



Inesperata accident magis saepe quam quae speres.
(Things you do not expect happen more often than
things you do expect) Plautus (ca 200(B.C.))



Project no: 027787

DIRAC

Detection and Identification of Rare Audio-visual Cues

Integrated Project
IST - Priority 2

DELIVERABLE NO: D5.4

Report on High-Level (Categorical) Audio-Visual Integration Results

Date of deliverable: 30.06.2007
Actual submission date: 07.08.2007

Start date of project: 01.01.2006

Duration: 60 months

Organization name of lead contractor for this deliverable:
Leibniz Institute for Neurobiology

Revision [1]

Project co-funded by the European Commission within the Sixth Framework Program (2002-2006)		
Dissemination Level		
PU	Public	X
PP	Restricted to other program participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	



Inesperata accident magis saepe quam quae speres.
(Things you do not expect happen more often than
things you do expect) Plautus (ca 200(B.C.))

D5.4 REPORT ON HIGH-LEVEL (CATEGORICAL) AUDIO-VISUAL INTEGRATION RESULTS

Leibniz Institute for Neurobiology

Abstract:

The work associated with this deliverable explores how audiovisual category transfer, a high-level from audiovisual integration, might provide a strategy of coping with the problem of rare event identification. An experiment is designed in which a suitable animal (rodent) model experiences a rare and unexpected visual event. It is demonstrated that previous experience with auditory stimuli might or might not give rise to a transfer of abstract rhythm categories learned in the auditory modality to the visual modality. While such transfer cannot in principle be considered a typical categorization problem (as will be discussed) it is an example of meaningful behaviour that is typical for certain biological organisms but has so far not been exploited for artificial cognitive systems. Here we present evidence derived from Granger-causality analysis that direct information transfer between auditory and visual cortex underlies the emergence of crossmodal transfer or the lack of it.

Table of Content

1.	Rare-Event Processing and Crossmodal Integration.....	4
1.1	The Problem and a Possible Strategy for its Solution.....	4
1.2	The Categorical Nature of Crossmodal Transfer	5
1.3	An Experimental Model for Audiovisual Integation Fostering Rare-Event Processing.....	5
2.	Material and Methods.....	7
2.1	Electrodes.....	7
2.2	Animals Preparation	7
2.3	Recordings	7
2.4	Stimuli	8
2.5	Test Measurements Before and After Training	8
2.6	Granger-Causality Analysis.....	8
3.	Behavioral Analysis.....	8
4.	Neurophysiologic Analyses	10
5.	Conclusion.....	12
	References.....	13

1. Rare-Event Processing and Crossmodal Integration

1.1 The Problem and a Possible Strategy for its Solution

In the present deliverable we report about an experimental strategy within DIRAC to investigate how *crossmodal sensory integration* might contribute to the solution of the *problems of rare-event processing*.

Rare-event processing faces two fundamental problems, the *detection* of a rare-event and the triggering of appropriate responses to that rare event - the latter is sometimes referred to as "*identification*" or "*classification*" of the event, although these terms might be misleading as to the nature of possibly underlying appropriate mechanism. This is because "rareness" of an event, in the sense of its occurrence being infrequent and/or unexpected, entails that it is not well represented in the "world model" of the cognitive system facing or experiencing a rare event. Biological cognitive systems (some animals including man) are apparently equipped with powerful mechanisms for detection of rare events as evidenced by both behavioural responses (e.g. orientation responses) and neuronal responses (e.g. the classical observables of the "oddball research programs", like the "P300" component of event-related brain potentials or the "mismatch negativity", and others). The larger problem for a cognitive system is the triggering of appropriate responses to such an event. Biological organisms typically show three types of responses to such events: The first type of response consists of *ignoring* the event. From an evolutionary viewpoint, this might in fact be a very economical strategy of dealing with such an event and biological organisms are known to more or less quickly return to their behaviours that have been interrupted by orientation responses or attentional responses when the rare event just had occurred. A second strategy is *avoidance*. Here a cognitive system might flee from the estimated source of the event, maybe as a measure of precaution. Note, that this strategy does not entail any deeper analysis of the event or its possible source, beyond "classifying" it as "potential danger" (or the like). In fact, such a strategy could even be prepared in an a-priori fashion and would then require no analysis of the event at all. Once a rare event is detected, both types of responses, ignorance and avoidance, can easily be implemented into artificial cognitive systems also. The avoidance strategy is for example represented by any form of alarm-signalling artificial system.

