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The timing of processing along the visual pathway in the cat

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WE obtained visual response latencies and response durations following visual stimulation of neurones recorded in the lateral geniculate nucleus (LGN), areas 17, 18, 19, the posteromedial lateral suprasylvian sulcus (PMLS), and area 7 of the cat. We found an increasing lengthening of the mean response latencies, consistent with the view of a progressive advance of processing from stage to stage. However, we also observed a substantial and increasing scatter in these latencies. Moreover, response durations vastly supersede this gradual increase in latencies. Taken together, these results suggest that most of the neurones within different stages of a hierarchically organized sensory pathway are simultaneously active when stimulated. Implications of a time-based processing scheme for models of information processing in highly interconnected, multi-layered systems are discussed.

Key words: LGN; Visual areas 17, 18, 19; Lateral suprasylvian areas; PMLS; Area 7; Visual latencies; Time dependent receptive fields; Temporal distributed processing

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Introduction

Sensory systems of higher mammals represent typical examples of multi-layered systems. Their architecture consists of sets of multiple, highly interconnected stages that allow serial and parallel processing of sensory information. This has been especially well-documented for the primate visual system.[1] Here, the most common properties of a sensory pathway are briefly outlined for the cat visual system.[2,3] Based on the pattern of thalamocortical connections, both areas 17 and 18 are regarded to represent parallel stages of primary areas, directly and independently receiving input from the lateral geniculate nucleus (LGN). The same is essentially true for area 19, however, it is regarded to occupy a somewhat different position in the processing stream since it receives also input from the LP pulvinar complex. This part of the visual thalamus located more medial to the LGN in turn receives input from the midbrain and backprojections from areas 17, 18 and 19.[3] By contrast, the lateral suprasylvian visual areas clearly represent a different, more intermediate level of processing, as they receive their main input from the LP Pulvinar complex and from areas 17, 18 and 19, while the LGN input remains marginal. The functional role of PMLS is thought to be related to the processing of motion in 3D space including the interactions between figure and ground,[4] a role comparable to monkey mediotemporal cortex (MT). There is general agreement that in cats the main input to the extrastriate areas is of the y- and w-type with the x-type input exclusively relayed via area 17.[5] Area 7 can be regarded as an example of advanced cortical processing, as it receives its main input from the lateral posterior Pulvinar complex (LP) via the Pretectum (PT) and the Superior Colliculus (SC). It is thought to play a role in updating a central neural image of the surrounding behavioural space and in preserving a perceptual constancy of the environment during body movements, as has been suggested for the IPL in monkeys.[6] The overall hierarchical arrangement of the visual areas is present in cats, although not as clearly defined as for the corresponding areas in the primate visual system.[1]

Important physiological indicators to establish the functional, hierarchical roles of different visual areas in the processing of visual stimuli are the absolute timing conditions of processing along the different stages of the visual system. On a psychophysical level, reaction times can provide a means to establish limits for absolute time scales and ranges of various aspects of visual information processing. In order to understand the neural timing at different stages within a largely hierarchical processing stream and to understand the temporal constraints imposed by multi-layer systems, we explored visual response latencies and response durations following visual stimulation in the LGN (example of subcortical processing), areas 17, 18 and 19 (examples of early cortical processing), area PMLS (example of intermediate cortical processing) and area 7 (example of advanced cortical processing). Previously described details[2,3,5] of the connectivity and projectional patterns between these substrates suggest that these areas cover at least 3 to 4 different levels of information processing.

Materials and Methods

For a general account of our methods see reference 7. Cats (2.5–3.4 kg) were anaesthetized for surgery with 25 mg kg^{-1} ketamin hydrochloride (Vetalar, Parke Davies) in combination with 1.5 mg kg^{-1} Xylacin (Rompun, Bayer). A metal head-holder was cemented on to the exposed skull to allow fixation without earbars and eyeclamp. A craniotomy was performed

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dependent on the required target area (LGN, areas 17, 18, 19, 7, PMLS), leaving the dura intact. All pressure points and wound margins were infiltrated with a local anaesthetic (Xylocain). The animal was then immobilized by injection of 15 mg kg^{-1} Flaxedil (Deutsche Abbott) and artificially ventilated with a mixture of nitrous oxide (70%) and oxygen (30%). Artificial ventilation was continued and the animal was infused with Flaxedil (10 mg kg^{-1} h^{-1}) and with a mixture of dextrose and fructose in a solution of various electrolytes (Sterofundin). Small dosages (3–9 mg h^{-1} of pentobarbital (Nembutal) were delivered intravenously. The body temperature was kept at 37.5 to 38°C, ECG and endexpiratory CO_2 (Binos 1) were continuously monitored; the latter was maintained at 3.5% to 4%.

