

## Crossmodal studies: cognitive neuroscience and experimental design

multisensory and crossmodal processing in the normal brain  
compensatory plasticity and sensory substitution

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## Misleading illusions vs multisensory estimates

- (spatial) ventriloquism
  - mislocalization of sound based on temporally coincident visual event for distant location
- McGurk effect
  - perception of speech sounds biased by seen lip movement
- joint estimates of external properties
  - each modality weighted according to its reliability
  - but how to match input across modalities?

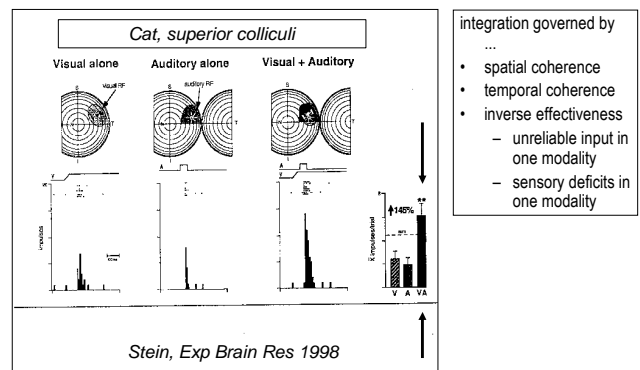
Review: Driver and Noesselt Neuron 2008

## Unimodal (unisensory) vs multisensory processing

- sensory processing and perception extensively studied
- most research on just a single modality (vision, audition, touch)
- real world situations often stimulate several senses at the same time
  - audiovisual speech (dubbed movies)
  - exploring a texture with the hand (motor contribution!)
- multisensory aspects of social perception
  - see another person being touched

Review: Driver and Noesselt Neuron 2008

## Multisensory processing: rules of integration (=research questions!)

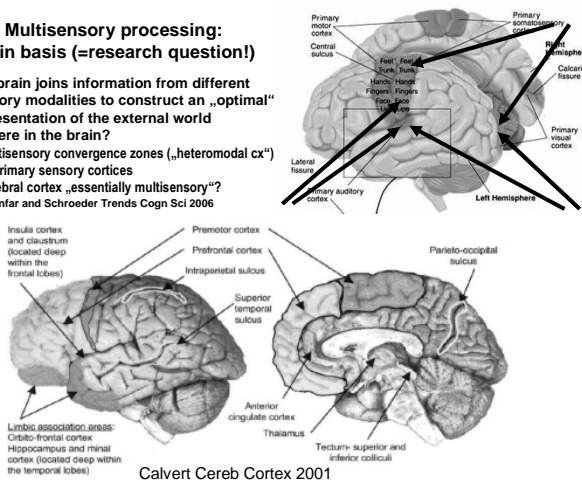


## Multisensory processing: brain basis (=research question!)

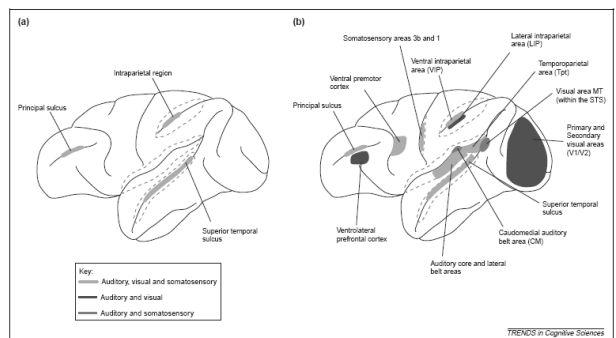
The brain joins information from different sensory modalities to construct an „optimal“ representation of the external world – where in the brain?

- multisensory convergence zones („heteromodal cx“)
- or primary sensory cortices
- cerebral cortex „essentially multisensory“?

