Acoustic Noise and Functional Magnetic Resonance Imaging: Current Strategies and Future Prospects

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Functional magnetic resonance imaging (fMRI) has become the method of choice for studying the neural correlates of cognitive tasks. Nevertheless, the scanner produces acoustic noise during the image acquisition process, which is a problem in the study of auditory pathway and language generally. The scanner acoustic noise not only produces activation in brain regions involved in auditory processing, but also interferes with the stimulus presentation. Several strategies can be used to address this problem, including modifications of hardware and software. Although reduction of the source of the acoustic noise would be ideal, substantial hardware modifications to the current base of installed MRI systems would be required. Therefore, the most common strategy employed to minimize the problem involves software modifications. In this work we consider three main types of acquisitions: compressed, partially silent, and silent. For each implementation, paradigms using block and event-related designs are assessed. We also provide new data, using a silent event-related (SER) design, which demonstrate higher blood oxygen level-dependent (BOLD) response to a simple auditory cue when compared to a conventional image acquisition.

Key Words: task design; auditory cortex; acoustic noise; gradient noise; functional magnetic resonance imaging


OVER THE PAST DECADE, magnetic resonance imaging (MRI) has superseded positron emission tomography (PET) as the technique of choice for mapping brain function. Functional MRI (fMRI) provides better temporal and spatial resolution and does not involve the use of radioisotopes; therefore, the number of images acquired per subject is not restricted by the risk of radiation exposure (1). However, the process of image acquisition for fMRI generates a very loud acoustic noise (2–5) that can interfere with auditory processing (6–10), and furthermore generates blood oxygen level-dependent (BOLD) contrast in the auditory cortex similar to that produced by vocalized words (11). Several methods of dealing with this problem have been described. Some focus on the source of the acoustic noise directly (12–19), while others involve the insertion of silent gaps between acquisition periods (8,20–23). There are already many variations on the latter approach, dependent upon the questions and requirements posed.

The aims of this work are to 1) review the literature regarding scanner acoustic noise, and 2) provide further, novel experimental data and a constructive critique of these different acquisition approaches.

NOISE SOURCE

Scanner acoustic noise is derived from the mechanical oscillation of the gradient coils placed in a magnetic field (24,25). The Lorentzian forces induced when an electrical current is applied to these coils make them physically move. This displacement is dependent on the strength of the static magnetic field, the amplitude of the acoustic noise typically varies from 94 to 135 dB SPL (specific pressure level) and depends upon the following parameters: the characteristics of the scanner materials and their assembly, the extent of vibration of the system, the type of pulse sequence applied, the number of slices acquired, the receiver bandwidth, the RF pulse envelope, the TR and TE, the FOV, the static magnetic field, and the rate and amplitude of gradient switching (13,16,27–29). Industrial guidelines in the U.K. and the U.S. stipulate that...
the maximum permitted daily noise dosage is equivalent to 90 dB (A) for 8 hours. Because dosage is a function of time and intensity, this precludes long-term exposure to a high dB (A) EPI scanning regime (30).

There are at least three ways by which scanner acoustic noise can be conducted to the internal ear (16): via bone, air, and head. Furthermore, the subject’s perception of such stimuli is modulated by a central (“top-down”) mechanism that regulates transmission through the cochlea, pons, and primary auditory brain areas (31). The interaction between all of these factors may interfere with the subject’s final perception of the sound (7,32,33). Moreover, these effects are not limited to tasks involving auditory stimuli, but can also occur with other sensory modalities, such as motor and visual paradigms, wherein the number of voxels activated and the percent signal change in the MR image differ with the absence or presence of acoustic scanner noise. This has been attributed to attentional effects (34,35).

The choice of the appropriate strategy to use is directed by whether a study requires less interference from ambient noise during the stimulus presentation (competition) and/or during task performance (processing), or simply requires decoupling of the BOLD signal originating from the stimulus of interest away from the scanner acoustic noise (analysis).

