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Effects of Jet Engine Noise and Performance Feedback on Perceived Workload in a Monitoring Task

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This study examined the effects of exposure to intermittent jet aircraft noise (70 dBA or 95 dBA maximum intensity) and knowledge of results concerning signal detections (hit-KR) on performance efficiency and perceived workload in a 40-min visual vigilance task. The noise featured a Doppler-like quality in which planes seemed to approach from the monitor's left and recede to the right. Perceptual sensitivity (d') was poorer in the context of noise than in quiet but only in the presence of hit-KR. The lack of noise-related performance differences in the absence of hit-KR most likely reflected a "floor effect" rather than some special relation between noise and feedback. When compared to subjects performing in quiet, those who operated in noise were less able to profit from hit-KR, a result that may reflect the effects of noise on information processing. In addition to its negative effects on signal detectability, noise elevated the perceived workload, as measured by the NASA–TLX. This effect was robust; it was independent of the presence of hit-KR, even though hit-KR generally lowered the overall level of perceived workload. The results provide the initial experimental demonstration that perceived workload is a sensitive measure of the effects of aircraft noise in monitoring tasks.

Monitoring or vigilance tasks represent an important class of functions in aviation. Such tasks can be found in a broad array of activities ranging from air traffic control to flight deck operations (Warm, 1984; Wickens & Flach,

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1988; Wiener, 1988). They have traditionally been characterized as tedious but benign assignments that place a minimal information-processing load on monitors (Frankmann & Adams, 1962; Loeb & Alluisi, 1984). This view, it should be noted, stems primarily from an intuitive examination of their requirements, in which it seems that all monitors need to do when engaged in these tasks is to observe displays and take appropriate action when relatively infrequent critical events occur. Recently, however, experimental evidence has revealed that monitoring tasks, although tedious, are not benign. Instead, they can be quite demanding and can induce considerable stress in those who perform them (Galinsky, Rosa, Warm, & Dember, 1993; Hancock & Warm, 1989). Much of this evidence comes from measurements of perceived mental workload or the processing resources required by a task, a dimension that is also of considerable interest in aviation (Kantowitz & Casper, 1988). Research on the workload of monitoring tasks has made use of a multidimensional scale known as the NASA Task Load Index (TLX; Hart & Staveland, 1988). The scale provides an index of overall workload (range, 0 to 100) and also identifies the relative contributions of six sources of workload: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration. The TLX is considered one of the strongest self-report instruments available for the measurement of mental workload (Hill, Iavecchia, Byers, Zaklad, & Christ, 1992; Nygren, 1991).

Investigations employing this instrument have demonstrated that, contrary to early beliefs, the cost of mental operations in vigilance is substantial. Overall workload scores in these studies have reached the upper level of the scale, with Mental Demand and Frustration identified as the primary contributors to workload (Becker, Warm, Dember, & Hancock, 1991; Deaton & Parasuraman, 1993; Dember et al., 1993; Dittmar, Warm, Dember, & Ricks, 1993; Warm, Dember, & Parasuraman, 1991). Moreover, workload ratings in vigilance have been related to task factors affecting performance efficiency. For example, the quality of vigilant behavior varies directly with signal salience and inversely with event rate (the rate of cascade of nonsignal events in which critical signals for detection are embedded; Warm & Jerison, 1984). Workload ratings have been shown to parallel these effects by varying inversely with salience and directly with event rate (Galinsky, Dember, & Warm, 1989; Gluckman, Warm, Dember, Thiemann, & Hancock, 1988). As is generally the case with subjective reports, the finding that workload ratings can be brought under experimental control enhances the validity of such ratings (Natsoulas, 1967).

