# Lost in localization: The need for a universal coordinate database

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## Abstract

One of the great advantages of neuroimaging research is the use of an established and uniform coordinate system. This 3-D coordinate system allows for the comparison of activation locations across studies. In order to capitalize upon this advantage, however, researchers must be able to find relevant studies based upon activation locations. A number of research groups have embarked upon solutions to this problem, but to date there exists no exhaustive, universal coordinate database. In this commentary we outline the nature of the problem, its current solutions, and propose alternate solutions. We close with suggestions on how those in the field can facilitate the process of developing a universal coordinate database.

Please cite as: Derrfuss, J. & Mar, R.A. (2009). Lost in localization: The need for a universal coordinate database. NeuroImage, doi:10.1016/j.neuroimage.2009.01.053.

One of the primary goals of cognitive neuroscience is to establish structure-function relationships in the human brain. That is, cognitive neuroscience aims at understanding what the different areas of the human brain do and how these areas cooperate to produce cognition and action. Functional neuroimaging plays a key role in this endeavour and, accordingly, the rate of empirical publications based on neuroimaging methods has been rapidly increasing for the past two decades (Fig. 1). Most of this increase can be attributed to the development of functional magnetic resonance imaging (fMRI) as a brain mapping technique. By the end of the year 2008 approximately 9,400 fMRI studies investigating human cognition and action will have been published in English language journals (Appendix). An estimated 74% of these studies (Appendix) report the locations of statistically significant peak activations in a 3-D reference space (Evans et al., 1993; Mazziotta et al., 2001; Talairach & Tournoux, 1988; see Lancaster et al., 2007 for a comparison of the variants of this reference space).

Despite the importance of a standard 3-D coordinate system for functional imaging, to date there is no comprehensive coordinate database. That is, there is no way to find *all* of the published studies that report coordinates in a certain location. The utility of such a database has long been in the minds of researchers (Fox & Lancaster, 1994), and some important and commendable attempts to address the issue have been undertaken (Fox & Lancaster, 2002; Hamilton, 2005; Nielsen, 2003; Van Essen et al., 2008). However, we believe that the current databases are insufficient in the number of articles they include and we are concerned that in their current form they will not be able to keep up with the increasing rate of publication. In this commentary we discuss the need for a universal coordinate database, examine the current solutions available to researchers, and conclude by proposing a number of additional possible solutions to this problem.

## How many relevant studies exist for a given location?

In order to establish structure-function relationships, researchers need to identify studies that report activations in similar locations. We can get a sense of the enormity of this seemingly mundane task by estimating the amount of information uncovered by an exhaustive search of this type. To estimate the number of studies that report a given location, we turned to the BrainMap coordinate database. This database contains coordinates that have been uploaded by researchers and students, for numerous studies (discussed below). As of October 2008, the BrainMap database contained 1601 papers and 58600 coordinates. Dividing the number of activations in the database by the total number of studies gives us the average number of activations reported by a study in BrainMap, which is 37. Extrapolating this to all published articles suitable for inclusion in a coordinate database reveals that around 258000 activations will have been reported by the end of the year 2008 (Appendix). Given that the average gray matter volume of the human brain is estimated to be 780 $\text{cm}^3$ (Lüders et al., 2002), this means that on average approximately 330 peak coordinates have been reported by different studies for every cubic centimetre of gray matter in the human brain. (This is assuming that activations are evenly distributed throughout the brain; in reality this number is likely to be more or less depending on location [cf. foci density map in Van Essen et al., 2008].) Or, put differently, if you were to draw a sphere with a radius of 6.2 mm around a single activation from your study, on average, there would be ~330 activations from other studies located within this sphere. It is difficult to estimate how many different papers contribute these ~330 foci, as many studies report several different contrasts that often result in similar activations. Even from a conservative standpoint, however, this is likely to represent a large number of relevant papers.