REDUcing SCANNER ACOUSTIC NOISE

Hardware Modifications

Perhaps the most obvious approach to address the problem of acoustic noise is to implement engineering modifications directly at the source of the problem, i.e., the MRI system (particularly its gradients) (17,18). Ravicz et al (16) and Price et al (5) recently characterized the scanner acoustic noise generated by different static magnetic fi eld strengths. Levels varied from 82.5 dBA for a 0.23 T system, to 118.4 dBA for a 3 T system using conventional acquisition (5) and 115 dB SPL for a 1.5 T, increasing to 131 dB SPL using EPI (16). The effects of Lorentzian forces can be compensated for by redesigning the gradient geometry, by means of providing a winding control loop that counterbalances the mechanical vibrating forces generated by a single electrical pulse (thereby reducing the acoustic output by as much as 34.9 dB (27,36,37)), or by minimizing sound propagation across the components of the scanner (38). Other approaches involve mainly passive attenuation (19). Most MR centers use headphones to attenuate the scanner acoustic noise, and the noise can be further muted by using ear plugs and packing the bore with high-absorbance acoustical materials (16). Vibration can be attenuated by using special cushioning, thereby reducing if not eliminating noise conduction through bone (16). These hardware modifications will undoubtedly form part of the next generation of MR systems. They will involve the use of different components and materials, improved isolation of the gradients (e.g., the vacuum system), and/or redesigns of the coil shape, while maintaining the wide bore and rapid gradient switching capabilities of our current systems (39).

More sophisticated techniques include active acoustic noise cancellation (12,40), which works in a manner comparable to current commercially available headphones. Here the scanner noise is sampled, and its spectrum is basically reversed to produce a stimulus with the same amplitude, but phase-shifted 180°. Through destructive interference, the waves cancel each other out; thus the subjects will not perceive the noise, or its intensity will at least be reduced. However, it is not 100% effective since bone conduction of the scanner noise would still be evident (41). Moreover, because of the high frequency of EPI pulse sequences, the system must be fast enough to detect and modify the noise, and present the appropriate phase-shifted stimulus. A failure in shifting the phase would amplify, and theoretically could double (by constructive interference), the noise instead of canceling it. Another interesting approach was proposed by Cho et al (42), whereby the use of a mechanically rotating DC gradient dramatically reduces the acoustic output of the MR scanner. However, major technical limitations in the slice plane (only axial slices are feasible), peripheral loss of MR signal, and practical maintenance considerations, including of the number of moving parts, could pose a challenge for mass production.

Although an MRI system that produces negligible acoustic noise would be the obvious solution for the whole scanning environment, this has to be weighed against the potentially large financial costs. Unless there is a particular need for fMRI with minimal scanner acoustic noise, it may be difficult to justify the cost of renewing or replacing substantial components of an existing system for this purpose. With this in mind, we now focus on the effectiveness of software modifications, especially on the pulse sequence design. These can be applied to existing MR systems (of which there are currently around 15,000 worldwide) and are relatively inexpensive to implement.

Software Modifications

For fMRI we are invariably required to collect images as fast as possible. Fast acquisition, however, poses a major acoustic noise problem. Slower ramp time, i.e., “smooth gradients” are very effective in reducing the amplitude of the noise (as low as 40–60 dB(A), but tend to be relatively slow, and although the BURST (an alternative ultra-fast single shot technique) scheme described by Hennig and Hodapp (43) can used for some fMRI studies, most implementations are not suitable for most fMRI experiments—especially event-related designs (15,44). However, recent advances in parallel imaging could lead to the utilization of smooth gradients while retaining the flexibility of existing EPI strategies. A recent work (45) reported a ~20 dB reduction using the sensitivity encoding (SENSE) (46) technique applied to a gradient-recalled echo (GRE) EPI acquisition. Currentl, most attempts to reduce scanner noise in fMRI studies are based on modifications to the acquisition sequence and the stimulus presentation strategy. These different strategies are the main focus of this report, and since they usually entail changes in the presentation of the stimuli, these have been described in two categories: block and event-related strategies.
BLOCK DESIGNS