Our study continued this line of investigation by examining the effects of an environmental factor—noise—on the perceived workload of a vigilance task. As described by Loeb (1986), noise is perhaps the most ubiquitous environmental pollutant and a major stressor in our industrialized society. It has also been studied extensively in relation to vigilance performance (Davies & Parasuraman, 1982; Hancock, 1984; Smith, 1991; Warm, 1993). The effects associated with noise have often been equivocal, a result that led

Koelega and Brinkman (1986) to suggest that lawful relations are not observable in studies of the effects of noise in this domain. Other investigators, however, are more sanguine about the presence of systematic effects in the literature and have indicated that, in general, the quality of sustained attention is degraded when subjects must perform tasks imposing high information-processing demands in the presence of high levels (90 dBA or more) of intermittent noise (Davies & Parasuraman, 1982; Hancock, 1984; Warm, 1993). Under such conditions, it is conceivable that noise will also elevate the perceived workload of the vigilance task, especially in light of Cohen's (1978, 1980) argument that subjects must expend processing resources to compensate for the distracting effects of noise. Along these lines, it is worth noting that aircraft noise has been identified as a problem for both pilots and the general public, giving rise to considerable annoyance and to potentially hazardous operating conditions in aircraft (Clark, 1984; Gunn, 1981; Hart, 1988). Accordingly, aircraft noise was used in our study as a likely candidate to elevate perceived workload in a monitoring situation.

Previous studies on the implications of noise for vigilance have, for the most part, neglected to investigate factors that might attenuate the adverse effects of noise on performance. One such candidate is knowledge of results (KR), or feedback, concerning signal detections. Knowledge of results has been shown to have a powerful enhancing effect on the accuracy of vigilance performance (Warm & Jerison, 1984). Indeed, the overall reliability of the findings with respect to KR led Jerison and Pickett (1963) to conclude that when there is room to improve in a vigilance task, improvement will occur when KR is available. In a recent study, Dittmar, Warm, and Dember (1985), using a signal-detection-theory approach, demonstrated that KR regarding correct detections (hit-KR) notably enhanced subjects' perceptual sensitivity to critical signals in a vigilance task. This effect was replicated by Becker, Warm, Dember, and Hancock (1991), who also demonstrated that such KR reduced the perceived workload associated with the vigilance task. Accordingly, a second goal of this investigation was to determine whether hit-KR could attenuate the adverse effects of noise on vigilance performance and subjective workload.

METHOD

Seventy-two students (36 men and 36 women) from the University of Cincinnati served as subjects to complete a course requirement. They ranged in age from 17 to 33 years with a mean of 21 years. All of the subjects had normal or corrected-to-normal vision and were free of any known hearing impairments. None of the subjects had participated previously in vigilance studies or in experiments involving acoustics.

Three levels of noise (high-intensity, low-intensity, and a no-noise control) were combined factorially with two KR conditions (hit-KR and a no-KR control). Twelve subjects were assigned at random to each of the six resultant experimental cells with the restriction that all conditions were equated for sex.

Subjects participated in a 40-min vigil divided into four continuous 10-min periods of watch. In all conditions, they were required to monitor on a video display terminal (VDT) repetitive flashes (150 ms) of a vertically oriented line (2 × 32 mm) for occasional increments in its height (3 mm). The lines appeared at a rate of 30 events/min. Critical signals for detection occurred on the average of 1/min (signal probability = .033) with intersignal intervals (ISIs) of 24, 48, 72, 96, and 120 sec. These intervals were varied at random for each subject within each 10-min period with the constraint that critical signals were separated three times by ISIs of 24 sec and 72 sec, twice by an ISI of 48 sec, and once each by ISIs of 96 sec and 120 sec. Feedback was provided to the hit-KR group in the form of a block of stars that appeared on the VDT for 200 msec immediately after the execution of a correct response. The failure of the star display to appear after a response in the KR group indicated that the response was a false alarm. The stars appeared after each response made by subjects in the no-KR group to control for accessory stimulation that occurred with the delivery of feedback but carried no evaluative information. Subjects indicated their detections of critical signals by depressing the spacebar of a computer keyboard.

