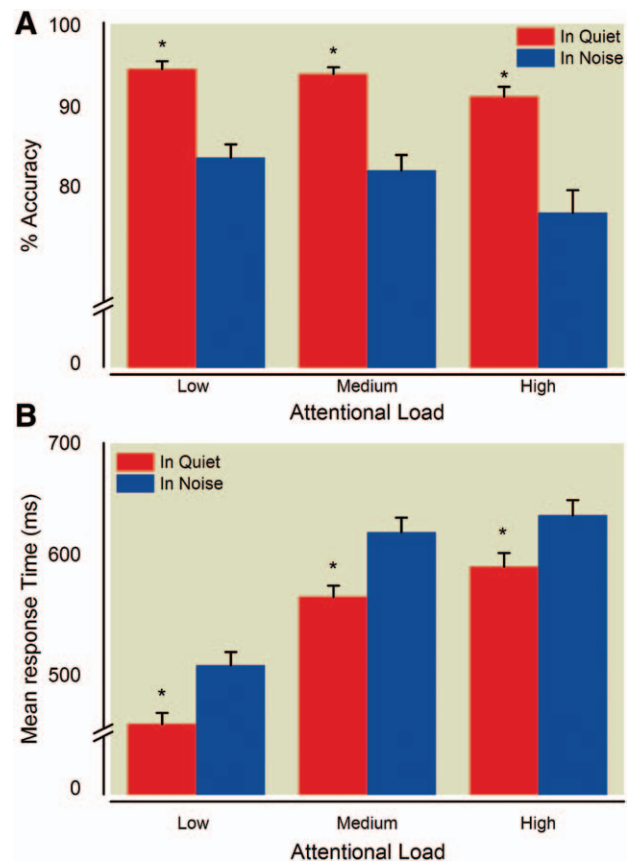


**Fig. 2.** Accuracies and response times with the pulse oximeter. (*A*) Pulse oximetry accuracy; (*B*) pulse oximetry response time: Resident anesthesiologists were less likely to detect changes in oxygen saturation as attentional load increased and in noise. These effects were additive. Anesthesiologists were also slower to respond to changes in oxygen saturation under high-attentional loads and noisy conditions. *Bars* represent mean responses, *error bars* represent standard errors, and *asterisks* represent significance.

two factors ($F = 0.20$, $P = 0.66$). Follow-up $t$-tests showed that participants performed as expected, with lower accuracies on the high relative to the low-attentional load task, and with lower accuracies in the conditions with noise relative to those without. These effects were additive with simultaneous increase in attentional load and noise.

An analysis of mean RTs provided similar findings (fig. 3B), with a $2 \times 2$ ANOVA showing a significant main effect of visual attentional load ($F = 462.91$, $P < 0.01$), a marginally significant main effect of audible noise level ($F = 4.04$, $P = 0.053$), and a significant interaction between these factors ($F = 5.47$, $P = 0.03$). Follow-up $t$-tests showed that responses were slower with higher attentional loads and noise. This pattern of results was also verified in median RT calculations.

## Discussion

The results from this study show that visual attentional load has a substantial impact on anesthesiologists' abilities to

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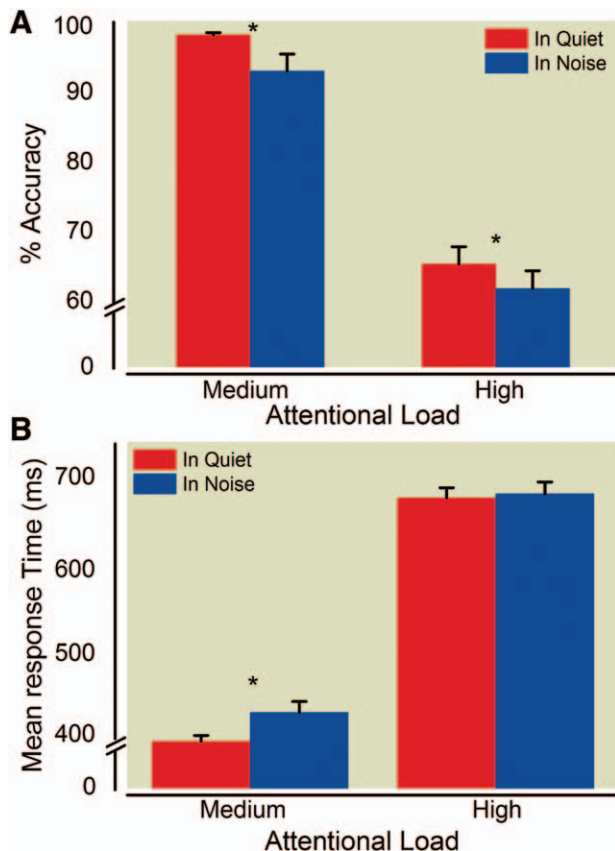
**Fig. 3.** Accuracies and response times with attentional tasks. (*A*) Visual task accuracy; (*B*) *visual* task response time: Visual tasks aimed at modulating attentional load through task difficulty were successful, as seen by the decrease in accuracy and slower response times with high-attentional conditions. *Bars* represent mean responses, *error bars* represent standard errors, and *asterisks* represent significance.