The third strategy is to *investigate* into the situation involving the rare event, usually with the aim of characterizing the possible source of the event further. This strategy is invoked by autonomous systems that can engage into a sort of "dialog" between itself and its environment and is highly developed in certain biological cognitive systems. Although this might require enormous amounts of flexible processing in any particular instance, the basic underlying strategy is nevertheless simple, in that it aims at making the rare "unclassifiable" event classifiable. Both biological and (autonomous) artificial cognitive systems can achieve this by *forming* and *testing* hypotheses about the event. The latter, the testing of an hypothesis, is done by autonomous behaviour, for example gathering new data from the environment or manipulating the environment and observing the effects of the manipulation, etc. What is currently less clear, is how biological cognitive systems achieve the former, the formation of hypotheses about an event which is unclassifiable by the current world model. This is a domain of cognitive behaviour that is associated with notions like "having the right instinct about something" or "making a brave decision" - notions that are currently insufficiently understood in biological systems and are hardly associated with artificial cognitive systems.

It has been proposed in DIRACs research program that crossmodal integration might be a potential strategy of biological cognitive systems to overcome the problem of unclassifiability of rare events. The "right instinct" in making sense of a rare event could be supported by information from a sensory channel that is (actually or apparently) unrelated to that event. It might nevertheless serve as a nucleus for forming the "right hypotheses" which will be pursued by further (autonomous) behaviour. One form of such crossmodal integration is the

transfer of learned meaning about certain features in one sensory modality to stimuli from another sensory modality. In case of a true unclassifiable event (i.e. an event which is not represented by the world model) the appropriateness of such a crossmodal transfer can only be "guessed", i.e. is of an a-priori nature. Only after experiencing the consequences of such a transfer, i.e. in an a-posteriori fashion, the appropriateness of the transfer can be evaluated. While the latter processes are well represented by both current biological research programs and engineering technologies, the underlying causes that determine whether such a transfer is invoked or not are only insufficiently understood in biological cognitive systems and yet not at all exploited for artificial cognitive systems.

It has been the aim of the present deliverable to establish an experimental strategy allowing the study crossmodal transfer in a biological system with the further aim of making the underlying principles available for artificial cognitive systems also.

Before this experimental strategy is explained in more detail, a discussion of how this research relates to other current research programs on multisensory processing seems appropriate.

1.2 The Categorical Nature of Crossmodal Transfer

In the previous section a special form of crossmodal integration, crossmodal transfer, was considered as a possible solution strategy to the problem of rare-event processing. In the present section the relation of this form of crossmodal integration with other, currently more commonly studied, forms will be discussed.

The investigation of crossmodal interaction begins with the selection of experimental conditions that should lead to the integration between sensory modalities. Straightforward, and often applied, is the approach to present stimuli of different modalities (e.g. auditory and visual) closely in space and time. It is then investigated which brain structures or neural processes are evoked and compared with what would be observed when the stimuli were presented alone [cf. Calvert et al. (2004) for an overview]. Conversely, in the present study, auditory and visual stimuli are to be integrated because they *share properties relevant to the response*. This is interesting in two respects: First, in this approach crossmodal integration is part of an intentional behaviour and not just the passive response of the brain as a consequence of stimulus presentation. Second, the cognitive process underlying the multisensory integration is *category formation*. The process of category formation, the abstraction of common features from the specific physical properties of objects, is one of the major solutions of the brain to cope with the diversity of things and can be regarded as absolutely basic to cognition (e.g. Kommatsu 1992; Ohl et al. 2001; Harnard 2005)

1.3 An Experimental Model for Audiovisual Integation Fostering Rare-Event Processing

The prime task of the present deliverable has been the development of an experimental paradigm of crossmodal integration fostering rare-event processing as described in section 1.1. The paradigm was established for an animal species, the rodent Mongolian gerbil (*Meriones unguiculatus*). This animal model seemed optimally suited for the intended paradigm since it has been demonstrated to be able to train in cognitively quite demanding tasks (e.g. Ohl et al. 2001, 2004; for review see Ohl and Scheich 2005 and Scheich et al. 2007). This ease in training and its easy availability make it preferable, for example, to monkey preparations. The model is also preferable to a human paradigm, mainly because it allows neurophysiological investigation of the underlying brain mechanisms by intracranial recording.