Tungsten microelectrodes (impedance 2 to 10 MΩ) were used to record extracellular single neurone activity. Recordings made outside of areas 17 and 18 were later histologically verified.[7] Action potentials were conventionally amplified and converted by window discrimination into TTL pulses and stored on computer hard disk. As a rule, receptive fields (RFs) of neurones recorded in LGN and areas 17, 18 and 19 were within 5 degrees of the area centralis projection. RFs of PMLS and area 7 neurones were within 10 degrees. The cortical responses to stimulation of the dominant eye were tested. First, the spatial RF structure was determined by handplotting. The subsequent quantitative analysis was done using a bright stimulus adjusted to cover the entire excitatory parts of the RFs. Stimuli were projected from the rear on to a screen 1 m in front of the animal and were flickered at repetition rates of 0.2 or 0.4 cps (1250 ms on- and 1250 ms off-stimulation, or 2500 ms on- and 2500 ms off-stimulation) and presented 16 to 64 times. Background luminance was kept constant at 0.2 cd/m^2; the luminance of the stimulus was 35 cd/m^2. The latency and the duration of the visual response were calculated on the basis of PSTH analysis using 2 ms bin-width resolution. The latency was defined as the time elapsing between the onset of stimulation (light on) and the time-window containing a maximal number of spikes (peak latency), a method that has been proven to give highly reliable estimates of visual latencies.[8] The duration of the response was defined as the time elapsing between the onset and termination of the response, using a criterion of two times standard deviation of spontaneous activity.

Results

Results were from a total of 409 recording sites in LGN (n = 68), area 17 (121), area 18 (64), area 19 (75), PMLS (66), and area 7 (15). The mean response latencies and response durations following on-responses for each processing stage are shown in Table 1 and the underlying distributions are illustrated in Figure 1. Since we employed the same experimental conditions,

TABLE 1. Mean response latencies and response durations

	LGN	area 17	area 18	area 19	PMLS	area 7
mean latencies [ms]	37.9	52.7	40.4	93.6	66.7	83.5
standard deviations	7.1	19.5	9.4	29.6	23.2	31.8
mean durations [ms]	280	208	284	245	236	175
standard deviations	155	127	103	98	124	80

