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Enhanced masking response to light in hamsters with IGL lesions

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Abstract Syrian hamsters with intergeniculate leaflet or sham lesions were given tests with a series of light pulses of gradually decreasing intensities. The light pulses were given early in the night, at zeitgeber time 14–15. The amount of wheel running during the pulses was compared to that in the same hour on a night with no light pulses. Hamsters with intergeniculate leaflet lesions showed a significantly greater suppression of their wheel running in response to light than the sham-lesioned animals. The lesioned animals also had larger negative phase angles of entrainment to the 14:10-h light-dark cycle than sham-operated controls. However, phase shifting in response to light pulses at either zeitgeber time 14 or 18 was not significantly altered by the lesions. Preferences for spending more time in a dark than a light area were not abolished by the lesions. It is concluded that the intergeniculate leaflet in the Syrian hamster cannot be of paramount importance for masking of locomotor activity by light but may play a modulating role.

Key words Circadian · Hamster · Intergeniculate leaflet · Locomotor activity · Masking

Abbreviations *CT* circadian time · *DD* constant darkness · *IGL* intergeniculate leaflet · *LD* light-dark · *NPY* neuropeptide Y · *SCN* suprachiasmatic nucleus · *ZT* zeitgeber time

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Introduction

In the Syrian hamster, a nocturnal species, a pulse of light in the night results in a rapid decrease of locomotor activity. This direct effect of light on activity is termed masking (Aschoff 1960). In general, masking by light may either decrease or increase activity, depending on the particular situation and species.

Masking by light does not require perception of form or movement, only assessment of the overall level of illumination. Neurons that fire tonically in the presence of light exist in the suprachiasmatic nucleus (SCN) (Groos and Meijer 1985); therefore, this area could be involved in masking. However, in our experiments with hamsters, lesions of the SCN did not eliminate or even attenuate masking (Redlin and Mrosovsky 1999, and references therein). Although these results do not rule out that in intact hamsters the SCN is involved in masking of locomotor activity (see Discussion in Redlin and Mrosovsky 1999), the SCN is clearly not essential. Possibly another brain area with neurons coding for luminance mediates masking of locomotor activity by light.

The intergeniculate leaflet (IGL) of the lateral thalamus is one such area. This area receives direct retinal input from the primary optic tract (Moore and Card 1994; Morin 1994; Morin and Blanchard 1997) and contains luminance-coding neurons (Harrington and Rusak 1989; Harrington 1997). Some of the retinal afferents innervating the IGL are collaterals of bifurcating neurons also innervating the SCN (Pickard 1985).

There are a number of suggestions in the literature that the IGL is involved in masking, but few hard data. Albers et al. (1982) speculated, in the light of persistence of masking by light in monkeys with SCN lesions, that the IGL may serve "some integrative function in the masking process". Edelstein et al. (1995) made similar suggestions.

An indication that the IGL may be involved in masking comes from experiments by Cipolla-Neto et al. (1995). Their study showed that acute suppression of melatonin by a light pulse (i.e. negative masking) can be

modified by lesions of the IGL. After IGL lesioning, rats had impaired melatonin suppression when a 1-min light pulse was given. In contrast, melatonin suppression was unimpaired when a 15-min pulse was given. An involvement of the IGL in a fast component of the masking response was proposed.

In summary, there are a number of reasons for investigating the effects of IGL lesions on masking of locomotion by light:

1. Luminance coding neurons are found in the IGL.
2. There have been suggestions and hints in the literature that the IGL might be needed for masking of locomotor activity but no experiments have been specifically directed at this possibility.
3. The SCN does not appear to be necessary for masking of locomotion.
4. The retinal projection to the IGL has not been associated with any major function.
5. If the IGL were involved in masking, the bifurcating projections of the retina to the SCN and the IGL would fit with the complementary functions that entrainment and masking have in confining activity to the night or day.

Because IGL lesions do not abolish circadian rhythms and do not depress activity as much as SCN lesions, it was possible to select a time when the animals could be counted on to be reasonably active and study their behaviour as a function of the level of illumination during the light pulse.

Materials and methods

General

Male Syrian hamsters (age 40 days) were bought from Harlan Sprague-Dawley (Ind., USA). They were housed individually in cages equipped with a wheel (17.5 cm diameter) in a 14:10-h light/dark (LD) cycle with lights off at 1200 hours (experiment 1) or at 1600 hours (experiment 2). With the exception of the 1st week in experiment 1, the wheels were covered on the outside with a plastic mesh to facilitate running (Mrosovsky et al. 1998). Water and food (rodent chow 5001; PMI, St. Louis, Mo., USA) were available ad libitum. Illumination for the entraining LD cycle was about 1300 lx at cage level. Temperature ranged from 17 to 21 °C. Wheel-running was monitored by a Dataquest III system (Minimitter, Sunriver, Ore., USA).