Ghazanfar and Schroeder Trends Cogn Sci 2006



## Brain areas with a role in multisensory processing



Classical view: only heteromodal areas are multisensory

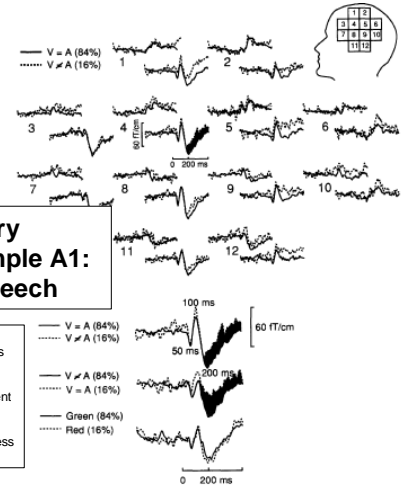
Modern view: multisensory input to heteromodal and unimodal areas

Ghazanfar and Schroeder Trends Cogn Sci 2006

## Examples of crossmodal studies

	Multisensory and crossmodal processing in the normal brain	Crossmodal plasticity after sensory deprivation
audiovisual	Speech and non-speech stimuli in MEG, fMRI Sight-reading in musicians (MEG study)	
visuotactile		TMS to visual cortex in blind subjects
audiotactile	Vibrotactile stimuli in fMRI, MEG	Vibrotactile activation of ... cortex in a deaf subject (MEG)

NB additional interaction with motor processes



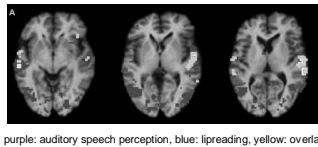
### Multisensory processing, example A1: audiovisual speech

**Sams et al Neurosci Lett 1991**

- subjects watched video of actress articulating /pa/ and /ka/
- auditory stimulus always /pa/
- waveforms explained by equivalent current dipoles (ECDs) at the supratemporal cortex
- visual information may have access to auditory cortex

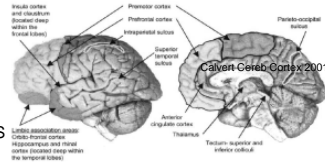
### Multisensory processing, example A2: audiovisual speech

**Calvert et al Science 1997 (fMRI):** lip-reading (numbers 1 to 10) activates auditory cortex



**Calvert et al. Curr Biol 2000 (fMRI):**

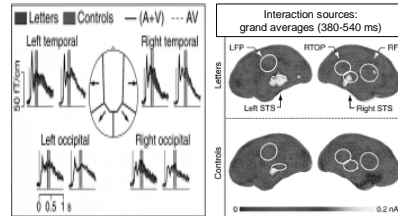
- semantically concordant AV speech
- semantically discordant AV speech
- heard speech, seen speech, rest interested in areas where
- $A > 0, V > 0, AV_{con} > A+V, AV_{dis} < A+V$
- only region that met criteria was left STS



### Multisensory processing, example A3: audiovisual letters

**Raj, Uetala, Hari Neuron 2001 (MEG):** integrating auditory (phonemic) and visual (graphemic) aspects of letters

- stimuli that have been associated through learning
- task: lift the left index finger as quickly and accurately as possible when a target stimulus occurs
- stronger interaction for letters than controls
- only in left/right STS, stronger interaction for matching vs non-matching letters
- NB interaction was suppressive!



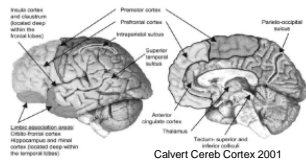
Stimulus category	Stimuli	Response
Visual Auditory		
Letters		
1. AL	Q	"q"
2. VL	K	"k"
3. AVLm (match)	E	"x"
4. AVLm (non-match)	F	"r"
5. AVLsA (semi-target)	R	"q"
6. AVLsV (semi-target)	R	"q"
7. ALT (target)	R	+
8. VLT (target)	R	+
9. AVLT (target)	R	+
Control stimuli		
10. AC	Q	-
11. VC	Q	-
12. AVC (random pairs)	Q	-

A=auditory V=visual AV=audiovisual  
L=letter C=control

### Multisensory processing, example A4: audiovisual, non speech stimuli

**Foxe et al. Cogn Brain Res 2000 (ERPs)**

- 1000-Hz tones paired with median nerve stimuli (mild „electric shocks“)
- somatosensory cx: 50 ms after onset
- auditory cx: 70-80 ms after onset
- supports „early integration in primary sensory areas“



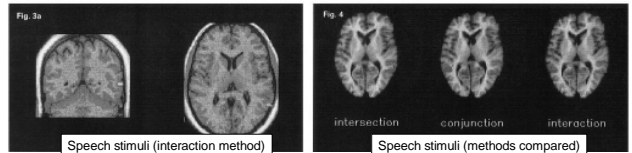
**Bushara et al J Neurosci 2001 (PET)**

- visual stimulus: circle on computer screen; auditory stimulus: 2000 Hz, 90 dB tones, both 100 ms
- detection of AV stimulus onset asynchrony activates insula and superior colliculus

