Review

Effects of Static Magnetic Fields on Cognition, Vital Signs, and Sensory Perception: A Meta-analysis

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To evaluate whether cognitive processes, sensory perception, and vital signs might be influenced by static magnetic fields in magnetic resonance imaging (MRI), which could pose a risk for health personnel and patients, we conducted a meta-analysis of studies that examined effects of static magnetic fields. Studies covering the time from 1992 to 2007 were selected. Cohen's d effects sizes were used and combined in different categories of neuropsychology (*reaction time, visual processing, eye-hand coordination*, and *working memory*). Additionally, effects of static magnetic fields on sensory perception and vital signs were analyzed. In the category "neuropsychology," only effects on the visual system were homogeneous, showing a statistically significant impairment as a result of exposure to static magnetic fields ($d = -0.415$). Vital signs were not affected and effects on sensory perceptions included an increase of dizziness and vertigo, primarily caused by movement during static magnetic field gradient exposures. The number of studies dealing with this topic is very small and the experimental set-up of some of the analyzed studies makes it difficult to accurately determine the effects of static magnetic fields by themselves, excluding nonspecific factors. The implications of these results for MRI lead to suggestions for improvement in research designs.

Key Words: magnetic resonance imaging; high static magnetic fields; MRI safety; neurocognitive function; meta-analysis
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MAGNETIC RESONANCE IMAGING (MRI) is a powerful diagnostic technique for mapping the structure and function of tissues and organs. It avoids the adverse effects of ionizing radiation in regular computer tomography and there are no well-documented nontransient adverse health effects such as those known for other medical technologies—for example, radiation or drug side effects (1). Nevertheless, there is still a debate concerning the possibility that it may have an influence on cognitive functions. In this context some recent studies have indeed shown a small but significant influence of static magnetic fields on neurocognition. In the few studies dealing with this topic a modulation of eye-hand coordination and working memory processes was reported and both showed very variable effects. While some studies reported impairment (2), others found improvement of function (3). Furthermore, static magnetic fields have been shown to impair the visual system (eg, 4) as well as long-term memory (5) and reaction time (4,5). However, to date the results are still inconclusive.

Several studies also investigated sensory effects in or near an MRI system. Some subjects reported metallic taste, nausea, and vertigo (eg, 6) as well as head ringing and nystagmus (3,7). Interestingly, most of the sensory effects appeared while subjects were moving in the static magnetic field, for example, when the stretcher was moved or when health personnel walked through the scanner room. This suggests that most of the side effects might not be caused by the static field itself but rather by gradients created by movement in the static field. Further, it is important to be mentioned that, except in a few locations, magnetic fields in and around an MR scanner are gradients, since the strength of the magnetic field declines with distance to the isocenter where the magnetic field is isotropic and homogeneous. However, most studies analyzed the effects while participants were not placed in the isocenter and were thus not directly exposed to the gradient of the static magnetic field. How patients and health personnel move in this field is therefore an important issue. It could be shown that fast movers experience more sensory side effects such as vertigo or metallic taste than slow movers (3). Finally, very few studies examined vital functions such as blood pressure, heart rate, respiratory rate, and blood oxygenation level during static magnetic field exposure and most of them did not report statistically significant results, except for a very slight rise of systolic blood

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Table 1
Tests and Categories

Study	Reaction time	Visual system	Eye-hand coordination	Working memory
1) Chakeres et al (5)	Reaction Time [1]			Digit span [2]
2) de Vocht et al (9)		Vistech [3]	Santa-Ana [4] Pursuit Aiming [5] Digit/symbol [6]	Digit span [2]
3) de Vocht et al (2)		Vistech [3] Tracking [7] Scanning [8]	Pursuit Aiming [5]	Visual [9] Auditive [10]
4) de Vocht et al (3)	Reaction Time [14]		Sinusoid/saw [14] Digit/symbol [6]	Digit span [2]
5) de Vocht et al (4)		Vistech [3] Tracking [7]	Pursuit Aiming [5] Line bisection [13]	Digits/Letters [11] N-back [12]

