3-D Audio in the Fighter Cockpit Improves Task Performance

J.A. Veltman, A.B. Oving and A.W. Bronkhorst

TNO Human Factors, Soesterberg, The Netherlands

Abstract

A flight simulator experiment was conducted to explore the benefits of a virtual 3-D audio display to support in-cockpit tasks regarding performance and workload. In half of the conditions, one or two tasks requiring information from a head-down display (HDD) were supported by 3-D audio. The performance on several tasks improved when 3-D audio was present, whereas no negative performance effects were found. Furthermore, the frequency of eye movements to the HDD was reduced more than 50% in all 3-D audio conditions. Physiological measures were not affected, indicating that mental effort was the same in all conditions. Only a small reduction in subjective workload in some 3-D audio conditions was observed. Pilots were also able to process the information from two independent 3-D auditory displays that were present at the same time. The results show that pilots can perform flight and in-cockpit tasks more efficiently when they are supported by 3-D audio.

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Requests for reprints should be sent to Hans Veltman, TNO Human Factors, P.O. Box 23, 3769 ZG, Soesterberg, The Netherlands; Veltman@tm.tno.nl

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A three-dimensional (3-D) auditory display makes use of the natural sound localization ability of humans. The technique that is used to create such 3-D auditory displays is based on real-time filtering of the sound with head-related transfer functions (HRTFs). These transfer functions simulate the acoustic effects of the listener's shoulders, head and external ears. Virtual sound sources created in this way can be localized with almost the same accuracy as real sources (Wightman & Kistler, 1989; Wenzel, Arruda, Kistler & Wightman, 1993; Bronkhorst, 1995; Kulkarni & Colburn, 1999; Langendijk, & Bronkhorst, 2000). Furthermore, localization performance of virtual sources improves when head movements can be made (i.e., presenting the sounds so that they remain fixed in virtual space independent of any head movements) and when the sound source is left on sufficiently long (Bronkhorst, 1995). Also, when 3-D audio is used in an auditory display one can benefit not only from the ability to localize sounds, but also from the internal noise suppression associated with binaural listening.

The application of a 3-D auditory display in the cockpit of an aircraft may offer several advantages to the pilot. Because most information is presented visually in the modern cockpit, the visual channel often becomes overloaded in high-workload conditions. The use of the auditory channel by means of a 3-D auditory display may lead to a reduction in workload (e.g., Nelson et al., 1998), and potentially to an increase in performance. In addition, communication efficiency can be improved by assigning different channels to sources located at different points in space (Drullman & Bronkhorst, 2000). Also, by presenting such auditory signals from locations that are spatially separated, their detection and discrimination can be facilitated. Only recently, studies have been performed that looked at the potential performance benefits of 3-D auditory displays in the cockpit.

Several flight simulator studies have investigated the use of 3-D audio for the Traffic alert and Collision Avoidance System (TCAS) which is installed in most commercial aircraft (Begault, 1993; Begault & Pittman, 1996; Begault, Wenzel & Lathrop, 1997;Oving, Veltman & Bronkhorst, this issue). These studies used a 3-D auditory display for the aural TCAS-warning to convey the spatial location of an intruding aircraft to the pilots. All studies showed that out-the-window visual search time for the intruding aircraft was reduced with 3-D audio, compared to monaural warnings.

Bronkhorst, Veltman and Van Breda (1996) examined the application of 3-D audio to indicate the location of a target jet in a fighter intercept task. In this simulator experiment, two different displays were used to convey the target location to the pilot: a visual 2-D radar display located in front of the pilot (head-down display or HDD), and a 3-D auditory display. They observed that the fastest target acquisition times were obtained with the combination of the visual HDD and the 3-D auditory display. No difference was found between the conditions with only the visual display or the 3-D auditory display.

A follow-up study was conducted by Veltman, Van Erp, Van Breda and Bronkhorst (1996). It differed from the previous study in that 3-D audio always served as an additional display to a visual HDD that was either in a 2-D format or a perspective format. This latter format has proven to be very effective for the intercept task (Van Breda & Veltman, 1998). To test if 3-D audio resulted in the hypothesized reduction of visual workload, a secondary visual task was present in a simulated head-up display (HUD). In addition, to examine the effect on performance of multiple sources in the 3-D auditory display, two targets were present in half of the trials. These targets had to be intercepted one after another. The results showed faster acquisition times and a higher percentage of targets found when 3-D audio was present, but only in the conditions with the 2-D visual display. No effect of 3-D audio was observed when the perspective visual display was present, which resulted in the best performance. The 3-D auditory display also proved to be beneficial for the secondary visual task, with less HUD targets missed when 3-D audio was present. Interestingly, this was observed for both types of visual HDDs. This shows that when 3-D audio is used in addition to a visual HDD, more visual attention can be directed to other visual tasks regardless of the quality of that visual HDD. No differences between the conditions with only one auditory target and with two targets were found. This indicates that the benefits of 3-D audio were independent of the number of auditory sources that were present.