The recorded sound of jet engines, played through stereophonic speakers, located inside the testing chamber provided a dynamic source of intermittent noise. The speakers were mounted in front of the seated subject immediately below the ceiling of the testing chamber. Each speaker was located at an angle of 130° from the center of the subject's head. The distance between the speakers was 0.75 m. The noise featured a Doppler-like effect, in which planes seemed to approach from the listener's left and then recede toward the right. This was achieved by having the engine sounds rise and fall in intensity during each episode of passage. Episode durations ranged from 17.91 sec to 42.90 sec(M = 26.89 sec, SD = 9.33 sec); interepisode intervals (periods of quiet) ranged from 4.90 sec to 12.25 sec(M = 6.98 sec, SD = 2.71 sec). Times to reach maximum amplitude within an episode ranged from 6.47 to 16.13 sec (M = 10.28 sec, SD = 2.94 sec). Decay times from maximum amplitude to quiet ranged from 9.36 sec to 25.12 sec (M = 16.48, SD = 5.79). Maximum amplitudes at the subject's ear in the low-intensity and high-intensity conditions were, respectively, 70 dBA (approximately the loudness of a normal automobile engine) and 95 dBA (approximately the loudness of a subway train).

A spectrographic analysis of the aircraft noise, using a Kay 5500 DSP Sonograph in conjunction with Ariel Corporation software, revealed that the fundamental frequencies embedded within the acoustic stimulus ranged from 87 Hz to 223 Hz (M = 129.53 Hz). The ranges for the first, second, third, and fourth formants were 1,336–3,645 Hz, 3,416–12,525 Hz, 5,860–15,649 Hz, and 12,642–17,833 Hz, respectively. For the most part, sound energies were concentrated below 4,000 Hz.

Subjects were tested individually in a 1.01 × 1.23 × 1.98 m Industrial Acoustics sound chamber. They were seated in front of the VDT, which was mounted at eye level at a distance of approximately 40 cm. The VDT screen was covered with a red acetate filter, which provided a 16.8 cm × 22.8 cm viewing field. The acetate was used to reduce glare and to minimize stimulus persistence resulting from phosphor decay after pixel offset. The elements of the display appeared as red stimuli on a dark background. The luminance of the stimuli was .60 cd/m^2, whereas that of the background was .0008 cd/m^2. Ambient illumination in the testing chamber was .10 cd/m^2 and was provided by a light source mounted behind and to the side of the subject to minimize glare on the VDT.

Stimulus presentations, the orchestration of critical signals, and the presentation of feedback or response acknowledgment were controlled by an Apple II plus microprocessor. The computer also recoded subjects' responses. Responses occurring within 1.85 sec after the onset of a critical signal were automatically recorded as correct detections; all other responses were recorded as errors of commission or false alarms. The 1.85-sec cutoff was determined by pilot studies, which indicated that if subjects were going to respond to a stimulus event, they would do so within that interval.

Before the initiation of the main vigil, subjects were given two 5-min practice sessions that duplicated the conditions of the test vigil, excluding the delivery of hit-KR or response acknowledgement. To be retained in the study, subjects were required to detect 70% of the signals during the second practice session, with a false alarm rate no greater than 10%. Subjects surrendered their watches at the outset of the experimental session and had no knowledge of the length of the vigil other than it would not exceed 90 min. Perceived workload was assessed by a computerized version of the NASA–TLX immediately after the conclusion of the vigil.

RESULTS

Percentages of correct detections (hits) and false alarms were calculated for each subject in all experimental conditions. The means for each condition are presented in Table 1.

Percentages of correct detections and false alarms for each subject were used to calculate signal-detection theory measures of perceptual sensitivity (*d′*) and response bias (β; Macmillan & Creelman, 1991). Mean *d′* scores for each condition are presented in Table 2. All subjects made at least one false alarm and missed at least one signal during each period of watch. Therefore, no corrections for missing responses (cf. Davies & Parasuraman, 1982) were required in calculating the sensitivity and bias measures.