Notes: 1: push a button as soon as you hear the third tone in a series of three; 2: repeat series of digits (in reverse order); 3: recognize direction of lines for shrinking contrasts with one blinded eye; 4: rotate pegs in a peg-board (twice left, twice right hand); 5: Pursuit Aiming: quickly place dots in circles within 60 sec; 6: pair symbols with digits; 7: track entangled lines on paper with the eyes; 8: scan lists of numbers and mark all numbers "6"; 9: reproduce series of visual stimuli in reverse order; 10: reproduce series of auditive stimuli in reverse order; 11: repeat randomized numbers in increasing order and letters in alphabetical order; 12: click when in a list of numbers the last (next to last) one appears again; 13: mark the middle of 32 lines as fast as possible; 14: not specified.

pressure (7). All studies showed only transient effects in neuropsychology, sensory perceptions, and vital sign measurements. When they were further assessed no long-term effects could be shown. A comprehensive review by the World Health Organization (8) concluded that to date no adverse effects of static magnetic fields on neurophysiological responses or cognitive functions have been reported for static magnetic fields up to 8 T, but that transient effects like vertigo and nausea were shown in volunteers who moved in static magnetic fields of 2–3 T or higher. However, it was acknowledged in the report that the studies reporting these results were based on small sample sizes and insufficient power and show methodological flaws.

It is therefore unclear how the strength of a magnetic field and the cognitive or sensory effects and the changes in vital sign measurements it causes are related to each other. For the sake of convenience this relation is usually assumed to be linear (eg, 2) without any investigation whether this is actually the case. Given that ultrahigh magnetic field resonance imaging systems are becoming more widely available because of shorter testing times and improved resolution, it is important to specifically analyze the effects of ultrahigh field scanners. Therefore, we present a systematic quantitative analysis on the effects of static magnetic fields on cognition, vital signs and sensory perceptions.

MATERIALS AND METHODS

Literature Search Strategy and Inclusion Criteria

We conducted a comprehensive search of the recent literature between January 2000 and August 2010 using electronic databases. Search words included static magnetic field, cognition, sensory, vital, effects, and exposure. We also screened the bibliographies of relevant articles of the above-mentioned time frame resulting in one additional study published in 1992. After discounting studies with nonrelevant subject matter (eg, animal studies or studies of human tissue), and duplicates, seven studies remained for this systematic analysis.

Tests and Categories

We analyzed the effects of static magnetic fields on 1) neuropsychological functions, 2) vital signs, and 3) sensory perception. Within the first category "neuropsychology" four subcategories were generated: "reaction time," "visual system," eye-hand coordination," and "working memory" (Table 1).

In the aggregated studies reaction time was examined by instructing subjects to push a button as soon as they hear a tone (5). In another case (3) the reaction time task was not specified.

The visual system was tested by the Vistech 6000 where subjects had to recognize the direction of lines for shrinking contrasts with one blinded eye, complete a tracking task where they were instructed to follow a line with the eyes, and a scanning task in which they were asked to scan a list of numbers and mark all numbers "6" (2).

Eye-hand coordination was analyzed by the Santa-Ana Test where subjects had to rotate pegs in a pegboard (9), by the Pursuit-Aiming Test where dots have to be quickly placed in circles, by a symbol-digit-substitution (3,9), or by a "sinusoid and saw shaped" eye-hand coordination task (3).

Working memory was analyzed by using a visual or auditory digit span task which required subjects to repeat series of digits or letters in correct or reverse order (4) or by an N-back task where subjects had to react when in a list of random numbers the same one appeared consecutively at increasing delays (4).

Statistical Analysis

For the first category "neuropsychology" Cohen's d effect sizes (10) were calculated for all test results reported in each of the studies using $d = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{(s_1^2 + s_2^2)/2}}$. In cases where only the standard error was given this was changed using $s = SEM^* \sqrt{n}$.