The present experiment

Based on the results of the simulator studies, it can be concluded that a head-up 3-D auditory display is beneficial for the performance of different out-of-the-window tasks. It appears that more attention can be paid to visual information outside the cockpit when 3-D audio displays are used in addition to visual HDDs. Apparently, pilots scan the visual HDDs less frequently when they are supported by 3-D audio. This hypothesis, however, has not been studied in a more direct manner. Therefore, we conducted a flight simulator experiment to study the effect of 3-D audio on the visual scan behavior of pilots more explicitly.

A second issue is that new technologies in the cockpit do not necessarily have a positive effect on both performance and workload. A new cockpit system can improve the performance when it provides more information, but when this system requires more attention, the workload might increase. Two different results can be expected when a new system requires less attention: 1) the overall workload will decrease or 2) the pilot will redistribute his workload by paying more attention to other tasks. A consequence of the second option is that the workload will remain the same but that the overall level of performance increases. To investigate the effects of 3-D audio on mental workload more thoroughly, several physiological measurements that are related to mental workload (see Veltman & Gaillard, 1998) as well as subjective effort ratings were included in the present study.

A third question involved the effects on task performance and workload when two auditory sources are presented concurrently. This question was also addressed in the study of Veltman et al. (1996). However, the experimental setup was such that the pilots did not have to pay attention to both sources at the same time. Only one source was relevant for task execution during a trial because the pilots had to intercept the targets one after another. That study thus looked at possible masking effects of the secondary auditory source on performance with the primary source only. In the present study, two different auditory sources were used that presented information for two different tasks. In some of the experimental conditions, these tasks had to be performed concurrently, making both auditory sources relevant for task execution at the same time.

Method

Participants

Twelve pilots, eleven males and one female, were recruited from the Royal Dutch Airlines Flight Academy (KLS). All participants were in the middle or final stage of their training or had recently completed their training. The age of the participants ranged from 19 to 28 years. On average, they had 190 hours of flying experience. All participants had normal or corrected to normal vision.

Tasks

Two primary flight tasks had to be performed: an intercept and a pursuit task. These tasks were combined with two secondary tasks: a HUD task and a head-down task. The primary tasks were never combined, whereas the two secondary tasks could be present together with one primary task. The primary tasks are described first, followed by a description of the secondary tasks.

Primary tasks

In the intercept task, participants had to locate a target jet that appeared somewhere around the own jet. This target could appear in one of 37 locations that were evenly distributed on a virtual sphere around the own jet. This virtual sphere had a radius of 10,000 ft. The target jet always flew away from the own jet in a straight line, with a relative heading and pitch similar to the initial angles at target appearance. The speed of the target jet was fixed at 500 kts.

The participants had to fly into the direction of the target jet as quickly as possible after which they had to keep the target within 3° around their own direction vector for one second. Successful capture of the target was indicated by a non-localized auditory signal (in all conditions) and a change in the color of several indicators in the HUD (i.e., the circle around the target, the altitude and speed indicators). After each trial, participants had to fly level again after which the own jet was repositioned at the starting altitude of 50,000 ft. Three seconds later, the target jet jumped to a new location, which was indicated by a non-localized auditory signal also. The target appeared at all 37 positions during one task block, with the order determined randomly. Thus one run for the intercept task consisted of 37 intercepts. The position of the target jet was always presented on the HDD, and in half of the experimental conditions it was also signalled by means of a 3-D audio display.

In the pursuit task, participants had to follow another aircraft at a target distance of 1500 ft. Information about distance to the target was presented on the HUD. The speed of the target was always 500 kts. The target jet flew a pre-defined route including vertical and horizontal maneuvers. By mirroring this first route, a second route was created with the same difficulty. Both routes were flown by each participant. One run for this task lasted 20 min.

Secondary tasks

The HUD task had to be performed concurrently with each of the primary tasks. For this task, three dots were presented at the top of the HUD. The color of each dot was either yellow or red, but this color could change every 10 seconds. Participants had to pull a trigger on the control stick as quickly as possible when all three dots became red. This was the case in about 30% of the trials. This task was added to provide additional data to see if the participants are able to fly in head-up position more often.