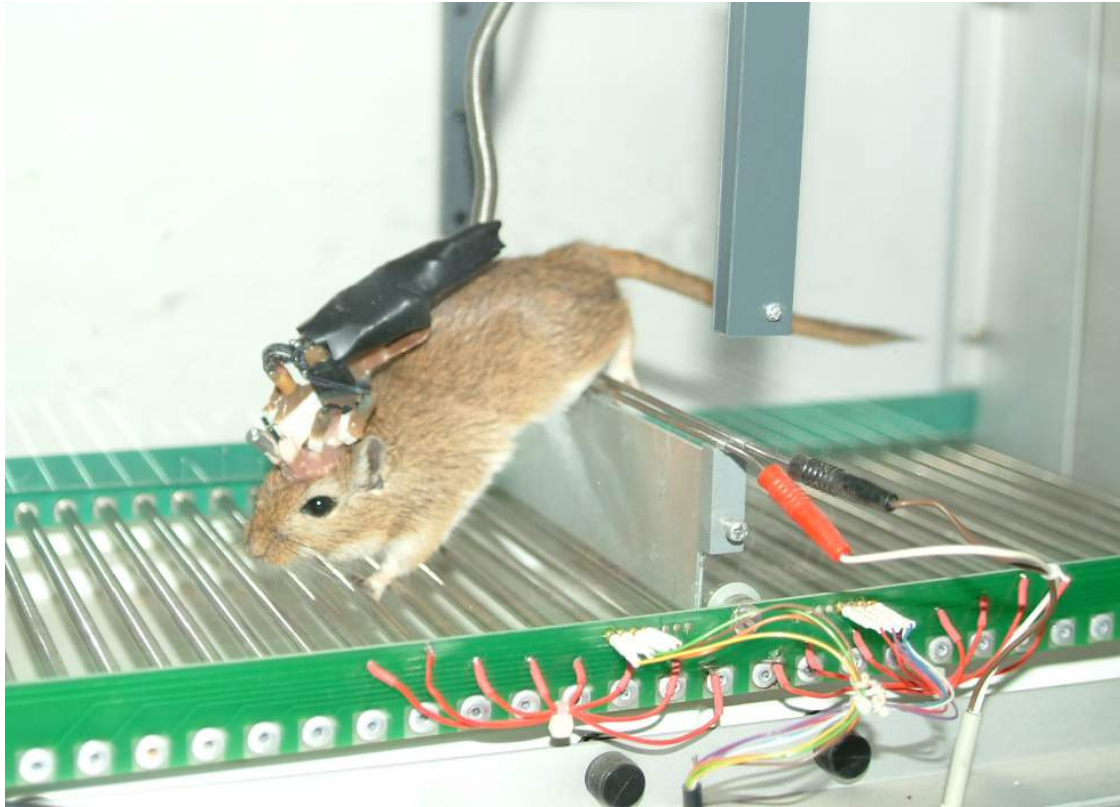


Figure 1. Audio-visual category transfer to foster appropriate rare event processing. A Mongolian gerbil, prepared for multichannel electrophysiological recording of brain activity, has perceived a fast blinking LED as a rare unexpected visual event for the first time in his life. His crossing of a little hurdle in his cage indicates that he transfers the abstract concept of rhythm categories (fast rhythm signal potential unpleasant current on the floor grid, slow rhythms signal safety) from the auditory modality (using tone beeps) to the visual modality.

In that paradigm, the sensory modalities involved are audition and vision. The rare event experienced by a gerbil is the light of an LED flashing at a certain repetition rate. The paradigm is so designed that the event is easily visible (so that stimulus salience is not an issue) but has never been experienced by a gerbil before. In that situation, a naïve gerbil will most likely show a behavioural orientation response and corresponding brain potentials in visual and central brain areas and might quickly return to whatever it has done before the event came on. This is different from behaviours and brain processes that can be observed in gerbils who had previously experienced that repetitive *auditory* stimuli (e.g. beeping tones) can be grouped into two categories: Auditory stimuli that are repeated at a fast rate (5.0 Hz) signal an unpleasant electric current through the metal floor grid following the tone beep series, while stimuli repeated at a slow rate (0.2 Hz) signal safety (or vice versa). The rare-event situation with the visual stimulus is potentially behaviourally relevant, because the animals have also learnt that they can totally avoid the unpleasant electric stimulus if they jump over a little hurdle separating two compartments in the cage before the tone beep series stops. How does this experience change the situation during the processing of rare unexpected *visual* event (Fig. 1)?