In this design, the same type of stimuli are presented sequentially within a block, and two or more blocks of different experimental conditions are then alternated. Each “block” is typically of 20–40 seconds duration. In a conventional fMRI acquisition sequence, images are acquired continuously for substantial time intervals, thus generating frequent acoustic scanner noise bursts of around 100 dB (i.e., gradient oscillation is turned on for every slice acquired, and the period between slices is typically very short). This perceptual background acoustic noise competes with the auditory stimuli, but usually it is not loud enough to prevent subjects from hearing. The brain regions responding to the paradigm can generally be detected, assuming that the scanner noise is constant, affecting both “on” and “off” conditions equally, and therefore can be treated as a nuisance variate (47–68).

Compressed Block Designs

A commonly used technique to avoid continuous scanner noise is to interleave a silent period between the acquisitions of each image volume (20,69). Since there is typically a lag of around 5 seconds between the onset of a stimulus presentation and the peak of the hemodynamic response (termed the “hemodynamic delay”), it is possible to present a stimulus when the scanner is not acquiring images (and hence is silent), and then subsequently obtain images that will reflect the neural correlates of that noise-free stimulus. Typically a silent gap of 1–4 seconds is used, which is long enough to permit a brief word or sound presentation with virtually no background acoustic noise (70–75). The cycle is then repeated until a number of stimuli of the same type have been presented in that block. This type of acquisition has been variously described as “clustered acquisition” (8,76,77), “flat-car design” (78), “sparse” (22), and “behavior interleaved gradients (BIG)” (20). Here we have grouped these approaches under the term “compressed acquisition,” since they all depend on keeping the gradients oscillating (the image acquisition process) close in time. This is achieved by minimizing the dead time (brief silent periods) between each slice of the multislice EPI acquisition. All of these brief silent periods are then shifted to one end of the TR, as the whole process of image acquisition is compressed to the other end. This leads to the additional benefit of less intravolume motion artifacts leaving a silent gap until the next RF pulse in the prescribed TR (Fig. 1).

The duration of this silent gap is a function of the number of slices acquired and the chosen TR. The number of slices is inversely proportional to the silent gap duration, so for a given number of slices the TR has a direct effect on the length of the silent gap. Increasing the total time (TR) to accommodate a silent period facilitates the recovery of the longitudinal magnetization, resulting in better signal-to-noise ratio (SNR) over the whole image. However, for a given number of images, increasing the TR increases the total time of the experiment. Since the typical time necessary to collect an
echo-planar image is about 80–120 ms, it means that the maximum number of slices allowed in 2 seconds would be in the range of 17–25, with virtually no silent gap between each slice acquisition. As a result, with the insertion of the gap, the real TR would vary from 3 to 6 seconds, which may result in a poor SNR per unit time (79). In general, a TR of 3–4 seconds (similar to that used in a typical continuous acquisition) allows the introduction of a silent gap long enough for stimulus presentation without excessive increase in the total duration of the experiment, while continuing to limit large vessel contribution due to inflow effects at very short TR. Furthermore, Eden et al (20) have demonstrated that this silent period can be used for the production of an overt speech response without introducing excessive head motion.

One disadvantage of this approach is that the BOLD response associated with the stimulus is also influenced by the scanner acoustic noise, as the hemodynamic response function (HRF) produced by scanner noise during the previous image acquisition is close to its peak when the subsequent image is collected (77). Thus each image acquisition will itself produce brain activation, sampled by the next acquisition. Figure 1 provides a graphical guide to this type of interaction. The general assumption (similar to studies in which scanner noise is present all the time) is that the BOLD response to scanner acoustic noise will be constant throughout the experiment and similar across conditions, and thus largely eliminated when images are compared between conditions. However, this “baseline” BOLD activation may impede the detection of subtle between-condition differences (23). At this time, the authors were not able to perform a direct comparison of the impact in sensitivity for the BOLD effect in brain regions other than the auditory cortex. However, in that region the percent signal change was increased by 17% to 21% when we compared a conventional image acquisition strategy with one designed to deal with the scanner acoustic noise (see below).

