

3-D Hardcopy: The Hosoya Cube

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Much effort in scientific visualization is put towards the representation and communication of three-dimensional objects. Typically, an investigator labors in front of a graphics workstation, twiddling knobs and flipping switches until meaningful views of the object are created. Once the investigator has found the correct representation of the data, the problem arises of how to communicate this three dimensional image using the two dimensional media available. Probably the most powerful means of communicating 3-D structure is via film or video animation. However, animations are time-consuming and difficult to produce, and expensive to reproduce. For wider distribution, print media are more cost-effective.

In print, 3-D structure can be communicated in a number of ways. A few well-chosen views of the structure can be presented, using perspective, shading, transparency, and other rendering techniques to enhance the photorealism of each view. Stereoscopic pairs of images can be printed, to further aid the perception of the 3-D structure. The choice of views is made by the researcher, who may unintentionally bias the viewer towards a particular perception of the structure. Another approach, commonly seen in architectural graphics, is to present top, side, and front views of the same structure. Here the choice of views is taken out of the hands of the presenter, providing the viewer with a standard visual framework to aid perception of the structure. However, the 3-D relationships between the three views, printed side-by-side on one flat sheet of paper, still need to be mentally reconstructed by the viewer.

The approach I'd like to suggest here is to print six views of an object, the six faces of a cube encompassing the structure, in such a manner that a paper cube can easily be constructed from the printed sheets. The advantage of the paper cube is its physicality—the viewer can readily perceive the spatial relationships between parts of the structure as seen in the six views, because the relationships between the views is encoded by their positions on the surface of the cube. The paper cube is a cheap, portable, reproducible means of delivering some of the interactive advantages inherent in a 3-D workstation display.

The Hosoya Cube

I'd like to be able to say that I saw the need for 3-D paper hardcopy, then searched diligently for the right means to achieve it. In actuality, the means appeared before an end was apparent. I have been enamored with the Oriental art of origami since childhood, and have attempted a few times to produce interesting results by folding designs I'd printed out from my home computer. The relevance of this hobby to my day job, scientific visualization, became apparent only recently.

The easiest way to construct a print for an origami folding is to fold the structure out of blank paper, sketch a design on the folded model, then unfold the paper and use the sheet as a template for the final design. My previous endeavors in printing origami designs had shown that the best results were obtained when the important faces of the model where comprised of contiguous areas on the unfolded sheet—faces constructed from an image printed in parts on the sheet never fit together well enough, due to the imprecisions inherent in paper folding. In my search for a paper cube with images on each of its six faces, I concentrated on models that met this criteria. The best model I found, the Hosoya cube, not only keeps each face as a whole image on the unfolded sheet, it is also one of the simplest to fold. The Hosoya cube is folded from two sheets of paper, producing a larger cube than one sheet would. Also, the images on the unfolded sheets are easily composited through scalings and 90-degree rotations of the source images.

Generating the unfolded sheets

Each of the two sheets consists of a square divided into nine sub-squares (See Figures 1 & 2). The cube faces appear as the central square and the left and right side squares. If we imagine the final cube centered at the origin of a right-handed coordinate system, we can label each of the faces according to the sign of the axis that pierces the face (X+, X-, Y+, Y-, Z+, and Z-). One sheet will contain the Z+ face in the center, with the X- face on the left, and X+ face on the right, each rotated so the positive Y axis points upward. The other sheet will contain the Z- face in the center, with the Y- face on the left and the Y+ face on the right, each rotated so the positive X axis points upward.

To aid in folding, I create a square image of two diagonal lines and place rotated versions of it in each of the four corner squares of each sheet (the reasoning behind the solid and dashed lines will be explained when we discuss folding, below).