With respect to the discussion in section 1.1., note that it is not clear in an a-priori fashion whether the visual event might have a special meaning for the animal or not. In particular it is not clear whether any inferences from what has been learned about auditory stimuli might be drawn for this situation. It turns out, however, that some gerbils seem to make such an inference and show the hurdle crossing response while other individuals don't. The first group of gerbils transfers the rhythm categories (slow vs. fast) learned in the auditory modality to visual stimuli, the second group doesn't. Note that at this point (when this behaviour of the

gerbils does not yet yield any particular pleasant or unpleasant consequences) one cannot speak of appropriate or inappropriate behaviour; the situation merely demonstrates different strategies that different subjects employ. While the experimenter can of course set the rules which strategy would be optimal, the more interesting question is: What are the brain mechanisms that gave rise to transferring or not transferring the categories established in one sensory modality to the other when information about the appropriate strategy is not available, i.e. when the rare event is truly unclassifiable?

In our present work, in addition to observing the spontaneous decision of animal subjects when the rare event has occurred, the a-posteriori evaluation of the demonstrated behaviour by the subject is made possible by providing a reinforcement of the behavioural transfer or the lack of behavioural transfer.

2. Material and Methods

2.1 Electrodes

Arrays were prefabricated from stainless steel, Teflon-insulated wire pieces with a diameter of 25 μm and a length of about 2.5 cm. To obtain an interelectrode distance of about 100 μm the wire pieces were pushed perpendicularly through an electron microscopy grid and fixed with dental cement. The array implanted into the visual cortex was made up of two lines of five electrodes, one line of ten electrodes was used for the array implanted into the auditory cortex. The longer endings of the wire pieces were crimped with male connector pins (Molex Inc., Lisle, USA) and inserted into a plug housing (Molex Inc., Lisle, USA). Reference and ground electrodes were made from stainless steel wire with a diameter of 185 μm , one of the endings was crimped with pins (Molex Inc., Lisle, USA).

2.2 Animals Preparation

(Höchst AG, Frankfurt a.M, Germany), then a 0.3 ml solution of Ketamin-Rompun (0.45 ml Ketamin, 0.05 ml 2% Rompun, 0.5 ml 0.9% (istone) NaCl-solution) was injected intraperitoneally. The same solution was used to maintain anaesthesia by injecting 0.03 ml every 30 min subcutaneously.

After craniotomy the dura was cut and electrode arrays were inserted stepwise and along the dorsoventral axis into a radial depth of about 250-350 μm of the primary auditory and the visual cortex. After implantation, the craniotomy openings were covered with KY-jelly and sealed with dental acrylic cement.

The electrodes serving as a common reference or ground were implanted at two different sites (one about half-length between the two openings of the visual and auditory cortex, one into the sinus sagittalis superior above the prefrontal cortex).

At the end of the implantation the connector housings were fixed with dental acrylic cement

2.3 Recordings

Recordings were performed in an electrically and acoustically shielded chamber. The electrocorticogram was recorded monopolarly with respect to a common reference electrode. The signals were first fed into a FET preamplifier (gain 1, impedance matching) and then into a high-impedance amplifier with a gain of 10000. Each channel was bandpass-filtered with cutoff frequencies of 0.1 and 100 Hz and digitized at a rate of 1000 Hz.

2.4 Stimuli

Acoustic stimuli were 2 kHz tones presented at 65-70 dB SPL from a loudspeaker located above the shuttle box; visual stimuli were flashes from two LEDs positioned in the middle of the two longer sides of the shuttle box. For stimulus presentation, repetition rates of 0.25 Hz and 5 Hz were selected on the basis of the pilot auditory discrimination experiments reported in deliverable D-4-6. In the pretraining measurements additional stimuli with rates of 1.4 Hz and 2.3 Hz were presented.