Phase angle of entrainment was determined by calculating the average activity onset of the 7 days before surgery (experiment 2) and of days 15–21 post-surgery (experiments 1 and 2). In five cases only six activity onsets, and in two cases only five activity onsets were available to establish phase angles. Activity onsets were defined as the first 10-min bin with at least 81 counts followed by at least another such bin within the next 40 min.

All results are given as means ± standard error. Differences in the masking responses to pulses of light were analysed by two-way ANOVA. Differences in phase angles of entrainment were examined by two-tailed *t*-tests (experiment 1) or by two-way ANOVA with Bonferroni post-hoc tests (experiment 2). Differences in phase shifting were tested by two-tailed *t*-tests. Significance for all procedures was set at $P < 0.05$. Two hamsters with IGL lesions were excluded from the data analysis: one hamster in experiment 1 had erratic wheel running and one hamster in experiment 2 died after surgery.

Experiment 1

Three days after arrival, the hamsters were either given sham operations ($n = 9$) or IGL lesions ($n = 15$) over a period of 6 days; all data from one animal in the latter group were excluded because of problems with recording activity. After surgery, the hamsters were returned to their home cages. Starting at 8 days after the last surgery, the hamsters were given two pilot light pulses of 1-h duration at zeitgeber time (ZT) 14.3 (data not reported). The animals were then transferred to a room in which light pulses of variable irradiance could be given. A series of light pulses was given starting 23 days after the last surgery.

The details of the light sources and neutral-density filters used to alter illumination during the pulses are given in Mrosovsky et al. (1999). The test procedure required 3 days for each light level. On the 1st day (maintenance day) filters were added and general animal care was carried out. On the 2nd day (baseline day) the animals were left undisturbed and home cage wheel running from ZT 14 to 15 was analysed. On day 3 (test day) the hamsters were given a light pulse at ZT 14–15. The number of wheel revolutions made during the light pulse was counted and compared to the baseline wheel counts on the previous day. Masking scores are given as percentages of baseline wheel counts.

Tests with pulses of seven different levels of irradiance were given, starting with the brightest, and continuing in descending order. Taken together, the seven separate tests constituted a masking threshold test. The illumination levels are given in stop values of the neutral density filters; for the higher levels, approximate lux values are given. For the lower levels, the light was too dim to be registered by our meter (ISO TECH ILM350). The seven light levels were: 0 stops (approximately 500 lx), 3 stops (approximately 60 lx), 6 stops (approximately 10 lx), 9 stops (approximately 2 lx), 12 stops (< 1 lx), 15 stops (< 1 lx), and 18 stops (< 1 lx).

Six weeks after surgery, the hamsters were tested for the strength of their preference for a dark over an illuminated chamber. The procedure is described elsewhere (Mrosovsky and Hampton 1997; Redlin and Mrosovsky, 1999). Briefly, the hamsters were put in a box divided into two compartments, the only difference being that one was completely dark and the other one was illuminated (approximately 5 lx on the floor). The hamsters were kept for 22 h in this apparatus and could move freely between the dark and light sides through an aperture in the wall between the chambers. The time spent in each side was monitored by a Med-PC photocell system (Med Associates, St. Albans, Vt., USA).

Experiment 2

In this experiment, in contrast to experiment 1, hamsters were tested both before and after the lesions. Two weeks after arrival the hamsters ($n = 24$) were given a series of masking pulses with varying light irradiances as in experiment 1. After this pre-operative test of masking thresholds hamsters were either given IGL lesions ($n = 15$, excluding one hamster that died post-operatively) or sham operations ($n = 8$). Twenty-five days after the last surgery, the masking threshold tests were repeated.

Following these masking tests, the hamsters were given two light pulses to test for possible differences in phase shifting between IGL-lesion and sham-operated groups. Hamsters were maintained in an LD 14:10 h cycle. Light pulses (duration 1 h) were given at ZT 14 and at ZT 18 (illumination about 60 lx). In addition, one sham pulse, with cardboard blocking the passage of light, was given at ZT 14. After the pulses, room lights remained off for 5 days (ZT 14) or 8 days (ZT 18). A regression through activity onsets of day 2 to day 5 (ZT 14) or day 4 to day 8 (ZT 18) in constant darkness (DD) was calculated. Activity onset was defined as the 10-min bin of activity with more than 81 revolutions followed by at least another such bin within the next 40 min. The regression line was extrapolated back to a point on the day of the pulse, and the phase shift calculated from the difference between this point and the actual onset on this day.

Lesions

Hamsters were anaesthetized with either an intraperitoneal injection of sodium pentobarbital (Somnotol, 80 mg kg^{-1}) or tribromethanol (250 mg kg^{-1}) and placed in a Kopf stereotaxic instrument. The incisor bar was set at −2 mm. Electrodes were made from nichrome wire (0.2 mm diameter) insulated except for 0.2–0.25 mm at the tip. The IGL was lesioned bilaterally by passing 1 mA of anodal current for 15 s at each of the following sites: anterior-posterior: −1.5 mm relative to Bregma, lateral: 3.1 mm each side of the midline, ventral: 4.6 mm down from the dura; anterior-posterior: −1.9 mm relative to Bregma, lateral: 3.0 mm each side of the midline, ventral: 4.7 mm down from the dura. For sham lesioning the electrode was lowered to anterior-posterior: −1.5 mm relative to Bregma, lateral: 3.1 mm each side of the midline, ventral: 3.5 mm down from the dura, and no current was passed.