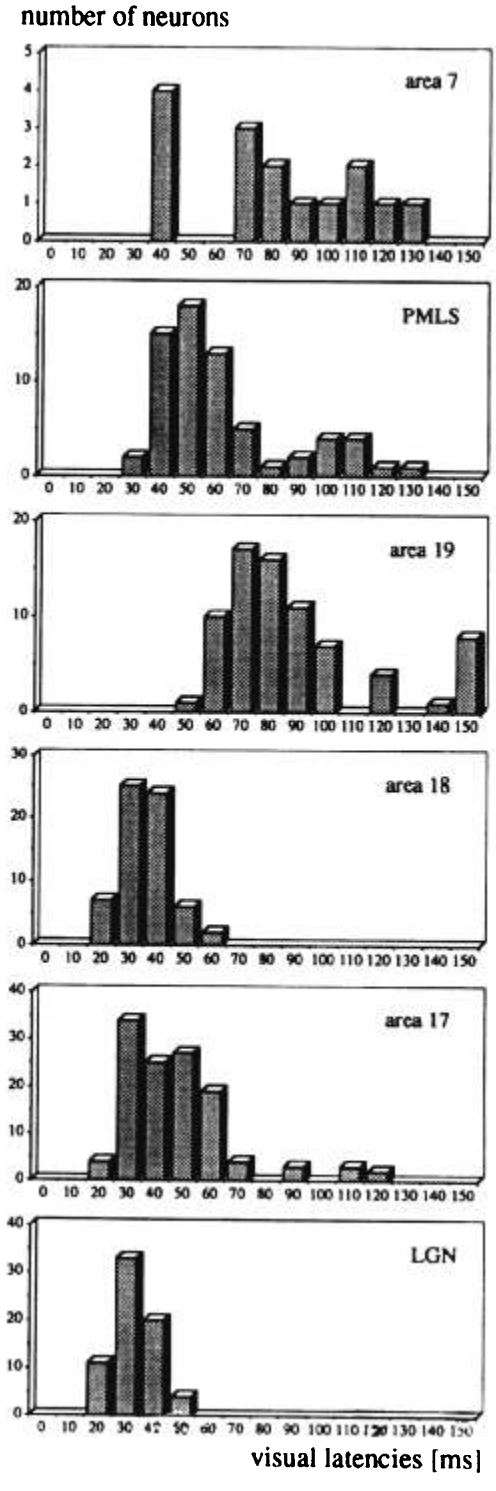

FIG. 1. Latency distribution of neurones following stimulation with on-stimuli (flickered at 0.2 or 0.4 cps) recorded in different stages within the visual pathway.

TABLE 2. Significancies of area-specific latencies

	area 17	area 18	area 19	PMLS	area 7
LGN	<0.00001	0.09739	<0.00001	<0.00001	0.00008
area 17		<0.00001	<0.00001	0.00006	0.00228
area 18			<0.00001	<0.00001	0.00013
area 19				<0.00001	0.26600
PMLS					0.07040

type of stimuli, and same response criteria for all neurones tested, a cross-areal comparison seems justified. Typical PSTHs of neuronal responses recorded in different areas are shown together with the timecourse of stimulation in references 9, 10.

Table 2 shows the p-values for a 2-sample assuming unequal variance t-test for the mean latencies between the areas. The differences between mean latencies between area 18 and LGN, between area 19 and area 7 and between PMLS and area 7 were not significant for a level of $p < 0.05$, all the other area specific mean latencies differed significantly. The latency data indicate an increasing lengthening of the mean latencies in the following order: LGN < area 18 < area 17 < PMLS < area 7 < area 19. With the exception of area 19, this sequence is compatible with the hierarchical sequence indicated by connectivity studies.[2,3,5,11] Latencies of area 19 neurones were considerably longer than those encountered in all other areas indicating special response properties of area 19 neurones and a specific position in the visual pathway.

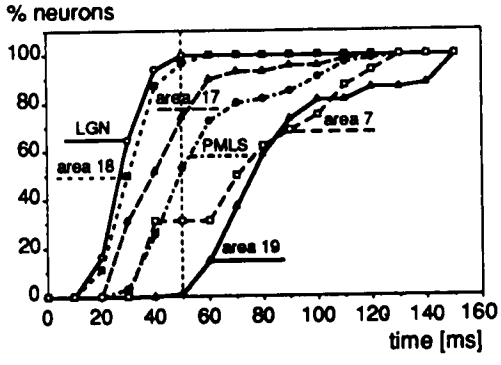

FIG. 2. Probability functions as obtained from the distributions of latencies for units of the LGN, areas 17, 18, 19, 7 and PMLS illustrating the probability of firing onset in all areas tested. Abcissa: time; ordinate: % of activated neurones.

As indicated by the large standard deviations and the shape of the distributions, there is a substantial scatter of latencies in each stage. This is documented in the probability histograms (Fig 2), illustrating the probability of firing onset in all areas tested. Within 50 ms after visual stimulation, all LGN neurones, 97% of the units of area 18, 74% of the units of area 17, 53% of the units of PMLS, 31% of the units of area 7 and 1% of area 19 neurones started firing.