## How can we go about finding these studies?

Hundreds of relevant papers for a single activation is an impressive amount of information. Locating these articles in any sort of an exhaustive manner is currently very difficult, and quite possibly untenable, given current means. For the large majority of studies, we have access only to the information indexed by databases like PubMed or ISI Web of Knowledge, which do not include brain location coordinates. If we want to find studies that report activations similar to those in our own studies, there are currently three major ways to search these databases: by structure, by Brodmann area (BA), or by topic. Each of these methods suffers from a number of shortcomings. Structure-based and BA-based searches are unsatisfactory because nearby activations might receive different anatomical labels or different BA designations, and activations quite distant from one another might be given identical anatomical labels or BA designations. For example, activations close to the junction of the inferior frontal sulcus and the inferior precentral sulcus (Brass et al., 2005; Derrfuss et al., 2004, 2005, 2009) might be referred to as lying in the inferior precentral sulcus, the inferior frontal sulcus, the precentral gyrus, the middle frontal gyrus, the inferior frontal gyrus, pars opercularis, Broca's area, the premotor cortex, or the inferior frontal junction. On the other hand, activations in the most ventral and the most dorsal part of the posterior frontal cortex might both receive the label "precentral gyrus" or "BA 6," although these activations might lie as far as 60 mm apart. The third way to search for relevant studies is to search for articles on the same topic as your own study, or from within the same paradigm class. While this approach might well assist you in locating relevant studies with similar activations, in many ways this constitutes a search for confirmatory information. From this method we may learn of similar studies that found similar activations, but will remain ignorant of dissimilar studies that found similar activations and thus limit our understanding of an area's function.

Searching current article databases like PubMed by structure, BA, or topic, are clearly inadequate methods for finding articles reporting activations close to a particular location. As a result, our functional descriptions of areas are likely to remain biased or incomplete. This problem will not only affect researchers who wish to put their results into context, but also researchers undertaking a meta-analysis or review. The neuroimaging community has become increasingly sensitive to the shortcomings of current search methods, which more often than not result in a very domain-centred approach. The end result is that groups of researchers from different topics all lay claim to a certain brain region—believing it specific to their own process of interest—and ascribe it different functions. By ignoring studies using a different paradigm or investigating a separate topic, one will capture only a very narrow picture of what is associated with a particular location in the brain. This is akin to the parable of the blind men and the elephant, with researchers each describing the function of a region in very idiosyncratic terms based upon the task employed. A number of recent publications illustrate the growing awareness of this issue. The journal *Cortex*, for example, recently published a special issue that attempted to reconcile and integrate various perspectives of Broca's area and the ventral premotor cortex (Schubotz & Fiebach, 2006). Other articles have attempted a similar integration of perspectives with regard to the superior temporal sulcus (Hein & Knight, 2008), temporoparietal junction (Mitchell, 2008), precuneus (Cavanna & Trimble, 2006) and posterior cingulate (Nielsen et al., 2005).

Of course, our best understanding of how the brain operates is bound to come from an understanding of networks of regions, how different brain areas interact and work together, rather than a modularist assignation of single functions to specific regions. That said, an understanding of how individual regions contribute to different networks in order to support very different processes, is likely to aid us in uncovering the underlying processes that contribute to these networks. The ability to easily locate studies that report activations in a particular area will be an essential part of this endeavour. A recent example of how looking across topics can lead to a better understanding of networks can be found in the growing interest in the default network, the collection of brain areas that appear active in the absence of external stimuli (e.g., Raichle et al., 2001; Mason et al.,