A good example of an experiment that benefited from the use of a compressed block design is the study of overt verbal fluency conducted by Fu et al (80) (Fig. 1). The overt verbal fluency task requires the subject to read a letter and then articulate a word beginning with that letter. When a continuous acquisition is used, it is difficult for subjects to hear their responses, and for investigators to monitor the subjects’ verbal output. By using a GRE-EPI acquisition with a TR of 4 seconds, and compressing the acquisition period of 12 × 7 mm slices into 1.1 seconds, the subjects are allowed a period of 2.9 seconds of silence to process and respond to each letter. Ten blocks of 28 seconds, alternating between two conditions (verbal fluency and word repetition), each comprising seven stimuli, were presented, for a total duration of 4 minutes 40 seconds. The length of the silent gap was sufficient to allow both control subjects and patients with schizophrenia to respond in the absence of scanner noise, and thus permit accurate measurement of task performance on-line, which is
critical in comparisons where differences in brain activation between groups are expected (81). The pattern of activation observed was similar to that evident in previous PET and fMRI studies of verbal fluency (82,83).

In summary, compressed sequences provide a simple and robust means of monitoring task performance in the absence of scanner noise. However, they do not eliminate the potential effects of acoustic noise on the BOLD response.

**Silent Block Designs**

To overcome the problem of sampling the BOLD response from the acoustic noise of previous image acquisitions, one can extend the silent gap to 10 or more seconds between acquisitions (31,35,84–91). This gap provides enough time for the HRF produced by the previous acquisition to return to near baseline, so that scanner noise does not contribute significantly to the subsequent acquisition (92). Furthermore, to avoid sampling the HRF produced by the current acquisition, the total acquisition time should be less than 2 seconds (77). Thus, a combination of an interscan gap on the order of 9 seconds and acquisition time 2 seconds provides a means of minimizing the contribution of the HRF generated by the scanner acoustic noise. A schematic representation of the design is presented below (Fig. 2). However, the relatively long period between acquisitions increases the total experiment time, making it less applicable in subjects who cannot tolerate long scanning sessions. In addition, as it involves presenting the same type of stimulus sequentially, and sampling only once, the temporal characteristics of the BOLD response cannot be investigated. On the other hand, the latter can be examined by using an event-related version of this approach, as described in detail below.

**EVENT-RELATED DESIGNS**

In this type of design, which involves the presentation of discrete events at a certain interval (the interstimulus interval [ISI]), the speed of data collection is fundamental to the quality of the information produced (93). The ability to show temporal changes in the BOLD response to a brief stimulus presentation is directly related to the TR (which should be minimized) and the relationship between the TR and the ISI (94).

Sampling the full HRF curve in an event-related design shows that discrete events can produce different BOLD responses in the same brain area (1,93,95–98). Although these may provide less statistical power than blocked designs, they are more flexible, permitting a greater variety of study designs (in a manner more akin to historical pencil and paper psychometric tests), and are less influenced by motion artifacts (99) because the behavioral response can be temporally resolved from the important functional images. They also provide another dimension to the study: the time component described by the HRF.

Time resolution on the order of 2 seconds or less is mandatory for this approach, since it determines the specificity achievable by the image analysis algorithms. This can be a serious problem, since using a fast acquisition may necessitate less brain coverage, thicker slices, and a poorer in-plane resolution, as well as a reduction in SNR. Despite these potential problems, many studies have successfully shown brain activation in response to an auditory stimulus (100–108).