Latency analysis is restricted to explain the condition when cells start firing. In order to obtain a more comprehensive estimate of the cells firing behaviour over time, we additionally analysed the cells response durations. Taking into account the mean latencies and the mean response durations of each substrate, we calculated the percentages of cells that are activated following visual stimulation (Fig. 3). The results indicate that the chain of processing across a multi-layered

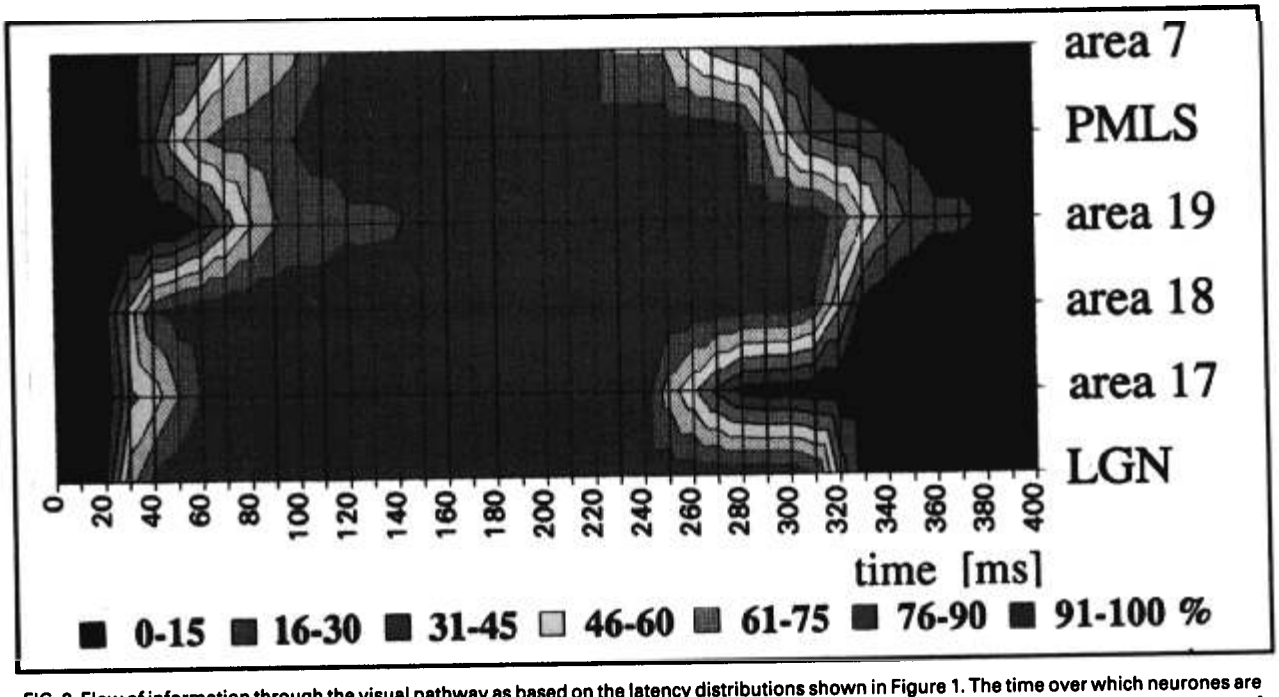

FIG. 3. Flow of information through the visual pathway as based on the latency distributions shown in Figure 1. The time over which neurones are active following visual stimulation was calculated on basis of the mean response durations found in each area. Shown are the percentages of neurones in each stage that are activated.

sensory pathway seems to be activated in a temporally continuous fashion. The high percentages of simultaneously activated neurones makes it rather unlikely that proceeding stages wait until the end of the processing of a previous one. On the contrary, the results favour a temporally continuous activation scheme across all stages of the visual pathway.

Based on the probability histograms (Fig. 2) and the information flow diagram (Fig. 3), it is possible to calculate a mean transmission time for the visual information to reach the next processing stage. Depending on the percentage of cells taken as a marker, this time is in the range of 5 to 15 ms.