**Calvert et al. Neuroimage 2001 (fMRI)**

- checkerboard reversal and 1000 ms white noise bursts
- if input synchronous, then activation in superior colliculus, insula, left STS, right IPS
- no extra activation in primary sensory areas

### Identifying multisensory areas: intersection, conjunction, or interaction?



**Intersection:** statistics for A gives map A, statistics for V gives map V, then  $A * V$   
NB 1: coexistence of two sets of neurons in the same voxel (Type I error, „false positive“)  
NB 2: might overlook an area where weak responses to unimodal stimuli are enhanced for bimodal stimuli (Type II error, „false negative“)

**Conjunction:** statistics on combined A+V data  
Contrast unimodal stimuli with true bimodal stimuli:  $[AV-V] * [AV-A]$  ... but if AV is just A+V then this analysis is same as A\*V above

**Better: 2 x 2 design with interaction contrast**

$[AV-rest] - [(A-rest) + (V-rest)]$

shows bimodal response that cannot be predicted from the sum of unimodal responses

\* no Type I error as in NB1

\* no need for unimodal responses to reach significance

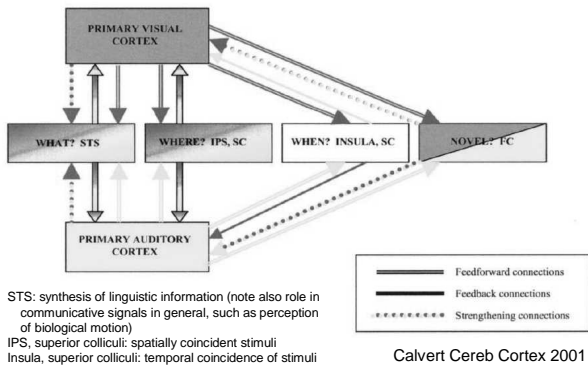
\* still difficult to interpret if BOLD responses to A, B are close to ceiling

\* best use parametric design where intensity of unimodal stimuli is systematically varied

\* still difficult if one of the unimodal responses is suppressive (e.g. visual tasks depress responses in aud cx)

	0	V
0	Rest	V
A	A	AV

## Model of brain areas contributing to AV integration



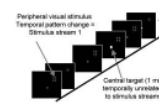
STS: synthesis of linguistic information (note also role in communicative signals in general, such as perception of biological motion)  
 IPS, superior colliculi: spatially coincident stimuli  
 Insula, superior colliculi: temporal coincidence of stimuli

## Feedback from convergence areas to primary cortical areas? – Example A5

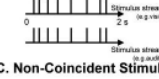
Noesselt et al J Neurosci 2007

- visual transients in the periphery of the subject's visual field (task: monitors fixation mark for changes in brightness)
- sound bursts either temporally coincident or non-coincident with visual transients
- for temporally coincident stimuli, activation in STS and in primary visual cx and primary auditory cx
- analyses of functional coupling suggest feedback from STS to primary areas

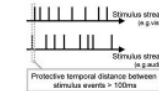
### A. Experimental set-up



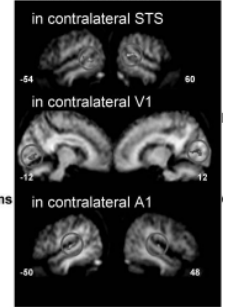
### B. Coincident Stimulus streams



### C. Non-Coincident Stimulus streams



### D. BOLD-effects of audiovisual temporal coincidence



## Multisensory processing, example A6: auditory cortex activated by visual stimuli

### Mind's ear in a musician:

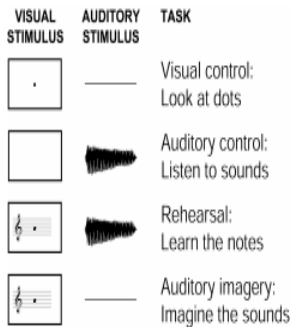
- Audiovisual association
- Trained musicians reading musical score may hear corresponding sounds in their mind's ear
- Studied earlier:** spatial pattern of brain activation identified, but no timing information (Sergent et al., 1992)
- Goal:** analyse time course of brain activation sites during visually triggered auditory imagery in musicians