**Compressed Event-Related Method**

This is similar to a compressed block design (above), except that the stimuli are presented in an event-related, as opposed to a blocked, fashion. As in all event-related designs, the TR should be kept as short as possible, which will inevitably constrain the duration of the silent gap. Therefore, the stimulus presentation time available with this design is usually in the range of 1–2 seconds (109,110). This approach is illustrated by a single subject studied during an overt verbal self-monitoring task (81,111). The images were obtained using a compressed GRE-EPI acquisition (TE = 40 ms, TR = 3.25 seconds, flip angle = 90°, 12 × 7 mm slices in an acquisition period of 1.1 seconds) in a total run time of 14 minutes 38 seconds. This scheme allowed subjects 2.15 seconds to verbalize, listen to their speech, and evaluate its acoustic qualities. The pitch of their speech was experimentally manipulated on-line, and they were required to identify (via a button press) whether the speech they heard was or was not their own. This would have been very difficult, if not impossible, in the presence of background scanner noise (Fig. 3).

**Silent Event-Related (SER) (One Time-Point) Method**

An alternative approach is to limit image acquisition to a single volume following a stimulus, and aim to collect this at a point close to the peak of the HRF (112,113). MacSweeney et al (112) recently employed this method in a study in which hearing subjects speech-read (lip-read) silently spoken numbers. An earlier study (114) had shown that such speech-reading was associated with activation in lateral temporal cortex, but could not exclude the possibility that this was some function of the noise generated by continuous image acquisition. Sampling a single volume at the time of the HRF peak (predicted from previous studies), with a compressed GRE-EPI acquisition (TE = 40 ms, TR = 15 seconds, flip angle = 90°, 14 × 7 mm slices, 14 seconds of silence between acquisitions), allowed the potentially confounding effects of scanner noise to be minimized. The study confirmed that the same temporal lobe areas were activated as in the earlier report (which used continuous acquisition), suggesting that this activity was indeed related to silent speech-reading (Fig. 4).

Another example of an event-related design with just one sampling point in the HRF curve is provided in the study conducted by Shergill et al (115). This study was designed to measure neural activity in a single-image volume and then relate this to whatever the subject had been experiencing in the preceding 5–10 seconds, just before image acquisition. Subjects described their experiences immediately after each acquisition, so the process of reporting post hoc had no effect on the im-
Figure 3. Compressed event-related design. Note the quiet period between image acquisitions. A: Overview of the acquisition, hypothetical ABC design: theoretical BOLD response to the stimulus (continuous line) and the scanner acoustic noise (dotted line), which fluctuates due to the gap between acquisitions (131). B: A detailed view of an event. C: Single-subject fMRI activation from an event-related overt verbal self-monitoring paradigm using compressed acquisition, showing areas involved in monitoring speech (111).

Figure 4. SER design (one time-point): the HRF curve is sampled at the assumed peak of the BOLD response. The next acquisition is too distant to be contaminated by significant effects of acoustic scanner noise. A: Overview of the acquisition, hypothetical ABC design: theoretical BOLD response to the stimulus (continuous line) and the scanner acoustic noise (dotted line). B: A detailed view of an event: stimulus presentation is synchronized with a single-image volume acquisition. C: fMRI activation from an SER design (one time-point) in a lip-reading paradigm showing bilateral temporal and frontal lobe engagement in a group of subjects (112).
aging data. This approach was used to study auditory hallucinations in psychotic patients, with a series of “sampled” events being characterized as hallucinatory or non-hallucinatory in each subject. This approach eliminated the potentially confounding effects of requiring subjects to press a button when hallucinations were occurring, and of scanner acoustic noise on the temporal lobe activation. The main findings and the experimental design are depicted in Figure 5. The study used a compressed GRE-EPI acquisition (TE = 40 ms, TR = 16 seconds, flip angle = 90°, 14 x 7 mm slices, 13 seconds of silence) the acquisition of 100 volumes per subject was accomplished in a rather lengthy 26 minutes 40 seconds.

There are some disadvantages to this type of design. One has to estimate the peak time for the HRF and assume that it will be constant across all subjects and trials (113), anatomical regions (116), medications (90), ages (117), and vascular diseases (118), and that specific pathologies do not create a significant shift to the hemodynamic delay.