For the head-down task, the participants had to monitor the position of a virtual object. They had to press a button on the throttle when the object got behind the own jet and press the button a second time when it got in front of the own jet again. Feedback about the response was presented on the HUD: a yellow triangle appeared in the lower left corner of the HUD when the participant indicated that the object was behind. The object was visible on the HDD only. The object completed an ellipse around the own jet (clock-wise or counter clock-wise), after which it started a next ellipse at a random position. The shape of the ellipse was chosen randomly. The speed of the object was made relative to the speed of the own jet. Therefore, on average, the time it was in front of the own jet was the same as the time it was behind the own jet. The position of the object was also indicated with a 3-D audio display in half of the conditions with this task. The purpose of this task was to see if the participants scanned the HDD less frequently when this task was supported by a 3-D audio display.

Apparatus

The experiment was conducted in a fixed-base flight simulator that consisted of three components: a video image generator with projection system, a mock-up of a cockpit, and a computer system running a simple aerodynamic model of the aircraft and processing the control input and model output. A three-channel Evans & Sutherland ESIG 2000 high speed graphics computer was used to generate high resolution synthetic video images (i.e., 1500 to 2000 textures polygons with 800×600 pixel resolution per channel) for the simulator vision system. The image update frequency was 30 Hz. The total field of view was 156° horizontal and 42° vertical. The video images were presented by means of a Seos PRODAS HiView S-600 projection system, consisting of a spherical dome and a set of video projectors.

A mock-up of a cockpit was positioned in the center of the dome. The distance from the participants' viewing point to the screen was about 3 m. The mock-up was a partially instrumented cockpit of a fighter jet. The mock-up had a force stick on the right side (controlling roll and pitch) and a throttle on the left side (controlling thrust). A computer monitor that displayed the HDD was positioned in front of the participant.

The HUD was simulated by projecting it on the dome in front of the participant. The HUD provided primary flight information (i.e., airspeed, altitude, pitch, roll and heading). For all tasks, the distance to the target jet was presented with a digital indicator to the left of the HUD. In addition, when the target was within 12° of the point directly in front of the subject , a yellow circle that was projected over the target appeared in the HUD. This was a strong visual cue indicating that the target was in front of the own jet.

The HDD was used for the presentation of radar information. The position of the own jet was presented heading up in the center of the display, with the positions and orientations of the target jet and the virtual object (when present) displayed relative to the own jet.

Information about the relative position of the target jet was color coded: the target jet symbol was blue when it was above the own jet and red when it was below the own jet. In addition, the pitch angle needed to get the target in front of the own jet was indicated by changing the saturation of the symbol color. This varied in ten linear steps to white when the actual pitch was the same as the required pitch. The symbol was a saturated blue when the deviation was more than +20° and a saturated red when the deviation was less than –20°. This color scheme was implemented to provide comparable information on the visual radar as was provided by the 3-D audio display for the intercept task.

3-D audio system

Three-dimensional audio was generated with a set-up consisting of an AKAI S3200 XL sampler, a PC equipped with two Loughborough DSP32C boards, a mixer, a headphone amplifier driving Sennheiser HD 530 headphones and a Polhemus Fastrak head tracker. The PC was synchronized to and controlled by the simulator PC through a parallel port connection. The two DSP boards in the sound PC performed the convolution with head-related transfer functions (HRTFs). The outputs of the boards were then mixed, amplified and fed into the headphones. Head movements of the participant were registered by the head tracker and transmitted through an RS232 interface to the sound PC.

The HRTFs that were used to create 3-D audio were individualized according to one of two methods. For four persons that had participated in earlier experiments, HRTFs could be used that had been measured individually. Because the HRTF measurement setup was not available during the present experiment, the HRTFs for the other eight participants were selected from 9 existing sets, using localization tests. These tests are described in Veltman and Oving (1999). A set of HRTFs includes 976 sound directions, almost evenly distributed over the sphere around the listener except for elevations less than –60° (Bronkhorst, 1995).

Because this corresponds to a high resolution (5–6°), no interpolation between measured directions was performed. The raw HRTFs, measured with a 10 ms test sound, were transformed to minimum phase impulse responses with lengths of 3.4 ms. A sample frequency of 37.5 kHz was used. HRTF-filtering was done in the frequency domain, using the overlap-add algorithm (see e.g., Oppenheim & Schafer, 1989). This introduced a delay of about 34 ms between an update of the virtual sound source position by the sound PC and the actual modification of the 3-D auditory signal.