**Subjects:** 11 experienced professional-level musicians

**Stimuli:** Four different notes/tones, presented once every 1.5-2s

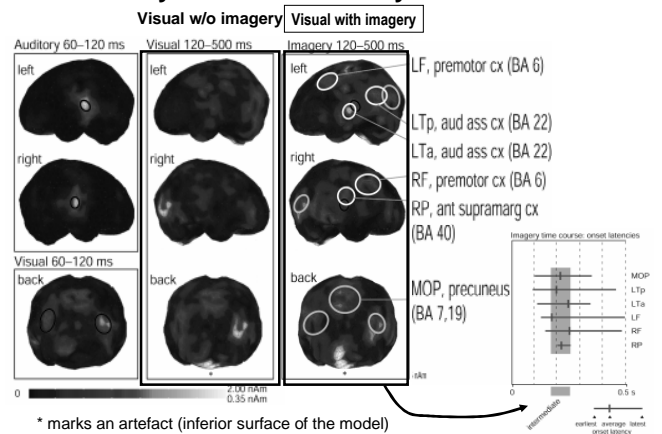
**MEG:** 306-channel whole-head device

**Source analysis:** minimum current estimates (Uutela et al. 1999)



Schürmann, Raij, Fujiki, Hari, NeuroImage 2002

## Auditory cortex activated by visual stimuli



## Multisensory processing example A7: audiotactile interaction

\* **Persons with hearing impairment** may perceive sounds (including speech) using their sense of touch

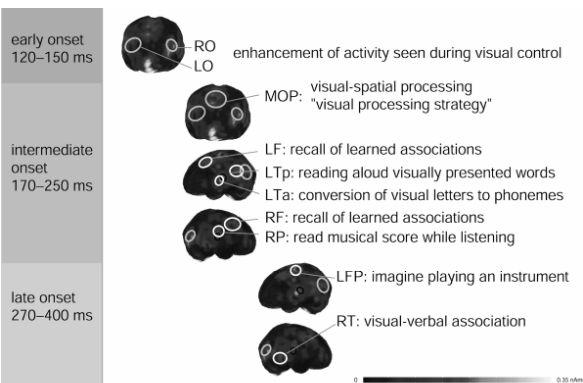
\* Audiotactile interaction not easily noticed in **everyday life**, needs experiments like **parchment-skin illusion**



Jousmäki & Hari Curr Biol 1998  
 Guest, Catmur, Lloyd, Spence Exp Brain Res 2002

\* tactile stimuli with a "sound-like" temporal pattern

>> **Objective:** study brain activation by auditory and vibrotactile stimuli: shared brain resources?

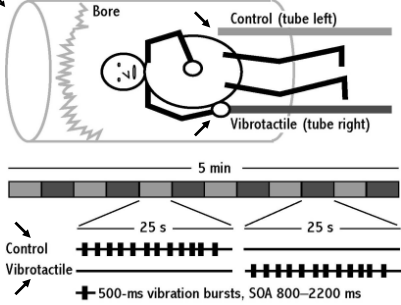


**Conclusion:** MEG shows neural activation in visually triggered auditory imagery  
 - with well-defined time course in multiple areas  
 - may reflect recalling of firmly established audiovisual associations

### Touch activates human auditory cortex: an fMRI study



**Stimuli:** \* **Vibrotactile** to fingers and palm  
 \* 200-Hz, 500-ms vibrations  
 \* stimulus onset asynchrony 1500 ± 700 ms



**How to prevent artifacts from vibration-induced noise?**

\* subject touching only **one** out of two vibrating tubes

\* brain activation in contrast  
 Vibrotactile-Control

Schürmann, Caetano, Hlushchuk, Jousmäki & Hari, *NeuroImage* 2006

### Touch activates human auditory cortex

**Stimuli:** \* **Vibrotactile** to fingers and palm  
 200-Hz, 500-ms vibrations, SOA 1500 ± 700 ms  
 \* **Noise bursts** in headphones  
 500-ms bursts, SOA 1500 ± 700 ms ≠ psychophysical study  
 \* **Touch** to fingertips  
 Air pressure pulses, SOA 300–500 ms