**Partially-Silent Event-Related Design**

In a partially-silent design, the stimulus is presented in a silent gap, followed by a period of continuous image acquisition, ideally with data being collected as fast as possible. Thus, the acoustic scanner noise generated by image acquisition has little bearing on images acquired immediately after the stimulus, but progressively influences the BOLD response sampled by subsequent acquisitions (119). Nevertheless, it is possible to define the HRF curve at different time-points after stimulus presentation.

Technically, this design poses a challenge: to keep the longitudinal magnetization in a steady state in all images, it is necessary to have the same TR for each volume acquired. This entails a constant RF interval for each slice. Thus, to maintain the steady state, in reality, the silent gap will not be completely silent, but it will be substantially less noisy (around 15 dB SPL less) at 1 KHz (the main frequency peak for echo-planar acquisitions (16)) than that generated during conventional image acquisition. This is because the slice-selecting gradients required during the RF excitation pulses themselves generate some acoustic noise, and still occur during the “partially-silent gap.” If the spins do not remain in the steady state (so that the silent period is completely void of scanner noise coming from the gradients), images acquired with an effectively longer TR will be brighter than those acquired with less time to recover their longitudinal magnetization. Although postprocessing of the images can correct this, such corrections pose a challenge. This is because there are three components to deal with: 1) deconvolution of signal reduction as the magnetization reaches the steady state, 2) signal change due to neural activity itself, and 3) signal accumulation from the HRF due to increasing contribution from background acoustic noise (77).
The main advantage of the partially-silent design is that the total duration of the experiment typically exceeds that of a continuous, conventional, event-related design by only 10% to 20% (depending on the duration of the silent gap). The additional time required is merely a function of the duration of each silent gap, multiplied by the number of events.

Figure 6 details the design, results, and temporal evolution of the image signal. The hypothetical design employed a fixed 20-second ISI event-related scheme similar to that used by Van De Moortele et al (119). The images can be acquired using a conventional GRE-EPI acquisition (TE = 40 ms, TR = 2 seconds, flip angle = 90°, 14 × 7 mm slices) in which 10 volumes are acquired contiguously. In the next volume, the slices are excited using the same RF envelope and slice-selection gradient, but with the x and y gradients turned off, which provides a “partially silent” period in which the stimuli are presented. In total, such a scheme would sample 20 events (200 volumes sampled), resulting in a total run duration of 8 minutes (400 seconds used to acquire images, and 80 seconds for the partially-silent gaps).

**SER (Full HRF Sampling)**

The SER approach includes experiments in which there is a long silent gap of typically 9 seconds (92) or more (such that the scanner noise produced by image acquisition does not contribute significantly to the final image), while using an event-related design and full HRF sampling. Although Fransson et al (120) have shown that the undershoot effect can last for as long as 90 seconds after the beginning of a 1-second visual stimulus, the critical region of the positive component of the HRF curve tends to have returned to (and crossed) the baseline by ~9 seconds. The duration of the HRF curve will also be influenced by the duration and other characteristics of the stimuli (121,122). Lohmann et al (123) showed that a constant repetition of a stimulus could produce a signal reduction attributed to habituation, as seen by fMRI. Such effects could be reduced using event-related designs.

This approach avoids the contribution of scanner noise to both stimulus presentation and BOLD sampling, but still permits sampling at different time-points on the HRF curve such that a series of data points are collected at “jittered” intervals post-stimulus (93). The method we have developed permits the sampling of eight points in an HRF curve, by sampling two points in the HRF curve per trial. Each condition is studied at four different sampling intervals (21). The design assumes that the BOLD response and subject performance for a specific condition are approximately the same during the four trials that yield the eight points for the HRF curve. Aguirre et al (124) have shown that the HRF curve can be very steady in the same brain area in the same subject across different sessions. Still, the response to successive trials may vary, depending on