3-D auditory displays

The signals of the 3-D audio displays were adapted more effectively to the requirements of the tasks in the present experiment. This was done by changing one or more characteristics of the sound sources in real-time. The signal used in the intercept task was a pulsed complex harmonic tone with a fundamental frequency of 300 Hz. The pulse frequency varied between 6 and 12 Hz as a function of the difference between the momentary roll-angle of the own jet and the ideal roll-angle needed for efficient task execution (i.e., higher frequency when the difference got smaller). The ideal roll-angle was obtained by getting the target in the upper half of the median-sagittal plane of the own jet, so that the pilot only needed to pull on the stick to intercept the target. In addition, when the target jet was within a window of 30° × 30° in front of the own jet, the signal was also raised in pitch such that maximum pitch occurred when the target was directly in front.

The location of the virtual object in the head-down task was also indicated by a pulsed signal. The pulse frequency was 4 Hz and the signal was either a complex harmonic tone with a fundamental frequency of 200 Hz (when the object was in front) or a complex harmonic tone that swept within the duration of a pulse over a frequency range of 2 octaves (when the object was behind the own jet). Such additional auditory cues were not used in the studies of

Bronkhorst et al. (1996) and Veltman et al. (1996) that both used a comparable 3-D audio display and task paradigm.

Experimental design

The intercept task was performed with and without the head-down task, while the HUD task was always present. The pursuit task was always performed in combination with both secondary tasks. These three task combinations were flown with and without 3-D audio support, resulting in six different conditions. Because two different 3-D auditory displays were used, one for the intercept task and one for the head-down task, two auditory sources were present when these two tasks were combined. In the other 3-D audio conditions, only one auditory source was present.

A within-subjects design was used, and the participants performed the six conditions in two blocks: one block with and one block without 3-D audio conditions. The order of these blocks was balanced across participants. The order in which the tasks had to be performed was balanced within these blocks. All participants performed one run in each condition.

Performance measures

Performance for the intercept task was quantified in terms of target acquisition time. Target acquisition time was defined as the time between target appearance and target capture (i.e., keeping target jet within 3° for 1 s). The acquisition times of the 37 trials in a run were averaged for each participant. Trials in which the target jet was not captured within 50 s were omitted from the analyses. This occurred 43 times (out of 1776 trials) and these trials were evenly distributed across the conditions.

To assess the performance for the pursuit task, the mean following distance during a run was calculated for each participant. The following distance was defined as the momentary distance between the center of the target jet and the center of the participants' aircraft. It should be noted that at the start of the pursuit task, the target jet was always placed at the criterion distance.

For the HUD task, the average response time of the correct responses in each run was calculated for each participant. A response was considered to be correct (i.e., a hit), when the trigger was pulled while three red dots were present in the HUD. Also, the percentage of hits was determined. This percentage was based on the total number of targets that was presented and the number of hits in a run.

The performance for the head-down task was expressed in the percentage of time the object was correctly indicated to be behind or in front of the own jet.

Workload measures

Mental workload was assessed with several psychophysiological measures: heart rate, heart rate variability, respiration frequency and amplitude, and eye blink duration, frequency and amplitude. The derivation of these measures is not described in the present paper (see Veltman and Oving, 1999 for details). Subjective workload was also determined. Participants filled out the Rating Scale for Mental Effort (RSME; Zijlstra, 1993) after each condition. This scale has to be rated between 0 and 150 and has text labels along the axis ranging from not at all effortful to extremely effortful.

To analyze the visual scan behavior of the pilots, the frequency of vertical eye movements was determined from the electro oculogram (EOG). The EOG was measured with three Ag/AgCl electrodes attached above and below the right eye and one centred on the forehead that served as ground electrode. The sample rate was 256 Hz. Shifts in the EOG signal were used for movement detection. A criterion of 7 μV difference between two succeeding samples (when these samples were not part of an eye blink) was used for movement detection. The parameters for eye movement detection were checked by inspecting video recordings of the faces of the participants during the experiment.

Statistical analysis

The dependent variables were analyzed with analyses of variance (ANOVA) in a within-subjects repeated measurements design. The data in the intercept conditions and the pursuit conditions were always analyzed separately. The design for the intercept conditions consisted of two factors: Intercept tasks (intercept only, and intercept + head-down task) and Audio (no audio, and 3-D audio). The design for the pursuit conditions consisted of the single factor Audio (no audio, and 3-D audio). An exception involved the performance on the head-down task, because this task was performed in intercept conditions as well as in pursuit conditions. Therefore, the statistical design for analyzing the relevant performance measure included two other factors: Primary tasks (intercept, and pursuit) and Audio (no audio, and 3-D audio).