Discussion

The fairly smooth progression of visual peak latencies seems to support the hierarchical nature of the cat visual pathway, as assumed from projectional and connectivity patterns. However, the fairly large scatter in peak latencies within each station suggests a high degree of overlap of peak latencies across all studied areas. One aspect contributing to the considerable differences between latencies of the same stage might reflect differences in the x-, y- and w-projections, which in the cat, reflect a predominant system of parallel processing.[5] However, based on the analysis of visually evoked responses for LGN x- and y-type neurones it was concluded that the conduction advantage of the y-pathway already at the level of the LGN seems to play a minor role in the detection of visual stimuli by the cat.[12] On the other hand, the observed long latencies of area 19 neurones are compatible with the predominant w-type input in this area[5] and the aspects of its special phylogenetic properties.[11]

It can be concluded from this study that according to the considerable high percentages of overlap in the latency distributions, most of the neurones within different stages of the visual pathway are simultaneously active when stimulated. This view of a virtually simultaneous activation across the entire pathway is further substantiated by the timing conditions in other modalities, which are characterized by much shorter response latencies. For example, mean response latencies in the primary auditory cortex (AI) are in the range of 10 to 15 ms, giving rise to latency differences between subcortical structures and AI of only a few milliseconds.[13] Similar considerations hold for the somatosensory system,[14] providing further arguments that differences in latencies reflect mainly conduction times with little emphasis on processing times.

The simultaniety in processing for LGN and areas 17 and 18 neurones (activation of all LGN neurones coincides with activation of 97% of the units of area 18 and 74% of the units of area 17) is especially striking as here rather distinct processing stages are involved (thalamus-cortex). Accordingly, the thalamocortical feedback loop must be assumed to be operating during most, if not during the entire duration of the neuronal responses. This is in contrast to a scheme in which feedback from the cortex starts to take effect after the thalamic cells stopped firing.

In order to demonstrate that the basic properties of the temporal flow of information as illustrated in Figure 3 are rather robust against variations or differences in the overall response durations, we recalculated the data based on a 40 ms response duration which can be assumed to capture only the very first transient response components. We obtained very similar results as shown in Figure 3, however, on a shorter time scale.

Reports concerning response latencies measured in monkey inferotemporal cortex (IT), an area which is regarded as an example of a sophisticated high-end substrate for processing of complex visual objects, were inspected following stimulation with faces[15] and complex geometric patterns.[16] According to these data, latencies in the range of 100 ms are a common finding. This fits remarkably well into the outlined framework of a continuous, interareal interaction that is essentially time-based. Together with reports about monkey V1 latencies, which are fairly similar to cat area 17 neurones,[17] an argument can be made that the same principles of a temporally distributed processing might hold for the primate visual system as well.

In view of these findings, the chain of processing along the visual pathway seems to be activated in a temporally continuous fashion. The high percentage of simultaneously activated neurones, makes it rather unlikely that later stages wait until the processing of a previous one has ended. Rather, a continuous activation scheme that links together all stages of the processing path seems to be more plausible. It is suggested that the first available information about external stimulation is fed without substantial delay through the entire pathway. This might reflect the feedforward aspects of the response characteristics. However, after this initial response component, different types of lateral interactions of excitation and inhibition and feedback mechanisms come into play. Among these are the thalamo-cortical feedback, the intracortical feedback and the feedback from higher areas. The time required for these actions to take effect might be variable for each of the described mechanisms and might depend on the type of stimulation. Taken together, these temporally delayed influences can be assumed to modify to a considerable but variable degree the informational content being processed. It seems therefore conceivable that neuronal responses are changed systematically over time, thereby potentially rendering late components different from early ones. Accordingly, these on-going interareal interactions can account for time dependent receptive field properties which have been demonstrated over the past for different sensory modalities.[9,10,18–22] Dynamic receptive field properties all have in common that late response components differ substantially and systematically from early ones

and are often found to carry either high-level or modified selectivities, both not present in the early components. Further support comes from experiments in IT and V1 of behaving monkeys revealing reproducible patterns of highly temporally modulated responses.[16,23]

The functional significance of our observation that most neurones are simultaneously activated over a considerable period of time (Fig. 3) is possibly reflected in human reaction time measurements. It is well established that a simple detection of stimuli can be performed within the shortest range of reaction times (about 200 ms), whereas recognition and discrimination of even simple geometric patterns leads to considerable lengthening in reaction times to the range of 400 to 500 ms. The initial activation reflected in the shortest latencies might thus correspond to recognizing the appearance of a stimulus. The stimulus evaluation, however, takes significantly longer, which is reflected in the fact that most neurones continue firing for a considerable period of time. Finally, this hypothesis is not restricted to sensory pathways but might be valid for multi-layer feedback systems in general. It remains to be seen whether retinal processing, which is also organized as a multi-layer system, follows a similar principle. Considering theoretical and technical applications, the observed lack of wait-states bears interesting implications for multi-layer models of brain function that rely on sequential processing.