**13 subjects** 28.1 ± 1.8 years (22–39), all right-handed, 4 females

**General Electrics 3T scanner, Helsinki Univ of Technology**

**Preprocessing: SPM99 (Functional Imaging Laboratory, UCL)**

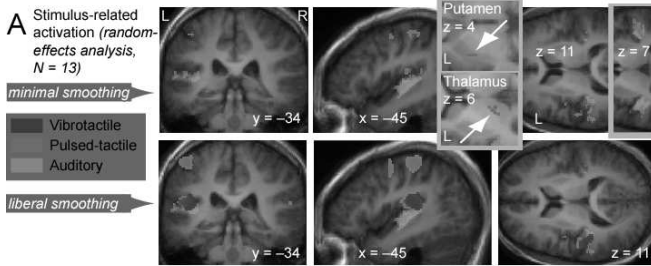
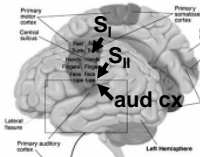
**Realignment** to correct for movement during scans

**Spatial normalization** to standard brain

**Smoothing kept to minimum** otherwise areas of multisensory co-activation appear larger than they are (statistical thresholds!)

### Results - Group analysis:

- minimal smoothing 3 x 3 x 4 mm
- liberal smoothing 9 x 9 x 12 mm
- contrasts for individual subjects:
  - Vibrotactile-Control, Noise-Rest, Touch-Rest
- group analysis: random effects, 13 subjects



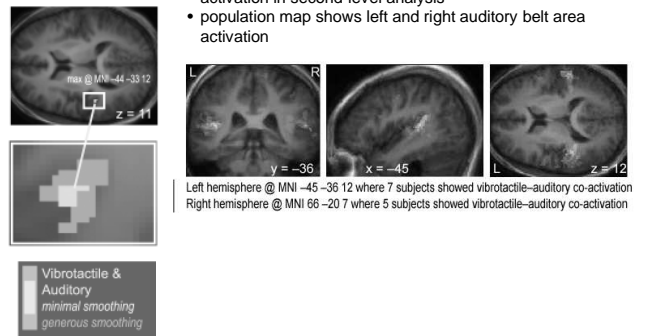
Schürmann, Caetano, Hlushchuk, Jousmäki & Hari, *NeuroImage* 2006

### Touch activates human auditory cortex

NB „extent“ of activation varies with smoothing

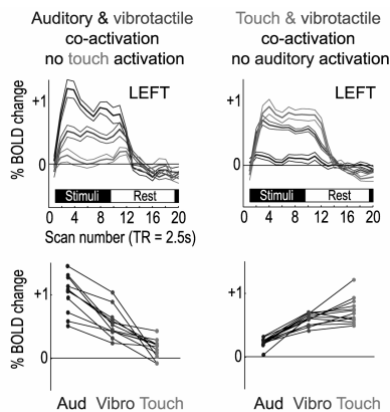
NB is activation bilateral?

- only left auditory belt area with suprathreshold activation in second-level analysis
- population map shows left and right auditory belt area activation



Schürmann, Caetano, Hlushchuk, Jousmäki & Hari, *NeuroImage* 2006

### BOLD signal time series from individual subjects' data



Co-activated area (in group analysis) as **region of interest (ROI)**

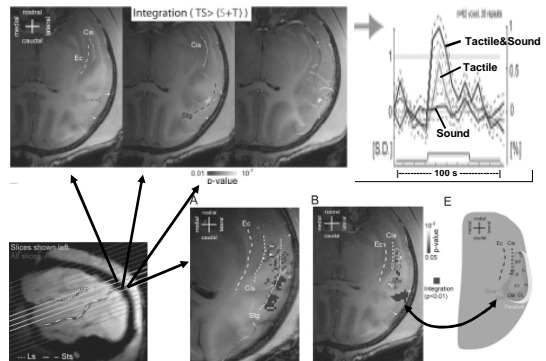
For each subject, choose **cluster next to ROI**, plot BOLD time series

plots show averages across recurring blocks and across subjects – left hemisphere