Procedure and training

Upon arrival, the purpose of the experiment and the intended schedule of the day were briefly explained to the participants. Subsequently, they received written instructions about the experimental tasks and conditions. Regarding the intercept task, the participants were instructed to fly into the direction of the target jet as quickly as possible and keep it within 3° for 1 s. For the pursuit task, they were instructed to maintain the following distance of 1500 ft and to minimize any error to this criterion distance as quickly as possible. The instruction for the HUD task was to respond as quickly as possible (by pulling the trigger in the stick) when three red dots appeared in the HUD. And for the head-down task, the participants were instructed to be as accurate as possible in signaling the position of the virtual object.

Next, the participants were trained in all tasks and experimental conditions for about two hours. It is important to note that during the training sessions of the intercept task with 3-D audio, the visual HDD was turned off during a number of trials. The participants thus had to locate the target with only the 3-D audio display as a source of location information. All participants successfully intercepted the target jet in most or all of these 'blind' training trials. After such blind trials, most participants remarked that they were surprised about the effectiveness of the 3-D audio display and their performance with this display. This finding indicates that it is important to train participants in the use of 3-D auditory displays without the presence of relevant visual displays. A similar procedure was applied during the training of the head-down task in the pursuit condition. When the 3-D auditory display was present, the visual display was turned off for a couple of minutes.

Results

The results from the performance measures are presented first, followed by the results from the subjective and physiological workload measures. The results for the performance measures are described per type of task.

Performance

The ANOVA on the intercept performance measures showed a main effect for Intercept tasks [$F(1,11)=9.67$, $p<0.01$].

Mean acquisition times in the intercept alone conditions (15.0 s) were faster than in the intercept conditions with the head-down task (15.6 s). No other effects were found. Thus 3-D audio did not affect the acquisition times.

The ANOVA on the mean following distance in the pursuit task showed a significant effect of 3-D audio [$F(1,11)=5.38$, $p<0.05$]. From Figure 1, it can be seen that the mean following distance was considerably closer to the criterion distance of 1500 ft in the 3-D audio condition. Thus the participants could follow the target jet better when 3-D audio was present for the secondary head-down task.

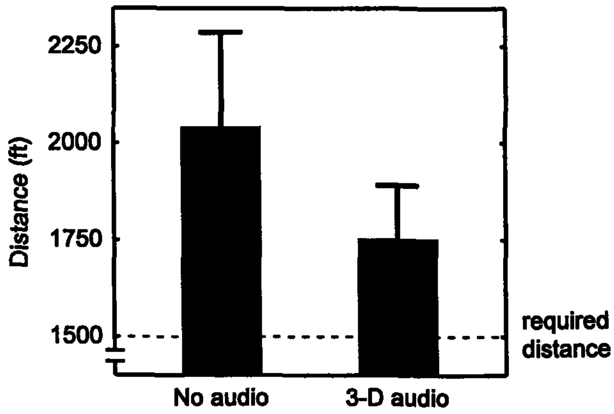

Fig. 1 Mean following distance (ft) (and standard errors) in the pursuit task as a function of Audio condition.

The data for the HUD task are presented in Figure 2 For the intercept conditions, the ANOVA of the factor Audio was significant [$F(1,11)=5.80$, $p<0.05$]. Participants responded faster to the HUD task when the intercept task was supported by 3-D audio. A trend ($p=0.05$) was observed regarding the presence of the head-down task during interception, with faster responses when the secondary task was absent. The HUD task was not affected by 3-D audio in the pursuit task.

For the percentage of hits, no analyses were performed because only 7 targets were missed in all conditions together. This indicates that the findings for the HUD response times were not the result of a trade-off between reaction speed and accuracy.