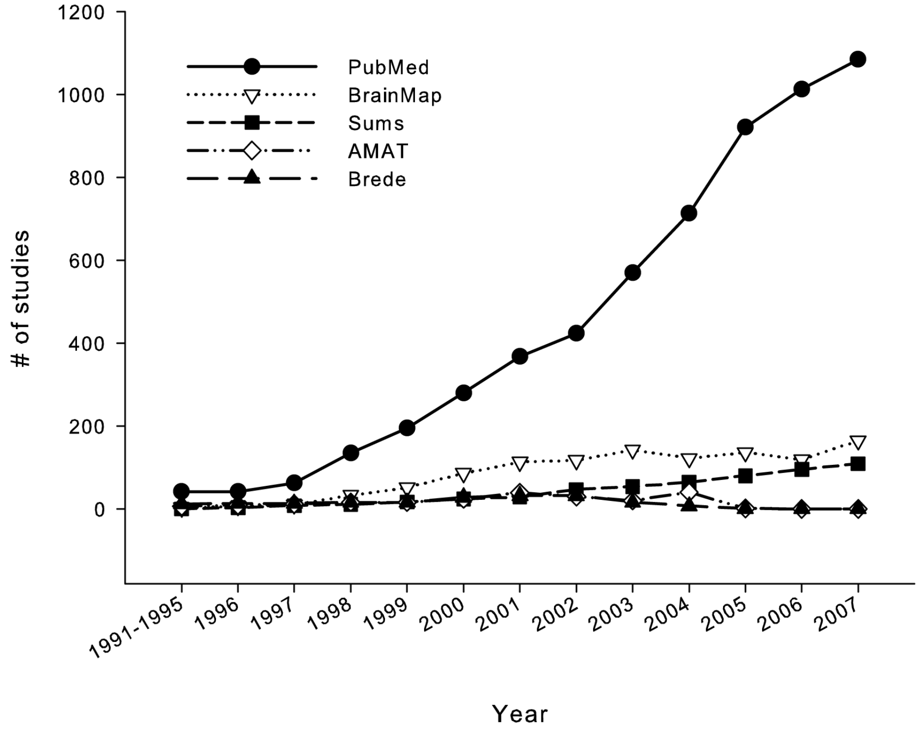

***Fig 1.*** *Total number of published fMRI studies reporting coordinates by year and number of studies included in current coordinate databases. A detailed description of this data is presented in the Appendix.*

***Table 1.*** *Comparison of four existing coordinate databases.*

| | AMAT | BrainMap | Brede | SumsDB/Caret |
|---|---|---|---|---|
| Creator(s) | Dr. Antomia F. Hamilton (University of Nottingham) | Dr. Peter T. Fox & Dr. Jack L. Lancaster (University of Texas, USA) | Dr. Finn Å. Nielsen (Technical University of Denmark/Copenhagen University Hospital, Denmark) | Van Essen Lab (Washington University in St. Louis, USA) |
| Link | http://www.antoniahamilton.com/amat.html | http://brainmap.org/ | http://hendrix.imm.dtu.dk/services/jerne/brede/brede.html | http://sumsdb.wustl.edu/sums/index.jsp |
| Scope (as of Oct. 2008) | 212 papers, 675 contrasts, 5379 foci | 1601 papers, 7338 contrasts, 58600 foci | 186 papers, 586 contrasts, 3912 foci | 1039 studies, 31052 foci[1] |
| Most recent study from | 2005 | 2009 | 2005 | 2009 |
| Coordinate submission | Send data (.csv format) to creator | Scribe (Java GUI) | Matlab interface (via Brede Neuroinformatics Toolbox), send data (.xml format) to creator | Import data (.csv format) into Caret and SumsDB[2] |
| Search interface | Matlab | Sleuth (Java GUI) | Internet | Caret or Internet[3] |
| Additional information | Requires SPM2 | Meta-analyses and coordinate transformation with GingerALE | Database also included in Brede Neuroinformatics Toolbox | |

Notes: [1]This includes studies and foci from imaging modalities other than fMRI or PET (e.g., morphometric studies). [2]Submission to SumsDB is still under development, but a beta version of the submission process has recently been released (a tutorial and instructions are available on the SumsDB website). [3]Internet search interface offers restricted search options only.

2007). It has been empirically demonstrated that a number of different processes appear to draw upon this same network of brain areas (Spreng et al., 2008), and theorists have proposed that it may support a single set of processes, such as self-projection (Buckner & Carroll, 2007) or scene construction (Hassabis & Maguire, 2007). Advances such as these would be greatly facilitated by a simple method of searching the entirety of relevant studies for a given area, based upon coordinate location.

Given that peak activations are reported in a common coordinate system, producing a database that associates these coordinates with the studies that report them would seem to be useful, necessary, and achievable. In practice, however, developing such a coordinate database has proven difficult and elusive, for reasons that we explore below.