2.5 Test Measurements Before and After Training

After one week of postoperative recovery test measurements started which were done at three consecutive days. At the first day the animals was familiarized with the shuttle box and stimuli were presented to check the conductance of the electrodes and the spike sorting. In contrast to the training sessions during the test measurements the animal was set into only one of two shuttle box compartments, an obstacle prevented the gerbil from jumping into the second compartment. In the next two pretraining measurements the same stimuli as during training (5 Hz and 0.25 Hz) and the also the 1.4 Hz and 2.3 Hz stimuli were presented but without shock.

The same measurements were also done after training.

2.6 Granger-Causality Analysis

Data were detrended, a 50 Hz notch filter was applied. The temporal mean of the prestimulus interval (6 s) was subtracted and the trial was divided by the temporal standard deviation of the prestimulus interval. Electroencephalogram data were averaged spatially across electrodes for both the visual and auditory array. A bivariate autoregressive model was fitted to the spatial average of auditory and visual arrays. The autoregressive coefficients were determined using the Nuttall-Strand algorithm. Trials were partitioned into 100 ms windows for which approximate stationarity can be assumed. Data windows were stepped through each trial in 20 ms intervals. The spectral content of the time series model was analysed using the directed transfer function (DTF, Kaminski & Blinowska, 1991) as explained in the deliverable D-5-1.

The peak of the DTF in the spectrum ranging from 1 to 100 Hz was determined for each data window. The differences of the peak of the DTF from visual to auditory cortex (in the following: VA-DTF) and from auditory to visual cortex (AV-DTF) was determined. Data analysis was done separately for windows with a higher peak of the VA-DTF and windows with a higher peak of the AV-DTF. Significance of effects was assessed using the student two-sample t-test (see for example Efron & Tibshirani, 1993).

3. Behavioral Analysis

Animals were trained in the shuttle box using an active avoidance GO/(NO-GO) paradigm in two subsequent training blocks.

First, animals were trained in an *auditory* paradigm developed in the deliverable D-4-6 (for details see there) to discriminate the repetition rate (0.2 Hz vs 5.0 Hz) of pure tone sequences. Misses (failures to show a GO response to the CS+) and false alarms (erroneous GO responses to the CS-) were punished by mild electrical foot shocks applied to through the floor grid of the shuttle boxes.

Expectedly, animals in the present experiment showed similar asymptotic performance levels and learning speeds as the animals used in the experiment of deliverable D-4-6, although the preparation in the present experiment (depth recording arrays in auditory and visual cortex)

differed somewhat from the unimodal auditory experiment (surface recording arrays only in auditory cortex).

After animals reached asymptotic performance in the discrimination of auditory repetition frequencies, they were transferred to the second training block in which repetition frequencies of LED-delivered light flashes had to be discriminated. Demonstration or lack of transfer of the learned auditory stimulus contingencies in the first encounter of the visual stimulus (when it was still a novel and rare event) were protocolled.

Since omission of any behaviourally relevant reinforcement would quickly lead to extinction of behavioural orientation responses and physiological oddball responses (cf. the "*ignoring strategy*" introduced in section 1.1.), the second block of the training was continued with delivery of a foot-shock reinforcement as in the first, auditory, training block. This was done in two ways: In one experimental group (*contingent group*) the fast and slow repetition rates had corresponding meaning for the auditory and visual stimuli, i.e. had to be responded to with the corresponding GO and NO-GO responses, respectively. In a second experimental group (*incontingent group*) the meaning of the repetition rates for the visual stimuli was reversed to the meaning they had for the auditory stimuli. This allowed to establish whether the learned associations between *auditory* stimuli and their meaning in the shuttle-box environment can foster the formation of corresponding associations between *visual* stimuli and their meaning (Fig. 2).