Listing 1 is a Unix csh script which uses the Portable Bitmap suite of tools to construct two Hosoya cube sheets from six images, xm.ppm, xp.ppm, ym.ppm, yp.ppm, zm.ppm, and zp.ppm (similar scripts could be written for other toolkits). The source images are renderings of a model of the human brain (see sidebar). Note that some of the images had to be rotated to obtain the proper orientation—it may take some experimentation with your images to get all of the orientations correct.

```
#!/bin/csh
#
# Make two Hosoya cube files from {x,y,z}{m,p}.ppm and corner.pbm
# (corner.pbm contains the folding lines for the four corner squares).
#
# PJM 901214
#

# Configurable parameters
#
# length of one side of {x,y,z}{m,p}.ppm
set side = 512
# length of one side of corner.pbm
set cornerSide = 128

# Computed parameters
@ size = $side * 3
@ twoSides = $side * 2
@ cornerScale = $side / $cornerSide

# make empty image
pbmmake -white $size $size > 1.ppm

# Insert the corners
# upper left
pnmenlarge $cornerScale corner.pbm > t.pbm
pnmpaste t.pbm 0 0 1.ppm > 2.ppm
# upper right
pnmenlarge $cornerScale corner.pbm | pnmflip -cw > t.pbm
pnmpaste t.pbm $twoSides 0 2.ppm > 1.ppm
# lower right
pnmenlarge $cornerScale corner.pbm | pnmflip -r180 > t.pbm
pnmpaste t.pbm $twoSides $twoSides 1.ppm > 2.ppm
# lower left
pnmenlarge $cornerScale corner.pbm | pnmflip -ccw > t.pbm
pnmpaste t.pbm 0 $twoSides 2.ppm > 1.ppm

# Save this for later use
cp 1.ppm blank.ppm

# Insert the pieces for sheet A
pnmpaste xm.ppm 0 $side blank.ppm > 1.ppm
pnmpaste zp.ppm $side $side 1.ppm > 2.ppm
pnmpaste xp.ppm $twoSides $side 2.ppm > A.ppm

# Insert the pieces for sheet B
# Note that some need to be rotated. This is specific to the particular
# animation script used to render these images.
```

```

pnmflip -r180 ym.ppm > t.ppm
pnmpaste t.ppm 0 $side blank.ppm > 1.ppm
pnmflip -cw zm.ppm > t.ppm
pnmpaste t.ppm $side $side 1.ppm > 2.ppm
pnmpaste yp.ppm $twoSides $side 2.ppm > B.ppm

# Clean up
ppmtorast A.ppm > A.ras
ppmtorast B.ppm > B.ras
#/bin/rm 1.ppm 2.ppm t.ppm blank.ppm A.ppm B.ppm

```

Listing 1

Folding the Hosoya Cube

In traditional origami, the use of scissors and measuring devices is frowned upon. However, this is science, so we're allowed to fudge a bit. We will preserve standard origami notation, in which creases made by "valley" folds are drawn using dashed lines, while "mountain" creases are drawn with solid lines. Proper folding technique is important for attractive results. A good approach to making a long fold is to pinch the paper at the two extremes of the fold, then work toward the center, finalizing the crease by running the fold between your thumbnail and forefinger for its entire length. Neatness counts.

Step 1: Using the extreme corners of the diagonal lines as reference marks, cut off the excess paper, leaving a square piece of paper containing the 9 sub-squares.

Step 2: Again using the diagonal lines as reference, fold the sheet into 9 sub-squares using mountain folds (see Figure 3a).

Step 3: If this were traditional origami, we'd next fold each of the four corners in, making valley folds along each of the long dashed diagonal lines (See Figure 3b). I find it easier to cut the corners off along these lines, resulting in a lighter cube with crisper edges.

Step 4: We now need to make four valley folds, along each of the short dashed diagonals (See Figure 3c). Pinch each fold at the outer edge, then work towards the center, tugging a bit on the fold to make a sharp corner. The result will be a cube with one missing face.

Step 5: Repeat steps 1 through 4 with the other sheet.

Step 6: This is the final assembly step, and it's the hardest (See Figure 3d). Orient the two halves in their final configuration, and insert each half into the other so that the blank faces are inserted inside the printed faces. This takes a little patience, but is not hard to master.