## Current Coordinate Databases

To date, a few research groups have set out to create a coordinate database akin to what we describe above; we briefly discuss four of the most popular databases here. All of these databases allow for coordinate-based searches and are freely available. Apart from these commonalities, the databases differ substantially in the number of articles included, the information available about these articles, the submission procedure, and a number of other relevant features (see Table 1 for an overview). It is apparent that BrainMap (Fox et al., 1994; Laird et al., 2005b) is the most comprehensive database (Fig. 1) followed by SumsDB; AMAT and Brede contain far fewer articles than these two databases. BrainMap and SumsDB also offer the greatest diversity of search options (Table 2) and, together with Brede (Nielsen, 2003), give the most detailed search results (Table 3). With AMAT (Hamilton, 2005), contributing new studies to the database is simple and fast, but as a result of low demands on the contributor the information provided by the database to users is rather limited. BrainMap and SumsDB, on the other hand, offers very detailed information about studies but this level of output means that a very time-consuming submission process must be completed by contributors.

All of the databases discussed are an important step in the right direction. However, even BrainMap contains only about 19% of the total number of fMRI articles published by the end of 2007 that are suitable for inclusion in a coordinate database (Appendix). In a 2005 publication, Laird and colleagues (2005) estimated that BrainMap would be able to keep up with the rate of publication for neuroimaging papers by shifting from a focus on voluntary submission to student coding of published papers. At the beginning of the year 2005, BrainMap contained approximately 500 articles (Fox et al., 2005). Since then the database has been growing at a mean rate of ~300 articles per year. Although this is a large number of articles and an impressive improvement over previous submission rates, this does not appear to be sufficient to keep up with current publication rates. Currently, around 1000 eligible articles are published per year, and this rate is rising annually. Moreover, it is unclear how studies are being selected for inclusion in BrainMap, an important concern since only a subset of the total number of articles is being included. Unless a new solution is proposed and implemented, we fear that BrainMap and other coordinate databases will be unable to provide a representative or exhaustive database of relevant studies.

The issue of how new studies can be included or submitted to a database seems to us to be the key obstacle for creating an exhaustive database, one that includes all of the relevant neuroimaging research. This, in turn, will affect the likelihood that such a database will be useful to researchers. We now move to a discussion of possible solutions to this problem.

## Possible Solutions to the Problem of a Coordinate Database

As shown above, even the most comprehensive database we have to date contains only about a fifth of the relevant studies. The question thus arises as to what can be done to create

**Table 2.** *Comparison of search options for existing coordinate databases.*

| Search options | AMAT | BrainMap[1] | Brede | SumsDB/ Caret[1] |
|---|---|---|---|---|
| Author | ✓ | ✓ | (✓)[2] | ✓ |
| Title | ✗ | ✗ | (✓)[2] | ✓ |
| Abstract | ✗ | ✗ | ✗ | ✓ |
| Keywords | ✗ | ✓ | ✗ | ✓ |
| Year | ✓ | ✓ | (✓)[2] | ✓ |
| Journal | ✗ | ✓ | (✓)[2] | ✓ |
| Subject characteristics | ✗ | ✓ | ✗ | ✗ |
| Stimulus/response type/modalities | ✗ | ✓ | ✗ | (✓) |
| Paradigm class | ✗ | ✓ | ✗ | ✓ |
| Coordinate search | ✓ | ✓ | ✓ | ✓ |
| Adjustable range | (✓)[3] | ✓ | ✗[4] | ✓ |
| Multiple coordinate search | ✗ | (✓)[5] | (✓)[6] | (✓)[5] |
| Brodmann areas | ✗ | ✓ | ✗ | ✓ |
| Anatomical structures | ✗ | ✓ | ✗ | ✓ |
| Logical operators | ✗ | ✓ | ✗ | ✓ |
| PubMed ID | ✗ | ✓ | ✗ | ✓ |

Notes: (✓) indicates search options with restricted functionalities; [1]Sleuth and SumsDB/Caret offer additional search options; for brevity, only a subset of relevant options is included in the table; [2]via Google; [3]the number of neighboring coordinates to be retrieved can be entered; [4]the 30 closest coordinates will be retrieved; [5]only an OR search is possible; [6]the 20 most similar studies (Nielsen & Hansen, 2004) are automatically retrieved