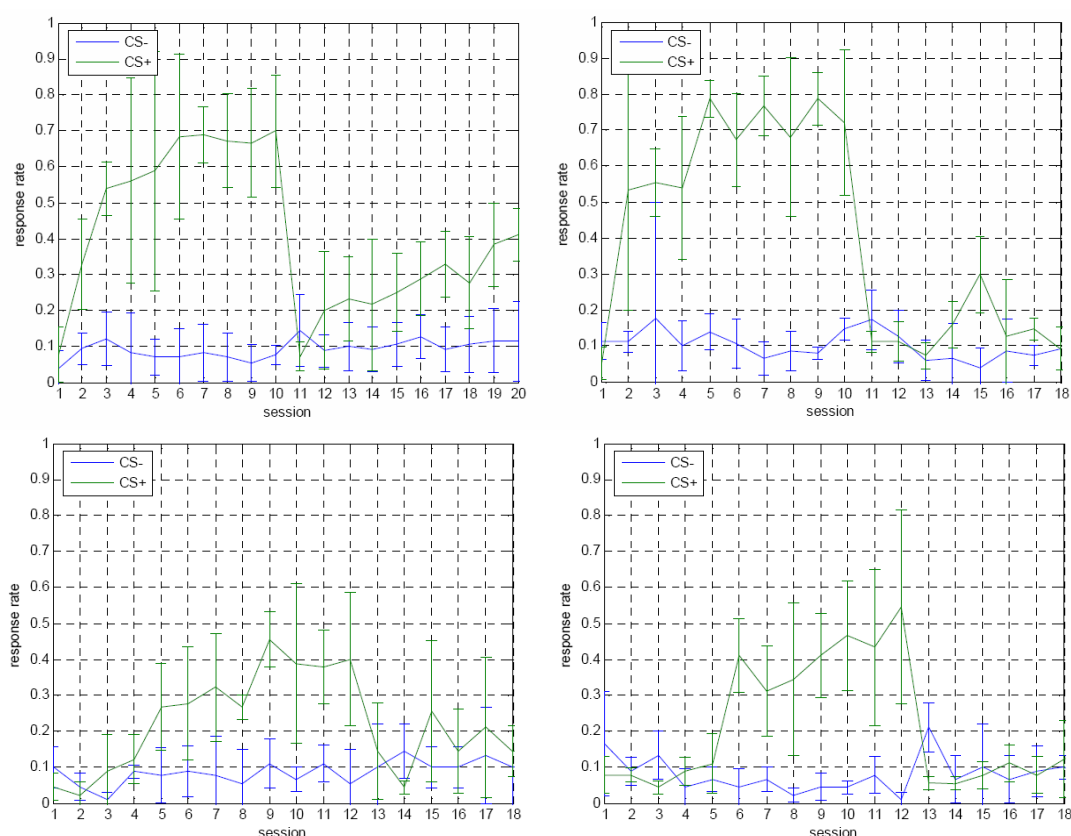


Figure 2. Audiovisual transfer or rhythm categories under contingent and incontingent reinforcement. A Contingent group, "learners"; B Contingent group, "non-learners"; C Incontingent group, "bad learners"; D Incontingent group, "non-learners".

In the contingent group, all animals (n=15) reached significant discrimination of tone repetition rates in the second or third training session ($\chi^2 > 6.62$, $p < 0.01$). The discrimination of flash repetition rates turned out to be more difficult for the animals: Seven animals were able to learn the discrimination (Fig 2A). For 3 animals the discrimination was significant

already in the second or third visual training session ($\chi^2 > 6.62$, $p < 0.01$; $\chi^2 > 3.83$, $p < 0.05$ in third and fifth visual training session (one animal)). For the remaining animals it took 3-4 more sessions to reach significant performance. But also for these animals hit rates tended to be higher than false alarm rates in earlier sessions (Fig. 2B). This might be evidence that even for these animals learning already started during the first sessions of visual training.

In the incontinent group (the group trained with a reversed contingency across modalities) seven animals were trained. Significant discrimination of tone repetition rates was observed in all animals from third to sixth session (animals had to respond to slower tone rates in this group) ($\chi^2 > 6.62$, $p < 0.01$). During visual training, three animals succeeded in learning the discrimination (Fig. 2C): one animal showed significant discrimination in 13th and 15th session ($\chi^2 > 6.62$, $p < 0.01$; $\chi^2 > 3.83$, $p < 0.05$), then stopped this behaviour in the following four sessions and regained significant performance from 20th onwards. The second animal started to respond significantly from 19th session on ($\chi^2 > 6.62$, $p < 0.01$; $\chi^2 > 3.83$, $p < 0.05$). Three animals failed to show any significant performance (Fig. 2D).