TABLE 1
Mean Percentages of Hits (H) and False Alarms (FA) Under All Experimental Conditions

			Period of Watch				
KR	*Noise*		*1*	*2*	*3*	*4*	*M*
Hit KR	Quiet	H	85.83	87.50	75.00	74.17	80.62
		FA	10.28	6.52	5.65	6.14	7.15
	Low	H	76.67	70.83	63.33	60.00	67.71
		FA	10.76	5.66	5.27	5.94	6.91
	High	H	75.83	65.00	55.83	44.17	60.21
		FA	13.58	8.28	7.98	7.47	9.33
No KR	Quiet	H	53.33	54.17	40.83	48.54	49.22
		FA	12.88	9.14	8.22	6.89	9.28
	Low	H	68.33	60.00	47.50	54.17	57.50
		FA	17.09	11.84	11.00	10.17	12.52
	High	H	59.17	45.00	35.00	33.33	43.12
		FA	13.32	10.69	10.38	8.42	10.70

Inspection of Table 2 reveals that noise had a degrading effect on overall signal detectability; *M*sec for the quiet, low-noise, and high-noise conditions were 1.96, 1.80, and 1.50, respectively. It is also evident in the table that hit-KR enhanced the overall level of signal detections; mean seconds for the hit-KR and no-KR conditions were 2.16 and 1.35, respectively. In addition, as has been found in several other vigilance experiments (cf. Parasuraman, Warm, & Dember, 1987), perceptual sensitivity declined over the course of the watch (see Table 2 for means).

These impressions were confirmed by an analysis of variance (ANOVA) of the perceptual sensitivity scores. The ANOVA revealed significant main effects for noise, $F(2, 66) = 4.25$, $p < .018$, feedback, $F(1, 66) = 36.82$, $p < .0001$, and time on task, $F(3, 198) = 5.02$, $p < .003$. The interaction between noise and KR also reached significance, $F(2, 66) = 3.61$, $p < .03$. However, neither noise nor KR had any significant impact on the vigilance decrement; all interactions involving time on task failed to reach significance, $p > .05$ in each case.

The Noise × KR interaction can be inferred from Figure 1. This interaction can be described in two ways. First, it is clear that the effects of noise were limited to the hit-KR conditions; in the absence of hit-KR, the effects of noise on d' were negligible. Moreover, it is evident in the figure that the effects of KR were modified by noise. Although tests of the simple effects of KR within each of the three noise conditions resulted in significant differences for all comparisons, $F(1, 66) > 5.00$, $p < .05$ in each case, it can be seen in the figure that the beneficial effects of hit-KR were greater in quiet than in either of the noise conditions.

Mean response bias scores for all experimental conditions are provided in Table 3. Perusal of the table indicates that subjects became more conserva-

TABLE 2
Mean *d′* Values Under All Experimental Conditions

KR	*Noise*	*Period of Watch* 1	2	3	4	*M*
Hit KR	Quiet	2.50	2.86	2.69	2.45	2.62
	Low	2.04	2.25	2.06	1.91	2.06
	High	1.94	1.98	1.76	1.47	1.79
	M	2.16	2.36	2.17	1.94	2.16
No KR	Quiet	1.30	1.56	1.24	1.13	1.31
	Low	1.54	1.58	1.32	1.69	1.53
	High	1.53	1.21	1.05	1.04	1.21
	M	1.46	1.45	1.20	1.29	1.35
M		1.81	1.91	1.69	1.62	