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**Figure 6.** Partially-silent event-related design: the stimulus is presented in silence, but scanner noise effects accrue in later acquisitions. **A:** Overview of the acquisition, hypothetical ABC design. **B:** A detailed view from an event: stimulus presentation is followed by several contiguous image acquisitions. **C:** Theoretical BOLD response to the stimulus (continuous line) and the scanner acoustic noise (dotted line). The BOLD response to the stimulus is potentially mixed with the BOLD response from the previous image acquisitions in brain regions involved with auditory stimulus processing (119).
the task; for example, there may be habituation or learning effects with repeated trials. Therefore, counterbalancing is important within and across subjects. An example of a study that employed the SER approach is depicted in Figures 7 and 8. The study involved passive listening to disyllabic, single words (125). The design comprised a variable ISI (mean value 18 seconds, range 11.5–24.5) event-related presentation of 40 words binaurally. We studied 30 normal, right-handed subjects (15 males and 15 females, mean age 25.3 ± 3.9 years) using a compressed GRE-EPI acquisition (TE = 40 ms, TR = 9 seconds, flip angle = 90°, 5 × 7 mm slices, 7.5 seconds of silence) to acquire 80 volumes, resulting in a total run duration of 12 minutes. The jittering scheme provided time-points sampled at 1, 3.25, 5.5, 7.75, 10, 12.25, 14.5, and 16.75 seconds from the start of event presentation. For comparison, each subject also performed the same task during conventional continuous acquisition GRE-EPI (TE = 40 ms, TR = 2.25 seconds, flip angle = 90°, 5 × 7 mm slices) scheme, using the same slice prescriptions (in a counterbalanced order across subjects). A fixed ISI (18 seconds) was adopted, and a total of 10 words were presented, in 3 minutes.

Almost twice as many activated voxels were detected using this SER technique (on average 320 voxels, or 21.9 mL in SER were deemed active across the sampled brain volume) compared to the conventional acquisition, in which the scanner noise was present during the whole experiment (mean = 164 voxels, or 11.3 mL). The total signal change due to the BOLD effect in the SER acquisition was 21% higher in the left temporal lobe and 10% higher in the right temporal lobe than with the conventional continuous acquisition strategy (126). These results could reflect a lower BOLD baseline with the SER approach (because of less temporal lobe activation due to background scanner noise), and/or the fact that a longer TR allows more time for the longitudinal magnetization to recover (69). Another aspect to be considered when analyzing SER acquisitions is the possible increased partial volume effect from the cerebral spinal fluid (CSF) at a longer TR, which could potentially reduce the BOLD contrast. Although a cause/effect relationship between these two cannot be established, the SNR and the number of voxels activated showed a linear correlation coefficient of only 0.1, suggesting that the lower BOLD baseline in the SER could be one explanation. Even so, other cognitive factors may be involved, such as the variable ISI implications in attention modulation (127).

Despite the advantages outlined above, the total time required to acquire data using the SER approach was
four times longer than with the conventional acquisition: 12 minutes (to sample 10 full HRF curves, with 40 trials), as opposed to 3 minutes. In other words, the power to detect response per unit of time is much higher with conventional continuous acquisition techniques.

**IMAGE ANALYSIS**

Apart from differences in the temporal characteristics of the data, the methods that are used to analyze the images produced from these studies are similar to those employed in conventional fMRI experiments (using either block or event-related designs) (128–130). Thus, in general, there is no need to modify existing movement correction, registration, and normalization methods. The only further considerations are: corrections for variable longitudinal magnetization when using partially-silent designs with different TRs; careful modeling of the "jittered," non-fixed TR designs; and reordering of the images when using SER designs. The statistics used for inference analysis in conventional designs are valid for all the techniques described herein.

The potentially confounding effects of acoustic scanner noise in fMRI studies can be significantly reduced by using modified image acquisition sequences. These can be readily employed on commercial MR scanners, and are particularly useful for studies of auditory-verbal processing. In the future, new developments in MR engineering will deliver silent hardware that will enable the use of event-related, block, or “behavioral” designs with continuous image acquisition. This will allow high-powered statistical assessments of clean stimuli, free from competing acoustic distractions.