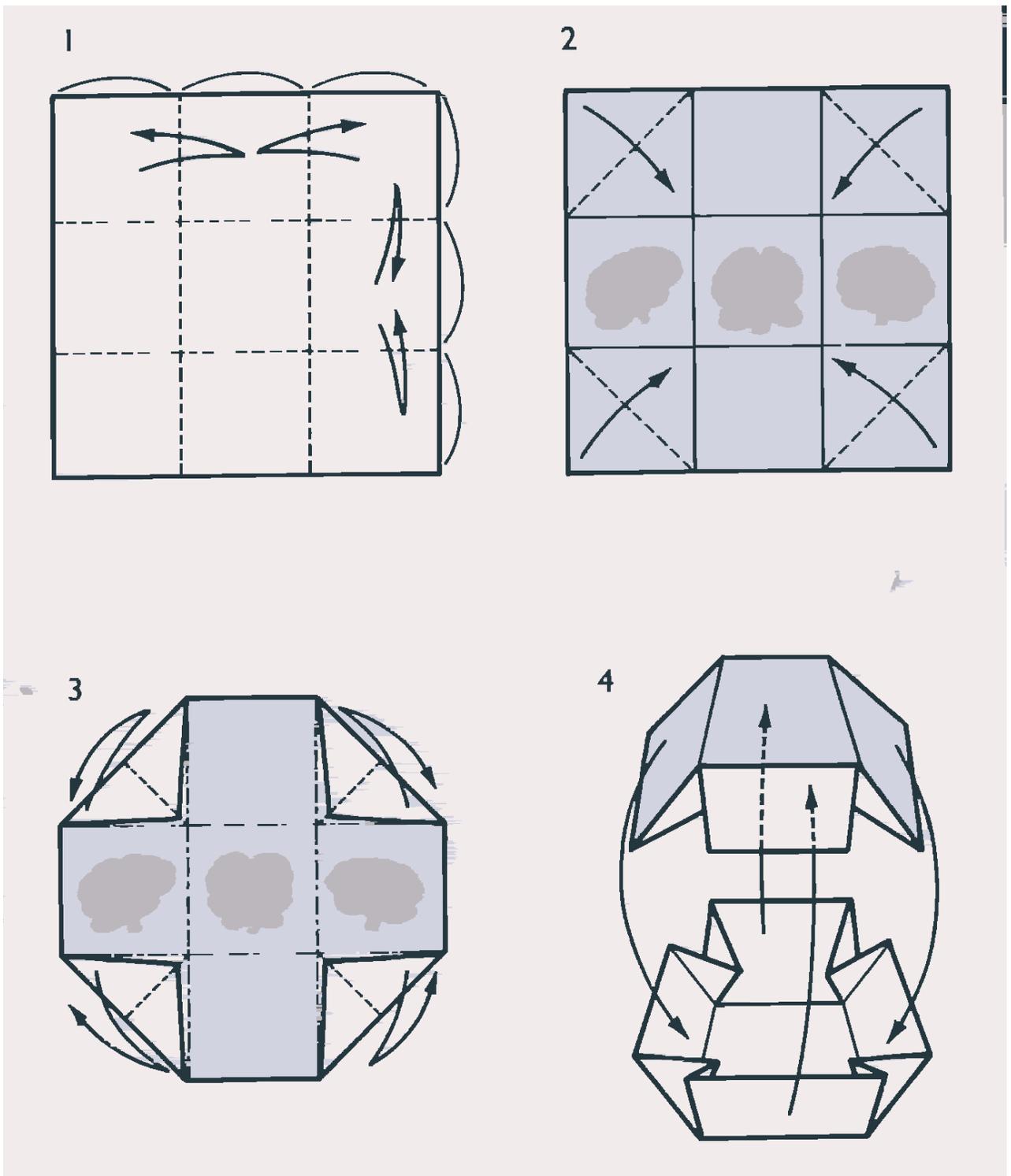


Figure 3 (figures 1 & 2 at end of document)

The Hosoya Cube as User Interface

The art of scientific visualization lies in making results accessible to the researcher and student via effective user interfaces which facilitate the scientific process. Research is being done to translate the direct manipulation properties

of the physical world into the virtual world of graphics workstations. The Hosoya cube is a different approach—it takes the virtual images and folds them into a physical artifact which is both intuitive to use and cheap to reproduce. It makes a unique addition to a scientific visualization toolkit.

SIDEBAR: The human brain

The images appearing on the faces of this cube are renderings of a human brain created using the Wavefront animation package. The data was created by Dr. Robert B. Livingston of the University of California, San Diego, Neurosciences department, in 1974-75. A normal human brain was encased in a block of paraffin. Successive thin layers were shaved off of the paraffin block, and the top of the block was photographed after each pass, resulting in about 100 slices spaced 1.1 millimeters apart. Livingston and others hand-digitized the contours of neuroanatomical structures from the photographs, creating a database of about 25 distinct brain structures. This data was used in Livingston's 1976 film, "The Human Brain, A Dynamic View of its Structures and Organizations". The contour data was converted into triangular meshes by Floyd Gillis at the Research Institute at Scripps Clinic in 1987.