Conclusions

We analysed the temporal flow of information in 6 different stages of the cat visual pathway, based on response latencies and response durations of single cells of these areas. Under the assumption that the mean transmission times of about 5 to 15 ms between different stages reflect mainly conduction times and synaptic delays, but with little emphasis on processing times, we found no indication for a sequential processing in the sense that some information is extracted at a given stage and the results of that processing are then used as inputs for processing in subsequent stages. On the contrary, the high percentage of simultaneously activated neurones suggests a continuous and simultaneous mode of activation across the entire visual pathway.

References

1. van Essen DC. Functional Organization of Primate Visual Cortex. In: Peters A, Jones EG, eds. *Cerebral Cortex Vol 3, Visual Cortex*. New York: Plenum Press, 1985: 259–329.
2. Rosenquist AC. Connections of visual cortical areas in the cat. In: Peters A, Jones EG, eds. *Cerebral Cortex Vol 3, Visual Cortex*. New York: Plenum Press, 1985: 81–117.
3. Graybiel AM and Berson DM. Families of related cortical areas in the extrastriate visual system: Summary of an Hypothesis. In: Woolsey CN, ed. *Cortical Sensory Organization*. New Jersey: Humana Press, 1981: 103–120.
4. Krüger K, Kiefer W, Groh A *et al. Exp Brain Res* **97**, 40–60 (1993).
5. Dreher B, Leventhal A and Hale PT. *J Neurophysiol* **44**, 804–826 (1980).
6. Joseph JP and Giroud P. *Exp Brain Res* **62**, 355–362 (1986).
7. Dinse HR and Krüger K. *Exp Brain Res* **82**, 107–122 (1990).
8. Best J, Reuss S and Dinse HR. *Brain Res* **386**, 356–360 (1986).
9. Dinse HR, Krüger K and Best J. *Concepts in Neuroscience* **1**, 199–238 (1990).
10. Dinse HR, Krüger K, Mallot HA *et al.* Temporal structure of cortical information processing: Cortical architecture, oscillations, and non-sparability of spatio-temporal receptive field organization. In: Krüger J, ed. *Neuronal cooperativity*. Freiburg: Springer Verlag, 1991: 68–104.
11. Diamond IT and Hall WC. *Science* **164**, 251–262 (1969).
12. Troy JB and Lennie P. *Exp Brain Res* **65**, 703–706 (1987).
13. Phillips DP and Irvine DRF. *J Neurophysiol* **45**, 48–58 (1981).
14. Armstrong-James M, Fox K and Das-Gupta A. *J Neurophysiol* **68**, 1345–1358 (1992).
15. Tovee MJ, Rolls ET, Treves A *et al. J Neurophysiol* **70**, 640–654 (1993).
16. Richmond BJ, Optican LM, Podell M *et al. J Neurophysiol* **57**, 132–146 (1987).
17. Bartlett JR and Doty RW. *J Neurophysiol* **37**, 621–641 (1974).
18. Aertsen A and Johannesma P. *Biol Cybern* **42**, 133–143 (1981).
19. Eggermont JJ, Aertsen A, Hermes DJ *et al. Hearing Res* **5**, 109–121 (1981).
20. Dinse HR and Schreiner CE. *Soc Neurosci Abstracts* **18**, 150 (1992).
21. Dinse HR, Spengler F, Godde B *et al.* Dynamic aspects of cortical functions: Processing and plasticity in different sensory modalities. In: Aertsen A, ed. *Brain Theory: Spatio-temporal aspects of brain functions*. Amsterdam: Elsevier, 1993: 209–230.
22. Eckhorn R, Krause F and Nelson JI. *Biol Cybern* **69**, 37–55 (1993).
23. Richmond BJ, Optican LM and Spitzer H. *J Neurophysiol* **64**, 351–369 (1990).

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