A small effect size is defined as $d \leq 0.2$, a medium effect as $d \approx 0.5$, and a large effect as $d \geq 0.8$. As sometimes increasing values of test performance mean improvement (eg, "digit span," Table 1) and in other cases deterioration (eg, "reaction time") we decided to follow a consistent procedure: negative effect sizes reflect a deterioration of cognitive performance, while positive effect sizes reflect improvement. We then combined the effect sizes of the individual tests to the subcategories "reaction time," "visual system," eye-hand coordination," and "working memory" as well as to the main category "neuropsychology," which contains all individual values out of the four categories and gives an overview about the effect on neuropsychological functions in general.

For the second category "vital signs," the data of three studies were aggregated. Only in one case are effect estimates given. The results of the other two studies are reported descriptively.

Data from four studies were integrated into the category "sensory perception." Twice we report the results in a descriptive manner and twice the effect size was estimated by $ES = \frac{2r}{\sqrt{1-r^2}}$ from the correlation of the reported sensory effects in the static magnetic field and the control condition. Variance of values is given by $s = \sqrt{\frac{n_1+n_2}{n_1 * n_2} + \frac{d^2}{2(n_1+n_2-2)}}$ for an independent sample (3) or by $s = \sqrt{\frac{2(1-r)}{n} + \frac{d^2}{2(n-s)}}$ for a dependent sample (6).

In order to evaluate the degree of homogeneity of the studies concerning our category "neuropsychology," which we examined for this systematic analysis, we conducted a Q-Test (11): $Q = \sum_{i=1}^{k} \frac{\left(ES_i - \overline{ES}\right)^2}{se^2_{ES_i}}$. This estimates whether the variability in study effect sizes is great enough to reject the hypothesis that they estimate a common population effect size. The Q statistic is distributed as a chi-square statistic with k-1 degrees of freedom (k indicating the number of study effect sizes).

We also coded the internal validity according to criteria based on previous work (12) on a scale of 0–3 to classify whether the results found in the studies examined for this analysis could also have alternative explanations (0 = no statistical analysis, highly nonequivalent groups, obvious bias; 1 = weak, nonexistent matching, inadequate statistics; 2 = random assignment but differential mortality or failed randomization, well-designed matching study; 3 = random assignment, mortality <15% and same between groups).

RESULTS

Demographic Data and Design of Included Studies

A total of 127 participants were included in the category "neuropsychology." Participants did not differ much in terms of age (20–59; mean: 34.8; SD = 9.5) but more males than females were included (81 vs. 26). Most studies used a case crossover design; only one (3) analyzed differences between two different groups: effects of exposure to a static magnetic field on system testers working with MRI were compared to a control group that worked in another department.

The second category "vital signs" contains 61 participants and there are again no differences concerning age (20–58; mean: 37.4; SD = 6.3) but more males were included (43 vs. 18). Twice a case crossover design was applied and once a medical examination before and after 1 year of work experience near a 4 T scanner.

The third category "sensory effects" consists of 77 participants with no differences in age (20–58; mean: 36.9; SD = 5.2) but gender (59 males, 18 females). Twice a case crossover design was used, once a comparison between two groups (see category 1), and once participants were given a questionnaire for which they had to rate their sensory experiences while being exposed to a 1.5 T magnet compared to a 4 T magnet.

Magnetic Field Strength

All studies used different field strengths ranging from 0.7 T (stray field of a 1.5 T magnet (9)) to 8 T (5). Where several field strengths were tested in a single study, we always used the widest interval available between control condition and test condition to examine the safety of strong static magnetic fields, because we assumed that any possible effects would be stronger at higher field strengths and the aim was to show the strongest possible effect. Field strengths of control condition varied from 0 T, ie, magnet is off (eg, 9) to 0.05 T, ie, subjects were sitting outside the magnet (5). Test conditions that were included in our analysis ranged between 1 T (stray field of a 3 T magnet (2)) and 8 T (eg, 7). So the differences between control condition and test condition ranged from 1 T (2) to 7.5 T (5).