These results demonstrate, that the devised paradigm does indeed represent an example of crossmodal (audiovisual) integration as fostering rare-event processing. Upon first encounter of a rare visual event, gerbils might demonstrate or might not demonstrate a spontaneous transfer of learned rhythm categories (slow or fast repetition frequencies) to the visual stimuli. As discussed in sections 1.1. and 1.3. neither behaviour can be considered more appropriate than the other at this point of the event processing. These behaviours do not reflect the usual categorizations of stimuli based on comparison of stimulus features with the internal model but represent non-categorical, "instinctive" (in the sense specified in section 1.1.). Nevertheless, brain mechanisms must exist that gave rise to them and have led to the one or other decision. This will be explored in more detail in the next chapter.

When after the rare-event experience subsequent behaviour is reinforced in a contingent or incontinent manner, behavioral performance in response to the visual stimuli is higher in the contingent group. This provides an independent demonstration that a transfer of learned categories from the auditory to the visual modality has occurred and might underlie the selection of the response strategy to the rare event.

4. Neurophysiologic Analyses

The aim of the neurophysiological analysis of the presented experiment aims at unravelling neuronal mechanisms underlying the transfer or lack of transfer of rhythm categories learned in the auditory modality to the visual modality.

Presently we are using Granger causality analysis (cf. deliverable D-5-1) to detect directed information transfer between the auditory and visual cortex. Granger causality analysis is based on the insight that causes always precede their consequences in time. If the prediction of one process is improved by data from another process, this second process is said to "Granger cause" the first process. Practically, k parallel processes

$$X(t), \quad X \in R^k$$

are modelled by a multivariate autoregressive process of order p

$$X(t) = \sum_{i=1}^p A(i)X(t-i) + E(t)$$

which is usually expressed in the frequency domain as

$$A(f)X(f) = E(f)$$

$$\text{with } A(f) = -\sum_{j=0}^p A(j) \exp(-i 2\pi j) \text{ and } A(0) = -I .$$

Since the inverse of the Fourier-transformed coefficient matrix can be formally considered the transfer matrix $H(f)$ of a linear system

$$X(f) = A^{-1}(f)E(f) = H(f)E(f)$$

its magnitude, called the directed transfer function (DTF),

$$\Theta_{ij}^2(f) = |H_{ij}(f)|^2$$

represents the Granger-causal influence of channel j to channel i . From this magnitude the normalized DTF (Kaminski and Blinowska 1991) is obtained by normalizing with respect to the joint influences from all other channels to channel i .

$$\gamma_{ij}^2(f) = \frac{|H_{ij}(f)|^2}{\sum_{m=1}^k |H_{im}(f)|^2} .$$

Figure 3 shows representative data of directed transfer functions from auditory to visual cortex (red) and from auditory to visual cortex (black) in various experimental phases.

Data from naïve gerbils yield consistently low values of causality with no prominent peaks at particular frequencies (top row). In addition to representing a "baseline measurement" for transcortical crosstalk this result indicates that in the naïve subject no significant directed transfer, and hence no cross-talk, between auditory and visual cortex existed. This was true for both auditory and visual stimulation. In contrast, gerbils that have formed the auditory categories but do not transfer them to visual stimuli show significant directional cross-talk (bottom row). The direction of this interaction is always from the directly excited cortex (auditory cortex during auditory stimulation, visual cortex during visual stimulation) to the corresponding not-excited cortex and does not show conspicuous peaks at particular frequencies. This is the characteristic of a passive system. Gerbils that *do* transfer the auditory categories to visual stimuli show a clear directional interaction with a clear peak in the gamma range (30-60 Hz) of brain activity at least from the cortex of the excited sensory modality to the other cortex but sometimes also in both directions (left and right, middle row).