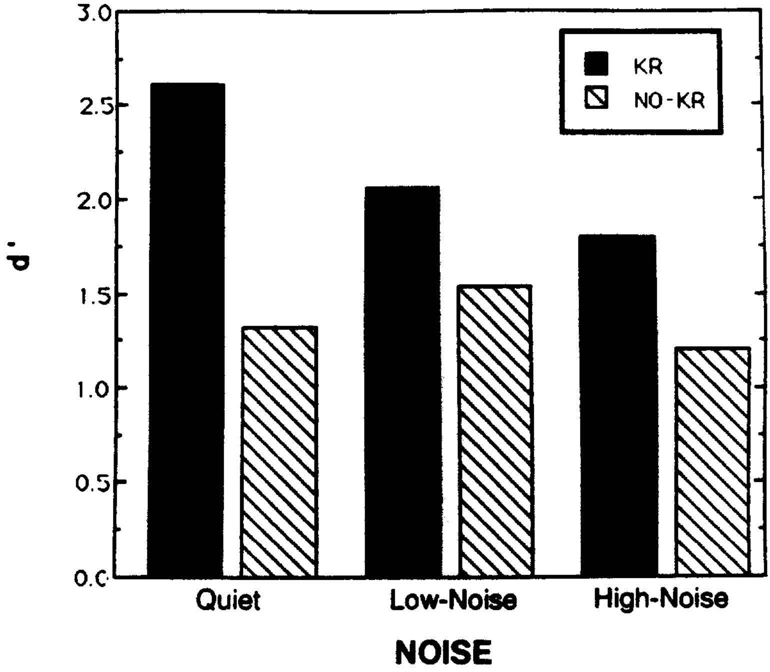

FIGURE 1 Perceptual sensitivity for three levels of noise in the context of the hit-KR and no-KR conditions.

TABLE 3
Mean β Values Under All Experimental Conditions

		Period of Watch				
KR	*Noise*	*1*	*2*	*3*	*4*	*M*
Hit KR	Quiet	2.85	3.91	9.39	5.68	5.46
	Low	1.94	2.05	3.35	4.88	3.06
	High	2.04	5.98	6.12	4.61	4.69
	M	2.28	3.98	6.29	5.06	4.40
No KR	Quiet	2.28	2.98	3.33	5.52	3.53
	Low	1.48	3.64	4.06	6.81	4.00
	High	2.06	3.38	3.10	3.25	2.95
	M	1.94	3.33	3.50	5.19	3.49
M		2.11	3.66	4.89	5.12	

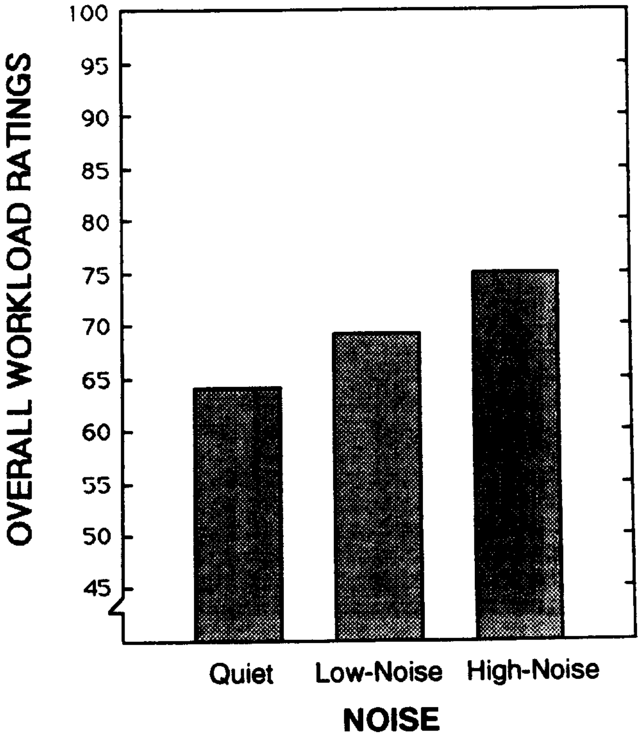

FIGURE 2 Perceived workload in quiet and in noise.

tive over time, a result that is typical in vigilance studies (cf. Parasuraman et al., 1987). The data also suggest that the effects of noise and KR on the criterion scores were unremarkable; means for the hit-KR and no-KR conditions were 4.40 and 3.49, respectively, whereas those for the quiet, low-noise, and high-noise conditions were, respectively, 4.50, 3.53, and 3.82. An ANOVA of the β scores revealed that there was a significant effect for time on task, $F(3, 198) = 7.77$, $p < .001$. All other components of variance involved in this analysis failed to reach significance.