Effects of Static Magnetic Field

Category Neuropsychology

Effect sizes of the category neuropsychology vary between −0.52 and 0.12 with an overall effect size of −0.14 (SD: 0.27). This signifies a very small impairment of cognitive functions due to a static magnetic field (Table 2).

For reaction time, effect sizes of 0.07 and −0.22 were found. In sum, the outcome of this is a nonsignificant reduction of performance (−0.08, SD: 0.20). The visual system is the only subcategory that was consistently negatively influenced with effect sizes between −0.25 and −0.72 (mean: −0.42, SD: 0.27). Of the four studies that investigated eye-hand coordination, two found a slight amelioration with 0.03 and 0.23 while the others reported deterioration with −0.19 and −0.88 (overall mean: −0.20, SD: 0.48).

For working memory a large deterioration effect of −0.85 was found in one study (2) while another study (3) reported a large improvement effect (0.77). The remaining three studies only observed small effects

Table 2
Effect Sizes of the Subcategories and the Category "Neuropsychology"

Study	Reaction time	Visual system	Eye-hand coordination	Working memory	'Neuropsychology'
1	0.07 (0.12)			0.13 (0.09)	0.10 (0.04)
2		-0.25 (0.17)	0.03 (0.14)	-0.02 (0.11*)	-0.08 (0.15)
3		-0.28 (0.31)	0.23 (0.33)	-0.85 (0.45)	-0.3 (0.54)
4	-0.22 (0.64*)		-0.19 (0.23)	0.77 (0.66*)	0.12 (0.56)
5		-0.72 (0.78)	-0.88 (9.58)	0.04 (0.01)	-0.52 (0.49)

Study numbers and titles are the same as in Table 1. Standard deviations in parentheses.
*Consist of only one value and 95% confidence interval is given.

and an overall effect size of 0.01 (SD: 0.58) for working memory remained.

A further investigation of whether sizes of the cognitive effects were significantly correlated with the strength of the static magnetic field used in each study showed only a very small nonsignificant correlation of 0.13.

Homogeneity

To evaluate the degree of homogeneity of effects on neurocognition among the studies that were entered in this systematic analysis Q statistics were calculated. Q reached a value of 251.95 for a set of five effect sizes. Since the critical value for χ^2 (4) at the 0.5 level is 3.36 the hypothesis that the reported effect sizes estimate a common population effect can be rejected. The study results in our analysis can therefore be classified as heterogeneous.

Categories Vital Signs and Sensory Perception

The category "vital signs" (vital sign measurements like blood pressure and heart rate) showed no significant effects (Table 3). Only one study (7) found a very slight overall effect. The arithmetic mean of all effect estimates in this study was 0.16, which results from an almost medium effect of 0.45 in increase of systolic blood pressure.

By contrast, effects on sensory perception were more homogeneous. Dizziness, vertigo, metallic taste, and nystagmus were reported (3,5–7). Whenever effect sizes could be calculated we found a medium effect of 0.49 (3) and a large effect of 0.78 (6). Where no numbers were given, we relate the effects as they were verbally reported in the respective study.

Validity

The mean validity rating for all studies was M = 1.21, SD = 0.43 (on a scale from 0 = no validity to 3 = high validity). Validity was coded by two raters. For the numerical value of effect size 83% agreement between raters was obtained.

DISCUSSION

The current article is a systematic analysis of the existing literature on the effects of static magnetic fields on cognition, vital signs, and sensory perception. In sum, the results on cognitive effects of static magnetic fields were heterogeneous. Only two studies examined effects of static magnetic field on reaction time and three examined effects on vision (Table 1). In both cases, general negative effects were found, whereas the negative effects on vision were more pronounced. Here, all studies examining the visual system showed a statistically significant impairment of near visual contrast sensitivity, which suggests that this is the only category of the cognitive abilities tested in the studies we reviewed that is genuinely influenced by a static magnetic field. In terms of safety for health personnel and patients this is an important finding, as impaired function of the visual system could pose a risk during surgical interventions, for instance.