**Table 3.** *Comparison of search results for existing coordinate databases.*

| Search options | AMAT | BrainMap | Brede | SumsDB/ Caret |
|---|---|---|---|---|
| Author | ✓ | ✓ | ✓ | ✓ |
| Title | ✓ | ✓ | ✓ | ✓ |
| Citation | (✓)[1] | ✓ | ✓ | ✓ |
| Abstract | (✓)[1] | ✗ | (✓)[1] | ✓ |
| Contrast | ✓ | ✓ | ✓ | (✓)[2] |
| Experimental Conditions | ✗ | ✓ | ✗ | ✗ |
| Distance between entered and retrieved coordinate(s) | ✓ | ✗ | ✓ | ✗ |
| Visualization of coordinate locations | ✓ | ✓ | ✓ | ✓ |
| Significance value | ✗ | ✓ | ✗ | ✓ |
| Volume of activation | ✗ | ✓ | ✗ | ✓ |
| Brodmann area | ✓ | ✓[3] | ✗ | ✓ |
| Anatomical structure | ✓ | ✓[3] | ✓ | ✓ |
| Brain template | ✓ | ✓ | ✗ | ✓ |
| Related volumes | ✗ | ✗ | ✓[4] | ✗ |
| Number of subjects | ✗ | ✓ | ✓ | ✗ |
| Imaging modality | ✗ | ✓ | ✓ | ✓ |
| Scanner type & strength | ✗ | ✗ | ✓ | ✗ |
| Export of search results | ✗ | ✓ | ✓ | ✓ |
| Link to PubMed | ✓ | ✓ | ✓ | ✓ |
| Link to DOI | ✗ | ✗ | ✓ | ✓ |

Notes: (✓) indicates restrictions in search results; [1]Sleuth and SumsDB/Caret offer additional search options; for brevity, only a subset of relevant options is included in the table; [2]via Google; [3]the number of neighboring coordinates to be retrieved can be entered; [4]the 30 closest coordinates will be retrieved; [5]only an OR search is possible; [6]the 20 most similar studies (Nielsen & Hansen, 2004) are automatically retrieved

an exhaustive database. In our view, the two major questions regarding this issue are whether a new database should be created and who should submit the relevant information to the database. Below we outline two approaches to answering these questions. These proposals should be considered merely examples of a possible solution and we acknowledge that a number of other workable solutions are likely possible.

### *The Bottom-Up Approach*

One approach to solving the current issue is to adopt a bottom-up strategy, in which an existing database is expanded and authors submit their own information to the database. As BrainMap is the largest coordinate database, it might be the best choice for such an expansion.

What advantages would this solution have? Obviously, a major advantage of this option is that no new database would have to be created, which means little effort and expense would need to be invested into this solution. The other main advantage is that authors know their studies best and thus appear to be in an ideal position to describe the tasks and analyses employed. Finally, we hope that a database created in this way will remain freely available, so universities and other research institutions would not have to pay for access to this valuable resource.

What problems would this solution face? In our view, the main problem with this option is ensuring that relevant articles are submitted to the database. We think that the limited success of current databases shows that an exhaustive database is not likely to be achieved with voluntary submission (Laird et al., 2005b). For this reason, we would argue that mandatory submission to the database is necessary if this approach is adopted. More specifically, neuroimaging journals could adopt a policy in which authors are required to submit their results (i.e., locations of peak activations for contrasts) to BrainMap as just another step in the publication process, along with signing the transfer of copyright and submitting final versions of figures. This would ensure that new articles are represented in the database.

If such a policy were adopted, however, a second problem arises related to the amount of information required to contribute to BrainMap. Currently, BrainMap requires a time-consuming submission process via Scribe. We suspect that the time and effort associated with this process is one of the reasons why this sophisticated database has not seen more submissions. The question arises whether this procedure could be changed in a way that would maintain the character of the database, but make submission easier and faster. In our view, a possible way to achieve this would be to explicitly define core information that must be entered into Scribe. In our view, this core information would encompass the complete citation (including the abstract), coordinates with their significance value and test statistic (e.g., F-value), the imaging modality, the name of the brain template employed, a short description of the task, the type of contrast computed (e.g., subtraction, parametric, functional connectivity), the number of subjects, the gender of the subjects, and whether the data come from an empirical study or a meta-analysis. Other entries could be made optional, with the possibility of updating a submission at a later point in time. This optional information might, for instance, include the size of the activation cluster, stimulus and response modalities, stimulus and response types, and the analysis software used. A further change that would significantly decrease time for submission to BrainMap would be the possibility to upload text files containing the relevant information (e.g., tables in comma-separated-values [.CSV] formatting).