Overall workload and individual dimensional weightings were computed from each subject's responses to the NASA–TLX. The overall workload ratings in this study were quite high, falling in the upper half of the of the NASA scale in all experimental conditions. The scores ranged from 54 to 81 with a mean of 69. An ANOVA of the overall workload data revealed that perceived workload was significantly lower in the hit-KR condition ($M = 62$) than in the no-KR control condition ($M = 76$), $F(1, 66) = 14.23$, $p < .0003$, and that there was a significant main effect for noise $F(2, 66) = 3.27$, $p < .04$. The Noise × KR interaction was not significant, $F(2, 66) < 1.00$. Mean overall workload scores for the three noise conditions are displayed in Figure 2. Newman–Keuls tests with an $\alpha = .05$ set for all comparisons were used to probe differences among these conditions. Although exposure to low-intensity aircraft noise did not significantly elevate the level of perceived workload in comparison to the quiet control, exposure to high-intensity noise resulted in significantly higher workload scores than were present in the control group.

Inspection of the mean dimensional (factor) weightings for the six TLX subscales revealed that Physical Demand ($M = 42.43$) contributed least to perceived workload. Given the paired-comparison procedure used in determining dimensional weightings in the TLX (cf. Hart & Staveland, 1988), the Physical Demand dimension was dropped from an ANOVA of the subscale data to meet the independence assumption of the statistical procedure. The ANOVA revealed that there were significant differences among the subscales, $F(4, 264) = 26.08$, $p < .0001$, and that these differences were independent of the effects of noise and feedback. None of the interactions in the analysis was significant. The rank order of mean weighted ratings for the subscales used in the analysis was Frustration (294.30), Mental Demand (265.48), Effort (172.64), Temporal Demand (138.89), and Performance (126.18). It is evident that Frustration and Mental Demand were the principal contributors to workload.

DISCUSSION

The purpose of this study was twofold—to examine the potentially negative effects of aircraft noise on monitoring efficiency and perceived workload and to determine whether providing subjects with knowledge of results concerning correct detections could attenuate these effects. The results with respect to performance were complex and unanticipated. Exposure to the recorded sound of jet engines diminished subjects' perceptual sensitivity to critical signals, but only when hit-KR was available. When such feedback was absent, noise exposure had a negligible influence on sensitivity. Moreover, whereas hit-KR generally enhanced the detectability of signals as compared to the performance of no-KR controls, a result consistent with earlier findings by Becker et al. (1991) and by Dittmar et al. (1985), this effect was minimized in noise. Thus, instead of hit-KR's attenuating the effects of noise, the latter reduced the effectiveness of feedback.

Some insight into the complex Noise × KR interaction observed in this study may be gained by considering the difficulty of the discriminations that subjects were required to make to separate signal from nonsignal events. Table 2 reveals that the *d′* scores in the absence of feedback ranged from 1.04 to 1.69, with a mean of 1.35. According to Craig (1984), sensitivity scores such as these reflect a very difficult to moderately difficult task. In contrast, hit-KR boosted subjects' perceptual sensitivity, particularly in quiet. The mean *d′* value of 2.62 in the quiet/feedback condition signifies, in Craig's analysis, a moderately easy task. With respect to the effects of noise on subjects' perceptual sensitivity, it is possible that the interaction in question does not imply some special relation between noise and hit-KR, per se. Rather, given the difficulty of the discriminations involved, it is likely that there was more opportunity for the degrading effects of noise to appear in the hit-KR condition and that a "floor effect" rendered the influence of noise less observable in the absence of feedback.

In terms of the second aspect of the Noise × KR interaction—the finding that noise reduced the benefits of hit-KR—it is important to note that the vigilance task employed in our study required a successive discrimination or absolute judgment (Davies & Parasuraman, 1982) in which subjects had to engage working memory to determine the presence of a critical signal (a single line that was taller than usual). Such tasks have been shown to be resource-demanding and to be especially susceptible to reductions in performance efficiency when the information-processing load placed on monitors is increased (Parasuraman et al., 1987). This characteristic of successive tasks, coupled with the notion that subjects must expend processing resources to compensate for the disruptive influence of noise (Cohen, 1978; 1980), may help to explain why noise attenuated the propitious effects of hit-KR. Becker et al. (1991) and Dittmar et al. (1985) argued that the sensitivity advantages associated with hit-KR arise from the ability of such information to augment signal definition by fostering subjects' awareness of important task-relevant characteristics. Given that subjects in this study were confronted with a capacity-demanding task and that they also needed to expend processing resources to combat the detrimental effects of noise, it is conceivable that the added drain on processing capacity resulting from the synergistic combination of these two sources of demand rendered subjects less able to use the cues to signal definition otherwise provided by hit-KR.