Results of eye-hand coordination were less conclusive and we found a negative tendency that is mainly based on one large effect (4). Five studies examined the effects of static magnetic fields on working memory and the results were inconsistent, showing improvement as well as deterioration, resulting in a nonsignificant effect. Thus, no conclusion can be drawn on whether static magnetic fields affect eye-hand coordination and working memory adversely or favorably.

We observed no significant correlation between the size of the cognitive effects and the strength of the static magnetic field that was used in the respective study. It can be concluded that the few studies that

Table 3
Effects of Static Magnetic Fields on Vital Signs and Sensory Perceptions

Study	Category 'vital signs'	Category 'sensory perception'
1	No effects due to static magnetic field exposure	'few participants' → mild dizziness or vertigo (not significantly relating to field strength)
4		ES = 0.49 (variance: 0.33)
6	ES 0.16 (SD = 0.18)	36% dizziness; 8% metallic taste; 4% nystagmus
7	No effects after one year exposure to 4T	ES = 0.78 (variance: 0.42)

Study numbers and titles are the same as in Table 1;
Additionally 6 = Chakeres et al (7), 7 = Schenck et al (6).

Table 4
Suggestions for Further Studies to Analyze the Effects of Static Magnetic Fields

Topic	Requirements and objectives
Participants	- Proportion men / women balanced and adequate sample size
	- Ignorance of type and status of the magnet (strict blinding)
	- No previous experience with MRI
	- Collection of personality characteristics (questionnaires)
Conditions	- Control condition of 0 T
	- Mock scanner (to create the same environment as in a real scanner)
	- Variety of scanners (different field strengths) to clarify the relation between field strength and effect
	- Movement in the static magnetic field (to test effects of movement- induced gradients)
	- Add gradients and RF pulses separately and together (to test the components of fMRI)
	- Randomization of different field strengths and mock scanner
Tests	- Analysis of more cognitive functions
	- Parallel versions of tests to avoid learning effect
	- Randomization of sequence of tests
	- Constant monitoring of vital signs
	- Stringent data collection on sensory effects
	- Broad test battery with nystagmography and evoked potentials
Objectives	- Safety for health personnel
	- Influence on the work of health personnel
	- Safety for patients
	- Setting of maximum value for daily exposure and speed of movement in static magnetic fields

exist on this subject cannot show a conclusive relationship between strength of magnetic field and level of effect.

The effects of static magnetic fields on vital signs are even less well understood. Only three of the studies we reviewed actually collected data on vital signs and only one of these reported a slight increase of systolic blood pressure in a static magnetic field. Overall, the amount of data available on this subject is far too small to draw meaningful conclusions.

Effects on sensory perception are slightly more conclusive and all four studies dealing with this topic reported effects. The most common complaint was dizziness or vertigo, which appeared consistently. However, this complaint might have been due more to the currents created by movement in the static magnetic field than to the static field itself.

The data examined for this analysis were extracted from only seven studies that could be found on this topic. In addition, we noticed various shortcomings in the design and execution of some studies. In one instance, subjects were not studied while actually in a static magnetic field, but before and after exposure (3). As the effects of static magnetic fields might be acute and transient, and only be impairing while a person is actually in the static field, this method may not reflect the resulting effects. In three studies, subjects were either placed on a chair near a magnet (eg, 4) or were walking in a room with an active MRI scanner (3), which is unlikely to reflect the effects a strong static magnetic field might have on a person lying in the scanner. Also, the level of neuropsychological testing was in general not satisfactory and the tests were prone to strong learning effects because no parallel versions were used (2,9). Not all of the studies assessed the subjects' sensory perceptions while in a static magnetic field and even fewer collected vital sign measurements.