**SUMMARY**

As we can see from the above, numerous strategies to diminish the effects of scanner acoustic noise have been designed. In many cases a conventional acquisition sequence may be perfectly adequate—for example in studies that do not involve auditory-verbal processing or investigation of brain activity in the lateral temporal cortices. For studies in which these latter factors are potentially important, there is no single “best” design that is optimal for every study. For example, when studying a task in which the neural response may change with successive trials, methods like SER (which characterizes the HRF curve by averaging the BOLD response at different points across multiple trials) are not ideal. On the other hand, if this is not an issue and the aim is to optimally characterize a relatively stable BOLD response to, for example, simple auditory stimuli (109), then the SER design may be appropriate. Furthermore, such compressed-design strategies provide the opportunity to record physiological response in the absence of potential electrical interference (from rapidly switching magnetic field gradients). The approach has recently been employed in the concurrent measurement of electroencephalography and performance of fMRI (see for example Ref. 72).
Table 1. Positive and Negative Characteristics of the Different Study Designs

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<tr>
<th>Design</th>
<th>Positive</th>
<th>Negative</th>
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<td>Continuous acquisition</td>
<td>Time efficient</td>
<td>Scanner noise may mask the stimulus presentation</td>
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<td></td>
<td>Good statistical power</td>
<td>BOLD effect from scanner noise present on images</td>
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<td>Compressed block</td>
<td>Time efficient</td>
<td>BOLD effect from scanner noise present on images</td>
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<td></td>
<td>Good statistical power</td>
<td>Potentially more sensitive to habituation effects</td>
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<td>Stimulus presented during a silent period</td>
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<td>Silent block</td>
<td>Minimum scanner noise contribution to BOLD contrast</td>
<td>Long total acquisition time</td>
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<td></td>
<td>Stimulus is presented in silence</td>
<td>Potentially more sensitive to habituation effects</td>
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<td></td>
<td>Better SNR than continuous acquisitions</td>
<td>No temporal information</td>
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<td>Compressed event-related</td>
<td>Time efficient</td>
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<td></td>
<td>Stimulus presented in a silent background</td>
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<td>Full HRF sampling</td>
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<td>Partially silent (block and event-related)</td>
<td>Time efficient</td>
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<td>Good statistical power</td>
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<td>Stimulus is presented in an almost silent background</td>
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<td>Partial spin saturation effects may interfere*</td>
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<td>Could be used in an event-related design</td>
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<td>Scanner noise BOLD effect present on images</td>
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<td>Low temporal resolution</td>
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<td>Silent event-related (one point)</td>
<td>Minimum scanner noise contribution to BOLD contrast</td>
<td>Long total acquisition time</td>
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<td></td>
<td>Better SNR than continuous acquisitions</td>
<td>Have to estimate the best time to acquire the image post stimulus</td>
</tr>
<tr>
<td></td>
<td>Subject driven isib**</td>
<td>No temporal information</td>
</tr>
<tr>
<td>Silent event-related (full HRF sampling)</td>
<td>Minimum scanner noise BOLD effect</td>
<td>Long total acquisition time</td>
</tr>
<tr>
<td></td>
<td>Stimulus is presented in silence</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Better SNR</td>
<td>Averaging risks combining correlates of correct and erroneous trials</td>
</tr>
<tr>
<td></td>
<td>Full sampling of HRF</td>
<td></td>
</tr>
</tbody>
</table>

*aDepends on the presence of rf pulses in the “silent” period.

*bAllows on-line ‘behavioural’ assessment.

In studies of clinical subjects, who may not tolerate lengthy scanning sessions, approaches with a relatively short total duration (such as a blocked design with compressed acquisition) are imperative. However, if the patients are likely to perform the task worse than controls, separating out the effects of impaired performance on activation is more difficult with block designs than with event-related strategies. Furthermore, presenting stimuli in blocks also increases the risk of habituation to repeated trials of the same stimulus (31).

Table 1 summarizes the main advantages (positive points) and disadvantages (negative points) of the different designs outlined in this article, as compared to conventional, continuous acquisition methods.

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REFERENCES