As in several earlier experiments (Becker et al., 1991; Deaton & Parasuraman, 1993; Dember et al., 1993; Dittmar et al., 1993; Warm, Dember, & Parasuraman, 1991), the cost of mental operations in this study was quite high—overall workload scores reached the upper level of the TLX, a result that supports the notion that the monitoring task was indeed capacity demanding. Both hit-KR and exposure to jet engine noise modified this effect. In a manner reminiscent of the initial report by Becker et al. (1991), hit-KR lowered perceived workload, and as anticipated, noise exacerbated the subjects' perceptions of overall workload, at least in a comparison between high-intensity noise and quiet. Unlike the results obtained for the perceptual-sensitivity measure, however, the workload data were quite straightforward: There was no interaction between noise and KR. The finding that the effects of noise were independent of KR in the case of perceived workload but not that of performance is potentially quite important. One of the key elements in assessing the effectiveness of a workload measure is its sensitivity or ability to reflect variations in task loading (O'Donnell & Eggemeier, 1986). The robustness of workload-measured noise effects in comparison to the performance-measured effects of noise in this study implies that even when noise effects are not revealed in performance data, they may appear in the form of workload differences. This, in turn, suggests that the use of a workload measure, such as the TLX, may help to reduce some of the inconsistency found with noise that led Koelega and Brinkman (1986) to the bleak conclusion that lawful relations are not observable with respect to noise and vigilant behavior.

In addition to sensitivity, another criterion for assessing the effectiveness of a workload index is its diagnosticity—its ability to indicate the source of workload imposed by a task (O'Donnell & Eggemeier, 1986). Toward that end, we examined the contributions of noise and hit-KR to the six workload dimensions provided by the TLX. Unlike the overall workload measure, the relative factor loadings of specific workload components were unrelated to either of these variables. A result of this sort could be taken as support for Nygren's (1991) contention that the dimensional weighting procedure of the TLX is ineffective. On the other hand, it is worth noting that our outcome, in which Frustration and Mental Demand were the major components of workload, is consistent with the results of several other vigilance experiments that also examined the relative contributions of the six TLX subscales (Becker et al., 1991; Deaton & Parasuraman, 1993; Dittmar et al., 1993; Gluckman et al., 1988). As we have suggested elsewhere (Becker et al., 1991), such consistency across different experiments implies that there may be a typical workload profile that reflects the particular demands imposed by vigilance tasks. Although the absolute magnitude of overall workload may vary as a result of experimental manipulations, the factor loadings of specific workload components seem to be relatively fixed, with Frustration and Mental Demand serving as the primary dimensions of workload.

In addition to their general implications for the study of monitoring behavior and the measurement of perceived workload, our results also have potentially important ramifications for aviation-specific activities involving monitoring functions. As noted in the introduction to this article, KR has been used successfully to improve monitoring performance in the laboratory. As a result, on-line KR has been suggested as a potential vehicle to enhance performance in a variety of operational settings (cf. Craig, 1984; Warm, 1993; Wiener, 1984). Our results, however, suggest that ground and flight deck personnel who must perform monitoring functions in the presence of jet engine noise may find it difficult to profit from on-line feedback. The results also suggest that the stress induced by jet engine noise is not easily attenuated by task-related KR when the tasks are demanding. In addition, the workload elevations engendered by such noise could lead to other negative consequences, such as fatigue, mood changes, and absenteeism. In that sense, the workload data of our study are consistent with several other reports indicating that exposure of people to aircraft noise can pose a serious threat to their health (Clark, 1984; Cohen, 1980; Gunn, 1981; Knipschild, 1977).

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