Schürmann, Caetano, Hlushchuk, Jousmäki & Hari, *NeuroImage* 2006

### Integration of touch and sound in auditory cortex: high-resolution fMRI in macaque monkeys

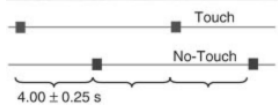
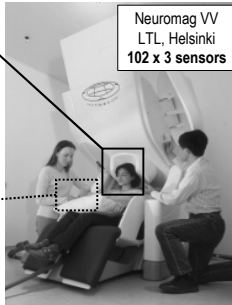
Kayser, Petkov, Augath, Logothetis, *Neuron* 2005



### Activation of auditory belt areas by vibrotactile stimuli: MEG study

Caetano and Jousmäki, Neuroimage 2006

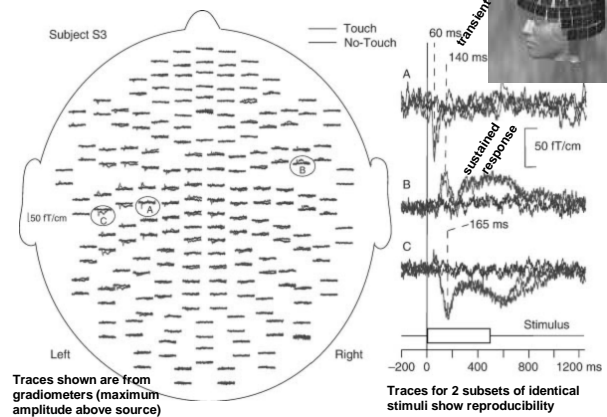
MEG combines  
 \* good spatial resolution (~5 mm in optimal cases)  
 \* millisecond temporal resolution



Vibrotactile stimuli to fingertips  
 ~20 dB above threshold, 500 ms duration  
 "No Touch": sound from tube?  
 Functional localizers:  
 \* auditory cortex: 60 dB, 1 kHz, 100 ms tones  
 \* somatosensory cx: median nerve stim

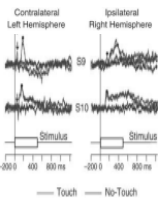
### Responses to vibrotactile stimuli: MEG topography

subjects report weak percept of vibration in the fingertips, perception of sound

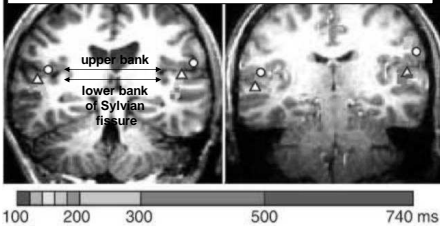


Caetano and Jousmäki, Neuroimage 2006

#### 1. MEG time series

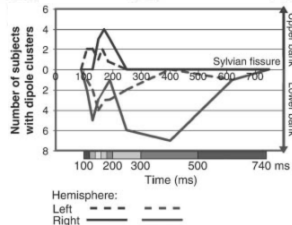


#### 2. MEG sources over time (two example subjects)



#### 3. Sources in group analysis (N=10)

sustained response (300 - 500 ms) to 500 ms stimuli, **only in lower bank** (p = 0.008, right hemisphere)



### Responses to vibrotactile stimuli

Caetano and Jousmäki, Neuroimage 2006

### Conclusion: Audiotactile interaction - brain basis?

Activation of auditory belt areas through vibrotactile stimuli

Shared neural resources might be needed for „binding“ across modalities or detecting temporal, spatial coincidence  
 >> correlate of facilitatory interaction in „hands help hearing“?  
 >> **analysis of temporal patterns** required in both modalities?

#### Caveat: activation of inner ear via bone conduction?

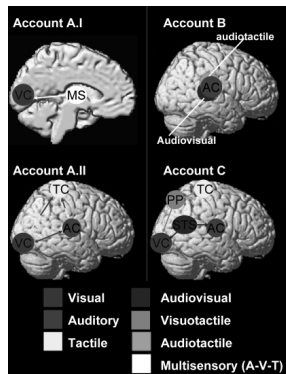
additional control in 8 subjects (Caetano and Jousmäki 2006):

- vibrotactile stimuli applied to wrist or elbow
- no perception of sound
- bone conduction does not explain MEG results

### Competing (?) explanations of the brain basis of multisensory processing

- A – „all multisensory“:** direct feedforward influences between modalities (arising at thalamic level or through cortico-cortical connections)
- B – „new bimodal areas“:** audiotactile and audiovisual areas immediately adjacent to auditory cortex
- C – „Critical Role of Feedback Circuitry“:** activation of STS and feedback to primary visual and auditory cortex ... test how ... ?