Along these lines, to facilitate the creation of such a database, it would make sense for a standardized data format to be created that would allow for easy uploading and sharing of neuroimaging results. Analysis software could then provide a toolbox for exporting results into this data format, and these files would then be available for easy upload to a database. Once this format has been established, it easy to imagine that users will create tools for creating custom databases, as well as develop new methods for search and data manipulation.*

We recognize that the mandatory submission policy described in this scenario might be a concern for some researchers because of the additional effort required for data submission. In our view, making database submission as fast and as easy as possible will be paramount for the database to gain acceptance in the neuroimaging community. Furthermore, researchers should consider submission to the database in their best interests, as doing so increases the likelihood that an article will be discovered by another researcher and thus cited.

To this point we have focused on articles that are to be published in the future. A separate problem is how to ensure that studies which have already been published are entered into the database. With the bottom-up approach, one solution is to appeal to researchers to submit all their previous studies. Societies such as Human Brain Mapping or Society for Neuroscience might encourage their members to participate in this undertaking for the good of the discipline, or perhaps by providing concrete incentives. Such a solution might lead to the exclusion of papers by researchers who are no longer active, however. Another possible solution is for societies to hire individuals, or perhaps recruit volunteers, who would work to enter old papers into the database. In line with this idea, one possibility is to establish permanent funding for the BrainMap database. This funding could then be used to ensure that the current backlog of published but excluded studies is eliminated, with BrainMap overseeing the volunteers and staff needed to enter these articles. Money could be contributed through donations, by societies who collect membership fees, or perhaps even by journals (who will pay to have their back catalogue entered into the database).

While we acknowledge that this bottom-up approach would require a great deal of organization and collaboration on the part of the neuroimaging community, this level of initiative and commitment is not without precedent. The establishment of the Neuroimaging Peer Review Consortium, for example, demonstrates the same level of collaboration on the part of neuroscience journals as would be required to organize mandatory author-based submission to a database.

### *The Top-Down Approach*

Another likely option is the creation of a new database by a private company or a government institution that would then be responsible for entering coordinate information into the database. For example, such a database could be created by an indexing company (e.g., Thomson Reuters, Ovid Technologies), by a consortium of neuroimaging journals, or by the National Library of Medicine (akin to the Genome database accessible via *Entrez*).

What advantages would this solution have? Arguments in favour of involvement by government institutions or private companies include the fact that these organizations are already in the business of making scientific publications searchable and have far more experience and resources at their disposal than any single researcher, journal, or even scientific society. This means that a more ambitious approach can be taken toward the database, without being hindered by a paucity of resources. Also, for companies that already index scientific articles, a lot of the relevant information regarding previously published studies already exists in their own databases; adding a coordinate-based search capability to these databases seems to be a manageable undertaking. These companies are already in the business of indexing research articles, and have in place the infrastructure necessary to support this database through subscriptions. Capitalizing upon these existing resources appears very attractive. Another advantage is that researchers will not have to spend their own time uploading their results to a database. This information will be collected from the published article by the indexing body, along with the information already indexed by these companies (e.g., abstract, keywords, etc.).

What main problems would this solution face? Provided that one of the above-mentioned organizations recognizes the need for a coordinate database and is willing to establish it, how long it would take until this new database could be made accessible is an open question. Apart from the necessary technical requirements, this solution would require a number of decisions to be made regarding the nature of the database, hopefully in consultation with neuroimaging researchers. Also, if a private company were to create the database, this would necessarily result in a database that requires some sort of subscription fee. If this fee is small, and not excessively prohibitive, we feel that this will be only a small hurdle for the database since academic institutions should be willing to shoulder the burden for researchers. However, if only a small number of neuroimaging researchers exist at an institution it might reduce the chances that a library will subscribe, especially in light of the current economic hardships faced by academic institutions. Clearly, cost will be a key factor in the success of a top-down approach.