detect audible changes in oxygen saturation concentrations. Furthermore, these effects are compounded by the presence of significant noise in the operating room. It must be emphasized that the impact of visual attentional load and audible noise were substantial, with a 17% decrement in accurately detecting pitch changes between the easiest condition (low visual attentional load in quiet) and the most difficult (high-visual attentional load with auditory noise) condition. These deficits were seen not only in the ability to accurately detect a change in oxygen saturation, but also in the speed of reaction when a change was detected. An additional point of emphasis here is that even the most difficult condition in this laboratory setting undoubtedly greatly underestimates the complexity and challenges of a real-world operating room.

Given that the majority of anesthesia-related accidents are derivative of compounding small errors,[10] such as not detecting a change in oxygen saturation, improving such monitoring performance may lead to reduced accident rates. Reducing environmental factors that lead to increased errors should be an important priority for increasing the safety of operating room environments. Specifically, efforts to reduce

distracters and decrease background noise should be considered during induction and emergence, periods of intense concentration for anesthesiologists[18] and during which they are required to further divide their attention and are thus susceptible to higher rates of error.[3–5,10]

One of the primary critiques of vigilance research is that findings in laboratory settings do not always transfer to the real world.[19] Although this study did take place in a laboratory setting, two points should be highlighted here. The first is that these participants were responding to simulated pulse oximetry tones as opposed to arbitrary visual cues in previous studies,[5,20] an important point given known differences between responses to visual and auditory monitoring.[21] Second, all participants were anesthesiology residents who had been trained in the use of such auditory cues. As such, we are confident that these results are of strong relevance for real-world performance with pulse oximetry. In fact, the negative impacts that divided attention and noise have on pulse oximetry measured here are in all probability conservative given that the visual tasks underestimate the complexity of the operating room, and the noise concentration (mean volume = 67 dB sound pressure level) is significantly lower than the average noise concentration in the operating room, previously measured at 77 dB sound pressure level).[1,2] With that said, the visual task used here requires constant attention, which is not the case in all stages of clinical anesthesia care, and as such could be viewed as less conservative than a real-world operating room situation. These results are consistent with two previous studies in an operating room setting. In these studies, anesthesiologists were asked to detect a change in artificial visual outputs on a monitor (*e.g.,* the number "5" changing to a "10"). It was found that this signal was missed more often during induction relative to emergence, and emergence relative to maintenance.[5,20] These studies thus provide converging evidence that time periods of high-attentional load, such as induction and emergence, are associated with increased distraction and less attention afforded to monitors such as pulse oximeters.

These current results illustrate that the increase in error rates with high-attentional load and environmental noise are additive, yet it is unknown how these factors relate to additional factors known to influence error rates. Future work should be conducted to explore the relationship between the currently studied factors and those that are clearly important from a performance perspective, including fatigue, sleep deprivation, stress, interpersonal factors, and alarm fatigue.[3,22,23] Furthermore, future effort should be put forth to explore ways in which anesthesiologists may improve their ability to attend to multiple stimulus inputs across sensory modalities. Specifically, these efforts should utilize research in the field of multisensory processing which has previously investigated the roles of attention and noise on perceptual processing, and which has recently shown the ability of sensory training protocols to enhance sensory performance.[24] Given the significant performance decline measured here

with attentional demands and noise, both factors that are ubiquitous in the operating room setting, these avenues of research have the capacity to decrease error rates and improve patient outcomes.

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