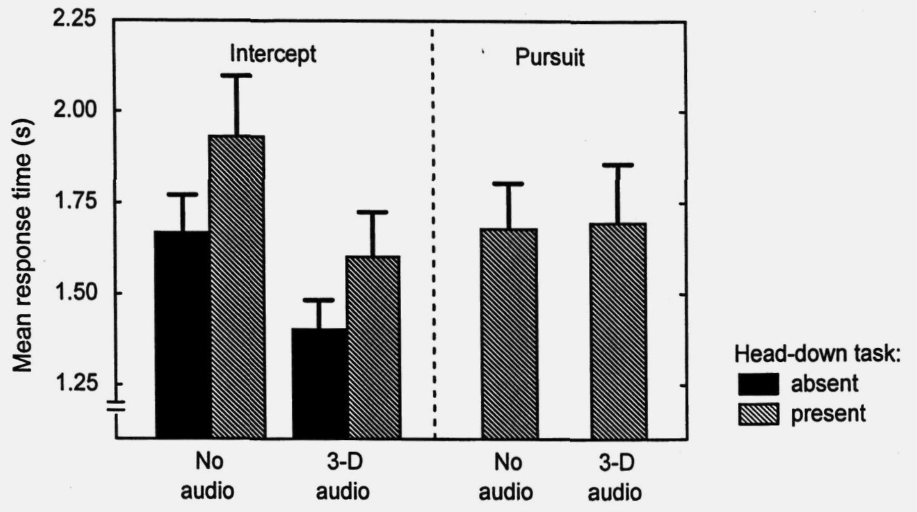

Fig. 2 Mean response time (s) and standard errors in the HUD task as a function of Task and Audio conditions.

The results for the head-down task are presented in Figure 3. The percentage of time with a correct response for the head-down task was higher in the pursuit task than in the intercept task [F(1,11)=10.2, p<0.01]. This indicates that the participants were better able to monitor the position of the virtual object when they performed the pursuit task compared to the intercept task. The interaction between Task and Audio was also significant [F(1,11)=21.6, p<0.01]. 3-D audio had a positive effect in the pursuit condition: the percentage of time with a correct response increased from approximately 77% to 83%. This was not the case in the intercept conditions, but the small decrease in performance with 3-D audio (about 1.9%) did not prove significant in a post-hoc analysis. Note that there were two different sound sources present in this latter condition, since both tasks were supported by 3-D audio.

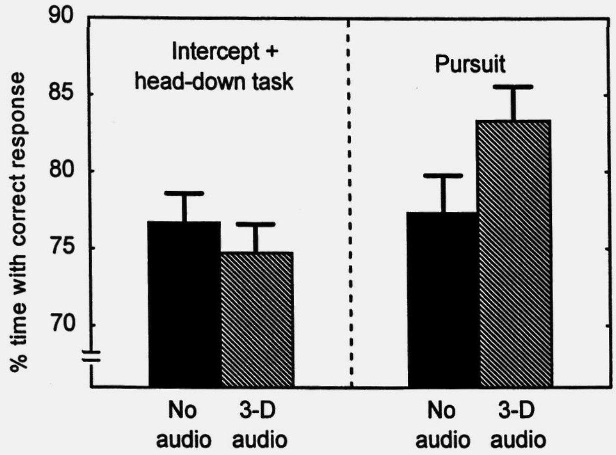

Fig. 3 Mean percentage of time (and standard errors) that the virtual object was correctly indicated to be in front or behind the own jet as a function of Task (intercept + head-down task, and pursuit) and Audio conditions. Note that higher values indicate better performance.

Workload

No effects were observed for any of the physiological measures for mental workload. The results for the subjective effort ratings (RSME scores) are presented in Figure 4.. Participants indicated that the effort investment was much higher when the head-down task had to be performed [$F(1,11)=27.2$; $p<0.001$]. No effect of Audio was found in the intercept task. Participants provided lower effort ratings in the pursuit condition when they were supported by 3-D audio [$F(1,11)=9.9$; $p<0.01$].

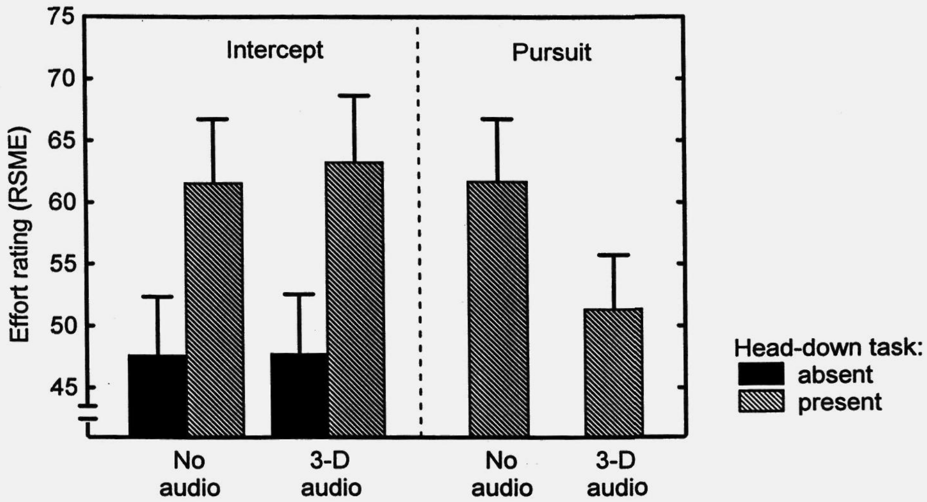

Fig. 4 Subjective effort (RSME) ratings and standard errors.