The subset of the human brain structures visible in these images comprise over 125,000 polygons. Each image took about 45 minutes to compute on an Alliant FX80. The outer objects are the cerebral cortex (transparent gray), cerebellum (transparent magenta), and brainstem (transparent blue). Two regions of the cortex responsible for language perception and production, Broca's and Wernicke's areas, are highlighted in dark and light blue, respectively. The corpus callosum, a bundle of nerve fibers connecting the left and right hemispheres of the cortex, is represented in a darker gray and is most apparent in the side views of the brain. The large transparent yellow structure atop the brainstem is the thalamus, and some of the smaller structures of the interior of the brain are visible within the thalamus and the brainstem (best viewed from the front or underneath). The two orange almond-shaped structures are the amygdala.

References

- Kasahara, Kunihiko and Toshie Takahama, *Origami for the Connoisseur*, Japan Publications, Inc, Tokyo, 1987
- Livingston, Robert B., Kent R. Wilson *The human brain : a dynamic view of its structures and organization*. Presented by Roche Laboratories; [made by] Wexler Films. [Berkeley, Calif.] Regents of the University of California ; Los Angeles, Calif. [Distributor] Wexler Film Productions, c1976. Film, 28 minutes.

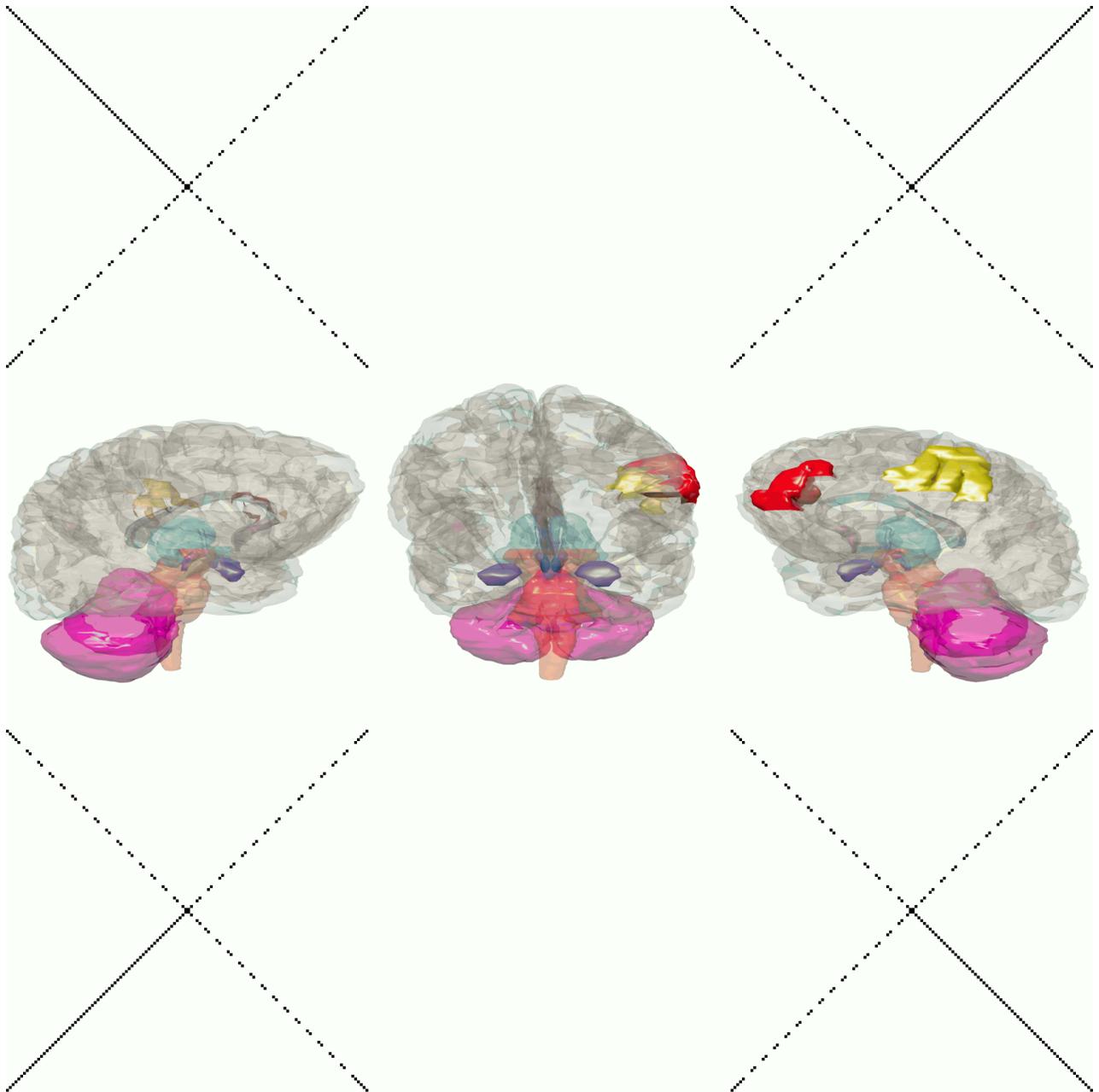


Figure1

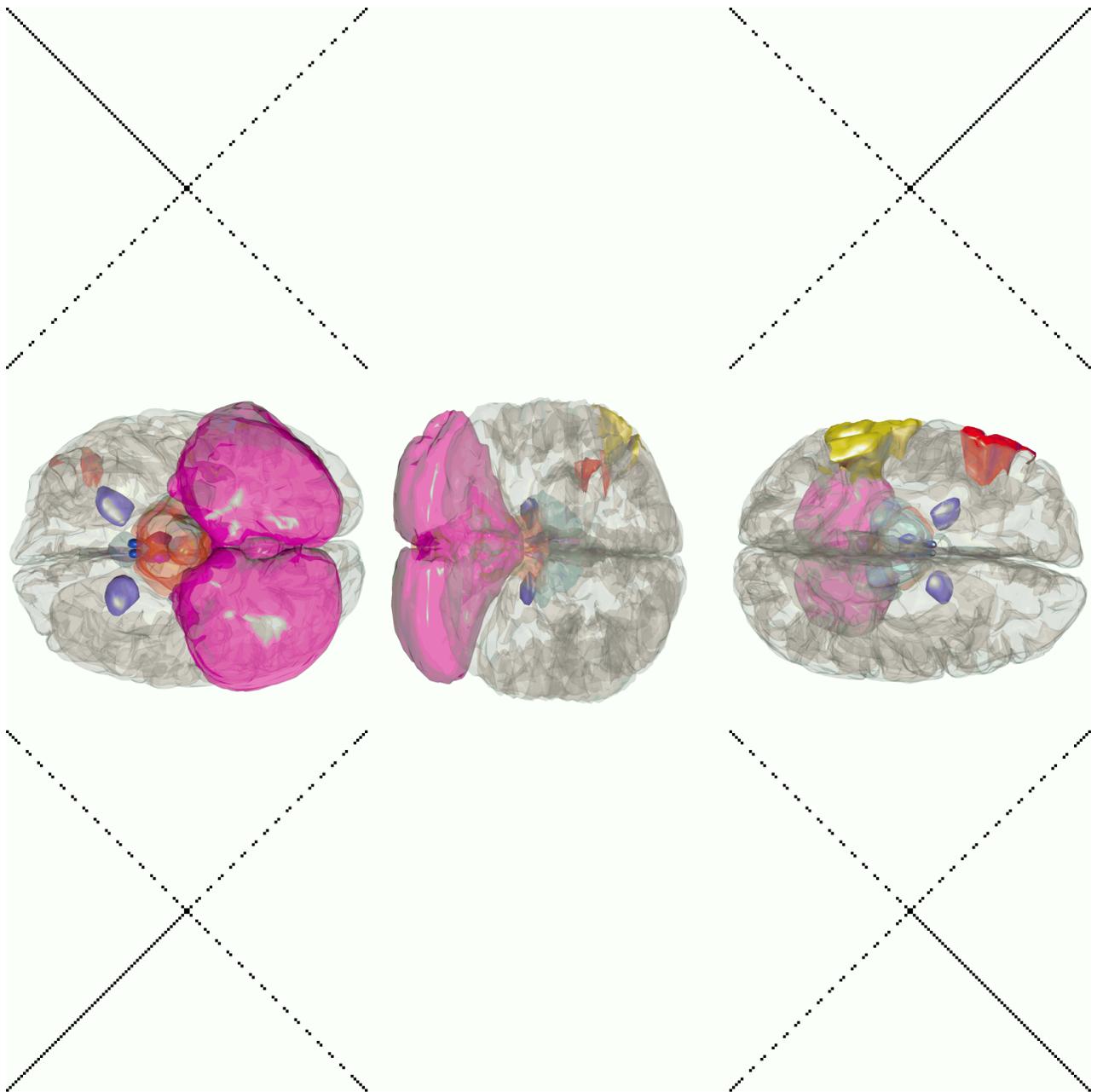


Figure 2