Altogether, the heterogeneity of the studies might also explain the inconsistent results. The low degree of internal validity in the studies examined for this analysis is a further factor that may have contributed to the inconsistency of the findings.

These findings reveal a research gap that should be closed. The effects of strong static magnetic fields on cognition and well-being should be more thoroughly examined, to determine that cognitive ability of patients and health personnel is impaired. Also, follow-up studies might be useful to see whether any impairing effects are transient or persistent and therefore pose a health risk. In Table 4 we have summarized some suggestions on how study designs could be resistant to the discussed problems.

First of all, sample sizes were usually too small, a limitation also mentioned by the WHO (8), and they included more males. So a balanced gender ratio should be implemented and participants' personalities should also be examined by questionnaires to clarify if certain characteristics lead to different effects. The use of comprehensive batteries of neuropsychological tests covering a broad area of cognitive abilities as well as questionnaires on sensory perception and the constant monitoring of vital signs throughout the entire testing procedure seems advisable to yield more solid results. Other tests like nystagmography or evoked potentials, for example, should be implemented as well to verify all possible effects and their origin. These tests should be implemented using a whole-body scanner, so subjects can actually be exposed to strong static magnetic fields while performing the tests. To control the environment effect, a mock scanner with no magnetic field should be used. This is essential to make sure that any change found in performance of cognitive tests, vital sign measurements, or sensory perception is actually due to the magnetic field and not due to other factors like a supine position or cramped environment. Since it is difficult to make a mock scanner match a real scanner in every detail, participants should additionally be blinded when they enter the scanner room to limit their view of their surroundings; the noise of a helium pump might be generated by speakers. For example, an old scanner that is no longer in use can serve as a control condition. Signs indicating the actual field strength have to be removed. It should be checked if the blinding procedure works by letting participants guess the actual field strength out of several possibilities. Working with participants that have no previous MR experience would possibly facilitate this blinding. Although the creation of a real mock scanner is complex, it is the only way to clarify which effects appear because of the magnetic field itself and which ones are due to nonspecific factors of being in an MR environment.

Ideally, a variety of scanners with different field strengths should be employed to clarify the relation between field strength and exposure effects, because this relation might not be linear. The objective of new studies should be to collect data that will permit setting a safety limit for the maximum value of the static magnetic field for MRI scanners. To examine the risks for health personnel working with MRI, the neuropsychological test battery and vital sign measurements should also be applied while subjects are moved in the static magnetic field. Movement in static magnetic fields causes electric currents in living tissues, which could also be the reason for the observed effects. This requires devising a procedure that allows presenting neuropsychological tests while the examination table is moved at high field strengths. Movement could be generated by a motor system, which could be connected with the stretcher. The objective here should be to employ a maximum value for the velocity of an MR worker or a patient in a given gradient static magnetic field. A possible solution to this would be to affix an MR-compatible monitor on the examination table of the scanner and present the tasks to volunteers via a mirror reflecting this monitor. MR-compatible virtual glasses would be another possibility to present tests in the scanner. The entire experimental set-up for a detailed study for the analysis of static magnetic fields needs extensive planning but should yield better generalizable results. As the safety of an MR scanner is important for many patients when being medically examined and manufacturers have little interest in this issue, federal offices should address this topic and support relevant studies. This issue is also very important for safety guidelines like the IEC safety standard or the Physical Agents (electromagnetic fields) Directive of the European Union, which should have assured data as a basis.

In further studies, the components of functional MRI (fMRI) studies should also be examined. Gradients and radiofrequency (RF) pulses should be added first separately and then together to ascertain the exact origin of any occurring effect during an fMRI examination.

In conclusion, existing data are not sufficient to arrive at firm statements about the effects of static magnetic fields and we provide recommendations how further studies can better evaluate potential adverse effects on patients and health personnel.

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