The results of the vertical eye movements are presented in Figure 5. The frequency of vertical eye movements was strongly reduced when the participants were supported by 3-D audio in both the intercept and the pursuit task [$F(1,11)=23.2$ $p<0.001$ and [$F(1,11)=94.4$; $p<0.001$ respectively]. This reduction was about 50% in the intercept task and about 60% in the pursuit task.

The presence of the head-down task had no effect on the frequency of vertical eye movements in the intercept task. It should be noted that the trials in the intercept tasks were rather short (about 15 s), which explains the relatively high eye movement frequency. In the intercept task without 3-D audio the average number of eye movements per trial was 6.5, whereas it was 3.5 when 3-D audio was present.

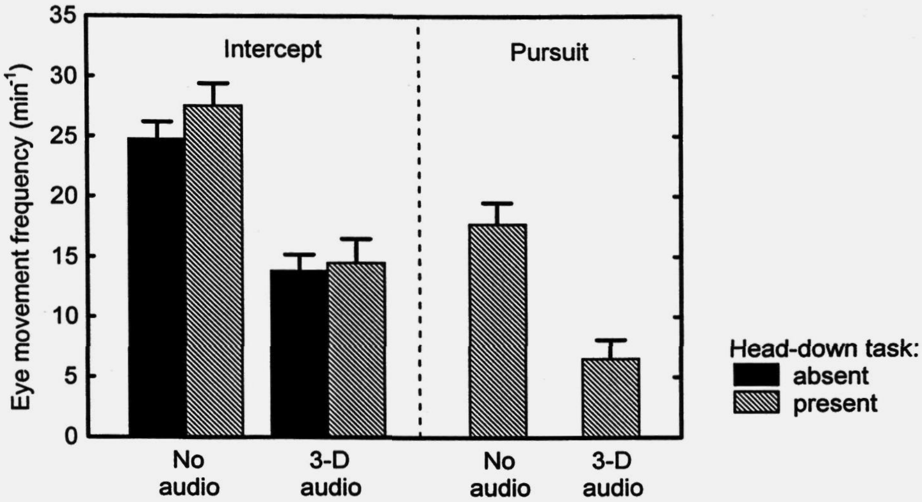

Fig. 5 Frequency and standard errors of vertical eye movements.

Summary of results

- 3-D audio did not improve the intercept performance. The performance on the pursuit task was improved considerably when the secondary task of locating the virtual object was supported by 3-D audio.
- 3-D audio improved the performance on the HUD task (detection of the three red dots), but only in combination with the intercept task.
- 3-D audio improved the performance for the head-down task, but only in combination with the pursuit task. It should be noted that the participants heard two different sound sources when the head-down task was performed along with the intercept task (i.e., position of the target jet and the virtual object) compared to one sound source when it was performed with the pursuit task (i.e., only position of the virtual object).
- The frequency of vertical eye movements was reduced considerably in all 3-D audio conditions (i.e., 50% in the intercept conditions and 60% in the pursuit conditions).

- Participants reported lower effort investment in the pursuit task condition when the head-down task was supported by 3-D audio.

Discussion

Do pilots scan head-down displays (HDD) less frequently when HDD information is also presented by 3-D audio?

The two primary and two secondary tasks can be divided into head-up and head-down tasks. The intercept task was mainly a head-down task, because the target jet was hardly visible in the out-the-cockpit view and information about target location was available only on the HDD. The HUD only displayed target information when the target was within 12° in front of the own jet. Therefore, the pilots had to scan the HDD frequently during most of the intercept task. In half of the intercept conditions, 3-D audio was used to support the head-down information. This did not improve the primary task performance (i.e., acquisition time was not affected). However, the results showed that participants looked 50% less often at the HDD. This means that the participants used the 3-D audio display to some extent to perform the intercept, without a degradation in performance. And because participants could fly more head-up, they were able to pay more attention to the HUD which resulted in improved performance on the HUD task.

The pursuit task was basically a head-up task. The target jet was clearly visible outside the cockpit and its distance was presented on the HUD. Pilots needed the HDD for the pursuit task only when the target jet was outside the field of view of the dome. The pursuit task was always combined with the secondary head-down task. For this latter task, the HDD was the only source of information, and participants thus had to scan the HDD to perform this task. In the pursuit conditions, 3-D audio was used to support the head-down task. This resulted in a reduction of 60% vertical eye movements, and thus in more head-up time. Therefore, the participants were able to pay more attention to the target jet which increased the tracking performance. Furthermore, the performance on the head-down task was also improved, which indicates that the use of different modalities for different tasks can be beneficial in high visual workload conditions. These results show that pilots can fly more head-up when 3-D audio is used to support head-down tasks.