### *How to Search?*

No matter what type of solution is adopted, some decisions will need to be made regarding how the database will be searched. This will inevitably be determined in part by the

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*An anonymous reviewer is kindly thanked for suggesting this idea.

type of information ultimately included in the database. In principle, we think that all the information entered in the database should be searchable. At bare minimum, searches should be possible using a variety of different methods, including single coordinates, spheres of possible coordinates, keywords, title, and authors. It should also be possible to conduct searches for sets of coordinates, so that it is possible to search for networks (i.e., find papers that report activations within a set of locations). In addition, we consider it important that quantitative meta-analyses (Chein et al., 2002; Laird et al., 2005a; Turkeltaub et al., 2002; Wager & Smith, 2003) be included in the database and it be possible to restrict searches to these types of papers. This would allow for the identification of relevant papers on a meta-level.

### *Information overload?*

A concern of some researchers might be how to deal with all the studies that are bound to result from searching an exhaustive coordinate database. Isn't it possible that researchers will avoid using the database once they realize that this entails sorting through hundreds of papers for each coordinate? We fully acknowledge that searches will inevitably result in a lot of information that needs to be digested, but we believe that this is not a good reason to ignore the problems we have outlined. This information already exists and remains relevant to our own studies. Currently, we ignore this information because it is easy to do so. If we want to understand the function of a brain area, however, we need to look at all of the available information. As scientists we have a responsibility to seek out all the information that informs our research and a universal database will help us to fulfill this obligation.

We also believe that with the large number of articles that will be included in the database, the developers of this index will inevitably find new ways to summarize this information and make it accessible to the user. As an example, the Brede database already incorporates an algorithm that identifies related functional volumes (Nielsen & Hansen, 2004), and can also present frequently mentioned words associated with the chosen coordinates. Meta-analysis techniques employing, for example, replicator dynamics to identify functional networks could further assist in organizing this information (Neumann et al., 2005).

### *How should we proceed from here?*

In our opinion, a universal coordinate database such as the one proposed here can only be successful if its utility is recognized by the neuroimaging community. For this reason, we believe that a survey that asks neuroimaging researchers their opinion on the utility of such a database and what sort of features they would find most useful would be advantageous. To this end we have created a survey to collect this information, so that future discussions of this issue may be informed by the community of neuroimagers. We would greatly appreciate it if readers completed this brief online questionnaire, and encouraged others to do the same. It can be found at http://www.tinyurl.com/db-survey (this URL redirects to Qualtrics.com where the survey is hosted). The results of this survey could help shape the development of a policy regarding database submission for neuroscience journals, or motivate article indexing companies to include this information in their own substantial databases.

Other initiatives that might prove helpful to initiate the process of developing a universal coordinate database include a symposium or open forum at major neuroimaging conferences. This could perhaps be followed by the formation of a task force to examine this issue more closely and generate a more complete set of possible solutions that can then be potentially voted upon.

## Conclusion

We would like to conclude by emphasizing that creating a workable universal database would benefit everyone involved in neuroscience research. Authors and journals will benefit from an increased likelihood of an article being cited, researchers will gain access to a wealth of relevant information, and the field as a whole is likely to progress at a faster rate by encouraging scientists to look outside of their own paradigm.

Of all the possible solutions that we have explored above, it is unclear what the best way to proceed may be. In our minds, however, we favour a solution that involves current indexing corporation in consultation with working neuroscientists. These organizations already have so much of the information required in their own databases, as well as the resources to undertake a project such as this and the infrastructure to make it sustainable. Overall, a solution that involves these corporations appears to embody a number of positives (e.g., increased likelihood of older studies being indexed) with few negatives. As neuroscientists, however, we must not forget that it is our responsibility to facilitate a solution to this important problem, be it through advocacy or innovation.

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## Appendix

The following search syntax was used to identify potentially relevant papers in PubMed:

("fMRI" OR "functional MRI" OR "functional magnetic resonance imaging") AND humans[MH] AND "magnetic resonance imaging"[MH] NOT review[PT] AND ("psychological phenomena and processes"[MH] OR "behavior and behavior mechanisms"[MH]) AND english[LA] AND <year>[DP].