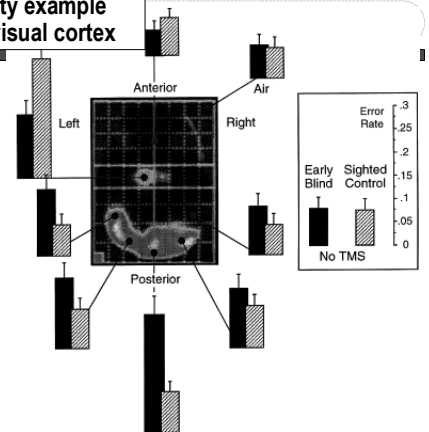
Driver and Noesselt 2008



Driver and Noesselt 2008

### Crossmodal plasticity example B1: tactile input to visual cortex

- repetitive TMS for virtual lesions
- errors during Braille reading for **early blind vs sighted subjects**
- error rates depend on site of virtual lesions
- cortical plasticity in early blind subjects

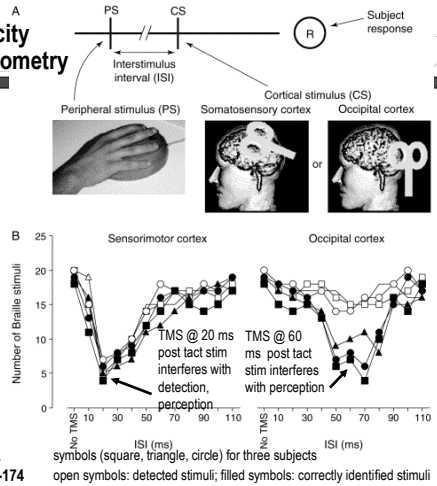


Cohen LG et al Nature 1997; 389: 180-183

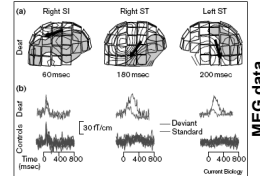
## Crossmodal plasticity example B2: chronometry

- crossmodal input to visual cortex
- single-pulse TMS
- early blind subjects
- real and nonsensical Braille stimuli presented via tactile stimulator
- subjects' task (a) detect stimuli (b) identify stimuli as real vs nonsensical
- conclusion: visual cortex contributes to tactile information processing in early blind subjects

Hamilton R, Pascual-Leone A. Trends Cogn Sci 1998; 2: 168-174

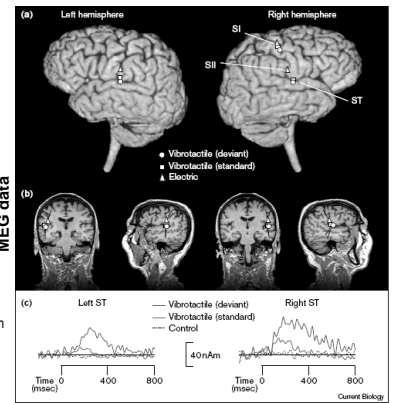


## Crossmodal plasticity example B3: Vibrotactile activation of auditory cortex in a congenitally deaf adult



(a) Field patterns (deviant vibrotactile stimuli) and (b) responses for all subjects, channels with max S1 and ST (supratemporal) cortex

Cortical sites activated in the deaf subject (a, b) Source areas projected onto individual MRI. (c) Time course of source strengths in the right and left ST cortices during vibrotactile stimuli, and when the subject did not hold his hand around the tube (control).



Levänen, Jousmäki and Hari, Curr Biol 1998

## Summary: crossmodal studies

	Multisensory and crossmodal processing in the normal brain	Crossmodal plasticity after sensory deprivation
audiovisual	Speech and non-speech stimuli in fMRI, MEG: activation of STS, IPS, SC [A1-A5] Sight-reading in musicians (MEG): visual notes activate auditory belt areas [A6]	
visuotactile		Braille reading affected by TMS to visual cortex in blind subjects [B1, B2]
audiotactile	Vibrotactile stimuli in fMRI, MEG: activation of auditory belt areas [A7]	Vibrotactile activation of auditory cortex in a deaf subject (MEG) [B3]

NB additional interaction with motor processes