It should be noted that, even though participants improved on the HUD task when they could fly more head-up during the intercept conditions, such an improvement was not observed during the pursuit conditions. This difference may be explained by the position of the target jet in the visual field compared to the location of the HUD. Most often the target jet was not close to the HUD due to the unexpected maneuvers of the target jet and a subsequent lag in tracking. Therefore, it is likely that the dots in the HUD were not within or close to the central field of view when the participants looked at the target jet. In addition, the pursuit task required attention almost continuously due to the rather small following distance. Therefore, moving the eyes away from the target, e.g. either to the HUD or the HDD, made the following more difficult.

Does 3-D audio have consequences for the workload of the pilot?

Making use of more modalities to obtain information apparently makes task performance more efficient, but this does not automatically mean that 3-D audio reduces the workload. When the extra attention that becomes available by using the auditory modality is used to improve task performance, then the workload will not be affected. This redistribution of attentional capacity seems to be the case in the present experiment. The level of performance was increased for several tasks due to 3-D audio. In addition, the physiological data did not show any differences between the conditions, indicating that the participants invested about the same level of effort in all conditions. The subjective effort however, did show a decrease in the pursuit task with 3-D audio, indicating a reduced workload due to 3-D audio. A reduction in subjective effort due to 3-D audio was also reported by Nelson et al. (1998). It is not uncommon to find such a dissociation between subjective and physiological workload measures. When participants improve their primary task performance, they tend to indicate that the task becomes easier and thus that it required less effort (e.g., Veltman, Gaillard & Van Breda, 1997). Based on these results, we conclude that 3-D audio resulted in a redistribution of workload. The visual tasks that were supported by 3-D audio required less visual attention and therefore less capacity was required to perform the tasks. The remaining capacity was not used to lower the workload, but to increase the overall level of performance.

Can pilots use two independent 3-D audio signals that are presented simultaneously?

In the intercept conditions with 3-D audio there was one auditory source when the head-down task was absent and two sources when the head-down task was present. In the latter situation, the position of the target jet as well as the position of the virtual object were presented continuously, which may have had consequences for the quality of perception of the individual sources. The results indicated that the participants were able to process the two auditory sources adequately.

Compared with the no-audio condition, the performance on the two supported tasks remained the same, while the participants scanned the HDD with visual information for both these tasks less frequently. The reduction in eye movement frequency was also the same in both intercept conditions where 3-D audio was present. When the participants would have had difficulty with interpreting the direction of two sound sources, as compared to only one source, they would have looked to the HDD more often to check the auditory information. In addition, the workload measures (both subjective and physiological) did not show significant differences. This indicates that the processing of information from two sound sources did not require additional effort. Moreover, the decrease in response time for the HUD task due to 3-D audio was the same in the conditions with one and with two auditory sources. Thus, it can be concluded that pilots are able to process and use two different sound sources simultaneously.

General comments

3-D audio was always presented in addition to visual information in the present experiment. During the intercept task, the target was always visible on the HDD, and the virtual object of the head-down task was also presented at the HDD continuously. Thus, no direct conclusions can be made about the effectiveness of 3-D audio when no visual information is presented. However, the HDD was turned off during some training trials when the participants were trained in the 3-D audio conditions. The participants were all able to track the target jet with only 3-D audio in the intercept condition. The same procedure was applied during the training of the head-down task in the pursuit conditions: when 3-D audio was present, the visual display was turned off for a couple of minutes. Again, participants were able to perform the 3-D audio supported task adequately. Also, after the training and experimental trials, most participants reported that they used the radar display only to verify the 3-D audio information. This suggests that the participants primarily relied on the 3-D auditory displays to execute these tasks. So it is reasonable to assume that when pilots are trained to work with 3-D auditory information more extensively, the tasks can be performed adequately with 3-D audio alone. Further research is required to investigate the type of cockpit tasks that can be performed adequately when 3-D audio is available only. Moreover, the level of performance that can be obtained in these situations has to be investigated more extensively.

This was the third experiment in a series of experiments on 3-D audio in the military cockpit conducted at TNO-HF. All three experiments showed positive effects on primary and/or secondary task performance when 3-D audio was presented. No performance decrements were found on any performance parameter in these experiment. All participants in these experiments had flight experience and therefore had much experience with visual displays. Only little training with 3-D audio was provided before the experiments. Therefore, it is reasonable to assume that the benefits of 3-D audio will increase even more when pilots get more training with 3-D audio.

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