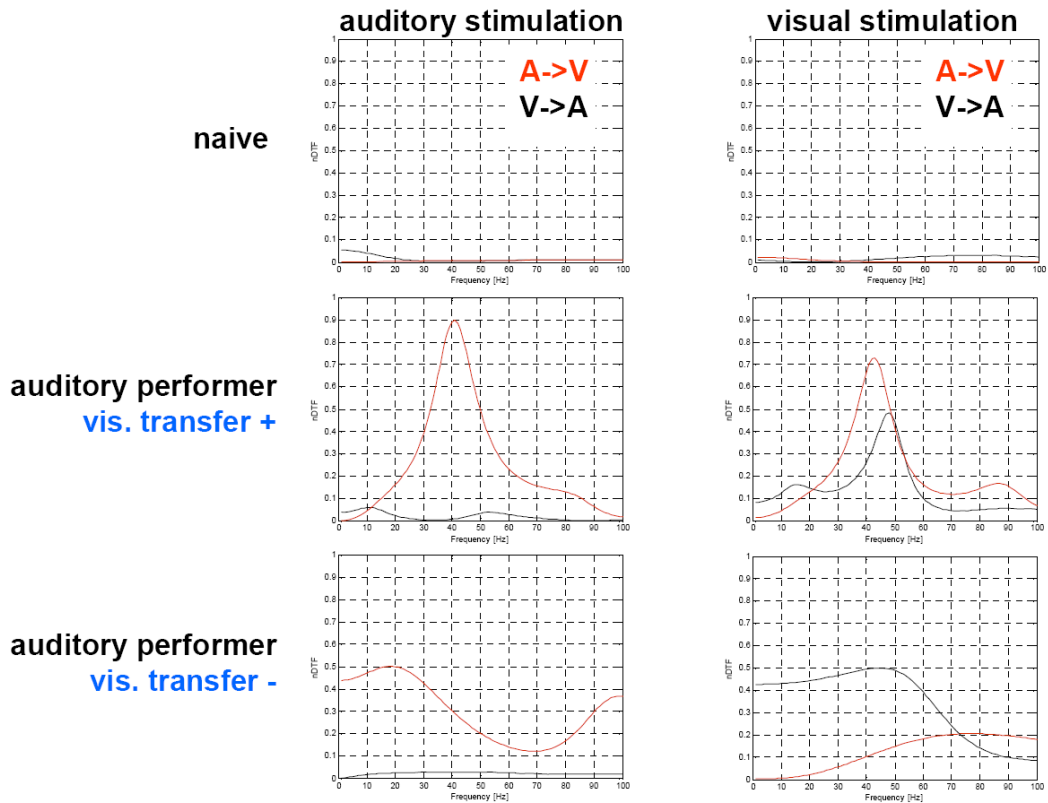


Figure 3. Analysis of electrophysiological data during audio-visual category transfer. Representative data about directional brain interaction from auditory to visual cortex (A->V) or from visual to auditory cortex (V->A) in various phases of the experiment. For explanation see text.

5. Conclusion

The behavioral data indicate that the designed experimental paradigm is suitable for the study of audiovisual concept transfer as a strategy to cope with the problem of rare-event identification, i.e. the meaningful interpretation of a rare event, although that interpretation cannot be based on a feature analysis of the internal world model as is the case in standard categorization tasks. Furthermore, Granger-causality analysis applied to recordings of depth electrocorticograms have indicated that direct information transfer between auditory and visual cortex might underlie the crossmodal concept transfer. With the fundamental paradigm designed, future work will focus on improved statistical testing of the significance of normalized DTF functions.

References

- Calvert GA, Spence C, Stein BE [eds] (2004) The handbook of multisensory processes. The MIT Press, Cambridge, MA, USA.
- Efron B, Tibshirani RK (1993) An introduction to the bootstrap. Chapman and Hall, New York.
- Fillbrandt A, Deliano M, Ohl FW (2007) Audiovisual category transfer - an electrophysiological study in rodents. Proc. 7th Göttingen Meeting of the German Neuroscience Society, T28-9B.
- Harnad S (2005) To cognize is to categorize: Cognition is categorization. In Cohen H, Lefebvre C (eds) Handbook of categorization in cognitive science. Elsevier, Amsterdam.
- Kaminski MJ, Blinowska KJ (1991) A new method of the description of the information flow in the brain structures. *Biol Cybern* 65: 203-210.
- Komatsu LK (1992). Recent views of conceptual structure. *Psychol Bull* 112: 500-526.
- Ohl FW, Scheich H, Freeman WJ (2001) Change in pattern of ongoing cortical activity with auditory category learning. *Nature* 412: 733-736.
- Ohl FW, Scheich H (2004) Fallacies in behavioural interpretation of auditory cortex plasticity. *Nature Reviews Neurosciences* (reviewed online comment, doi:10.1038/nrn1366-c1).
- Ohl FW, Scheich H (2005) Learning-induced plasticity in the auditory cortex. *Curr Opin in Neurobiol* 15: 470-477.
- Scheich H, Brechmann A, Brosch M, Budinger E, Ohl FW (2007) The cognitive auditory cortex: task-specificity of stimulus representations. *Hear Res* 229: 213-224.