*Explanation of the search syntax.*

1. ("fMRI" OR "functional MRI" OR "functional magnetic resonance imaging"): searches for these terms in all fields (e.g., title, abstract, keywords).

2. AND humans[MH]: restricts search to studies with the medical subject heading (MeSH, http://www.nlm.nih.gov/mesh) "humans".

3. AND "magnetic resonance imaging"[MH]: this term was included in addition to the first search term to make sure that only fMRI studies are found; by this search term we excluded studies using other techniques (e.g., near-infrared spectroscopy, NIRS) that might say something like "Previous studies using fMRI have shown that… Here, we use NIRS to…" in the abstract.

4. NOT review[PT]: excludes articles of the publication type (PT) "review".

5. AND ("psychological phenomena and processes"[MH] OR "behavior and behavior mechanisms"[MH]): uses MeSHs to restrict hits to articles that study psychological phenomena or behavior; PubMed automatically expands the search to subordinate MeSHs (e.g., Psychological Phenomena and Processes → Mental Processes → Cognition).

6. AND english[LA]: only articles in English.

7. AND <year>[DP]: restricts search to a particular year.

The number of hits that resulted from the search using the above search syntax is shown in Table A1. To estimate the number of articles published in 2008, we fitted a polynomial function of degree 4 to the existing data. This resulted in an estimated 1502 articles for 2008. Adding this number to the 7908 hits from 1991 to 2007 resulted in 9410 articles estimated to be published until the end of 2008.

However, not all fMRI studies report coordinates in 3-D coordinate space. Some perform only ROI analyses or present pictures without listing coordinates. For this reason, it was necessary to estimate the percentage of papers that report Talairach coordinates. We chose the hits from the year 2007 and drew a random sample of 100 studies. (Online access was not available for three of the 100 papers originally chosen, so these were replaced by other randomly chosen papers.) Using this sample, we then examined whether each study reported coordinates; this was the case for 74 papers. This percentage was then used to estimate the fraction of papers reporting Talairach coordinates and is shown in Figure 1 and Table A1.

To estimate the number of coordinates reported by the end of the year 2008, we took 74% of the 9410 papers (6963 papers) and multiplied this number with 37 (the mean number of coordinates per study in the BrainMap database). This resulted in 257631 coordinates.

For Figure 1, the databases were searched on a yearly basis, up until the end of 2007. For BrainMap and SumsDB/Caret, the search was limited to fMRI studies. The BrainMap search was performed on October 31st, 2008. The search of SumsDB/Caret was based on the October 2008 version of the stereotaxic foci database (archive: Human.PC-CC_STEREOTAXIC_FOCI_COMPOSITE_31K_ASSIGNED_Oct08.73730.spec, downloaded from http://sumsdb.wustl.edu/sums/directory.do?id=6529195). The search was performed with the search option "Data type = fMRI", limiting search results to fMRI studies. Numbers for AMAT and Brede include both PET and fMRI studies as these databases do not offer an option that restricts search to a particular imaging modality.

The estimate of BrainMap containing about 19% of the total number of fMRI articles published by the end of 2007 is based on the numbers shown in the two rightmost columns of Table A1.

***Table A1.*** *Number of articles found in PubMed, estimated percentage of these articles reporting Talairach coordinates, and number and percentage of fMRI studies in BrainMap.*

| Year | # of hits | 74% of hits | # of studies in BrainMap | % of studies in BrainMap |
|---|---|---|---|---|
| 1991-1995 | 57 | 42 | 3 | 7 |
| 1996 | 57 | 42 | 6 | 14 |
| 1997 | 85 | 63 | 10 | 16 |
| 1998 | 183 | 135 | 33 | 24 |
| 1999 | 263 | 195 | 51 | 26 |
| 2000 | 379 | 280 | 86 | 31 |
| 2001 | 497 | 368 | 113 | 31 |
| 2002 | 573 | 424 | 117 | 28 |
| 2003 | 770 | 570 | 142 | 25 |
| 2004 | 964 | 713 | 122 | 17 |
| 2005 | 1245 | 921 | 136 | 15 |
| 2006 | 1369 | 1013 | 119 | 12 |
| 2007 | 1466 | 1085 | 164 | 15 |
| Total | 7908 | 5852 | 1102 | 19 |