Histology and immunocytochemistry

Ten weeks (experiment 1) or 14 weeks (experiment 2) after IGL lesions, the hamsters were given an overdose of sodium pentobarbital (Somnotol) and were then perfused transcardially with 0.9% NaCl, followed by 4% paraformaldehyde in 0.1 mol l^{-1} phosphate buffer solution (PBS). Brains were removed, postfixed in the same fixative for about 4 h and then transferred to PBS, after which the brains were sent from Toronto to Copenhagen for histology. Two days prior to cutting, the brains were cryoprotected in a 30% sucrose solution in PBS. Serial sections (40 μm) were cut on a cryostat and transferred to PBS containing 0.02% potassium chloride at room temperature. Reactions for immunoreactivity to neuropeptide Y (NPY-ir) were carried out on freefloating sections; brains of the groups with IGL lesions and sham operations were processed simultaneously. NPY-ir was visualized using the ABC bridge method (Vrang et al. 1995). Briefly, one series of sections from each brain was incubated for 24 h at 4 °C in an NPY antibody diluted 1:1000 in PBS with 0.3% Triton-X-100 and 1.0% bovine serum albumin. This antiserum (code no. 8183), raised against synthetic NPY in rabbits, has been previously characterized (Mikkelsen and O'Hare 1991). Following incubations in secondary biotinylated antibody and ABC-streptavidin horseradish peroxidase complex (Datopatts) the sections were stained using diaminobenzidine as chromogen. Following two brief rinses in distilled water, the sections were mounted on gelatinized slides and embedded in Depex.

Results

Masking

IGL lesions did not prevent light from inhibiting locomotor activity in either experiment (Fig. 2). In fact, in both experiments the masking threshold curves of the hamsters with IGL lesions were shifted to the right compared to the sham-operated controls, indicating an enhanced masking response to light (two-way ANOVA, $P < 0.01$ in both experiment 1 and experiment 2). Because the data were not normally distributed, they were also analysed with a non-parametric test, with similar results (Friedman two-way analysis of variance, $P < 0.01$ experiment 1, $P < 0.05$ experiment 2).

Scoring masking responses to light as percentages of baseline activity, as done in this study, overlooks possible differences in baseline activity levels. This might be a problem especially when comparing control hamsters to those with IGL lesions, because hamsters tend to become less active after such lesions (Janik and Mrosovsky 1994). Therefore, in Fig. 3 the results of experiments 1 and 2 are redrawn with absolute numbers of wheel turns for the 1-h pulses and for the corresponding baseline running. Wheel running during the 1-h baseline periods on the days before the masking pulses was not significantly lower after IGL lesions when compared to that of the sham-operated controls (two-way ANOVA; experiment 1: $P > 0.05$, experiment 2: $P > 0.05$). However, comparing pre- and post-surgery baseline levels, there was a parallel reduction in baseline levels in both groups of experiment 2 (two-way ANOVA; $P < 0.0001$, for both IGL lesion and sham-operated groups).

Although there was no significant difference in wheel counts between sham and IGL-lesion groups for the 1 h of baseline running, wheel-running totals for each 24 h were lower in the hamsters with IGL lesions (two-way ANOVA; experiment 1 and experiment 2: $P < 0.0001$, Fig. 4). Average activity after IGL lesioning was reduced to about 69% (experiment 1) and 66% (experiment 2) of the average wheel counts in the sham-operated groups.

Light/dark preferences

When hamsters in experiment 1 were tested for their preference between a light or dark compartment, every individual spent more time in the dark side. On average, the sham-operated hamsters spent 88.4% of the 22-h test period in the dark side, significantly more than the IGL lesion group that spent 81.1% of their time in the dark ($P < 0.05$, two-tailed Mann-Whitney test).

Entrainment to the LD 14:10 h cycle

Phase angles of entrainment differed significantly between hamsters with IGL lesions and sham lesions in both experiments (Fig. 5). This is especially clear in experiment 2 in which before and after measurements were taken. It is corroborated by experiment 1, which was not designed to study changes in phase angles.

Phase shifting to light

Phase shifts to light pulses at ZT 14 and ZT 18 (experiment 2) were not significantly different between hamsters with sham and IGL lesions (*t*-tests, $P > 0.05$; Fig. 6), but there was a trend towards greater phase delays in the IGL-lesion group at ZT 14 (IGL-lesion group: -0.56 ± 0.06 h, sham-operated group: -0.31 ± 0.18 h).

Histological analysis

The counterstained slides revealed extensive damage to the IGL, with a variable degree of damage to surrounding regions, notably the dorsal and ventral lateral

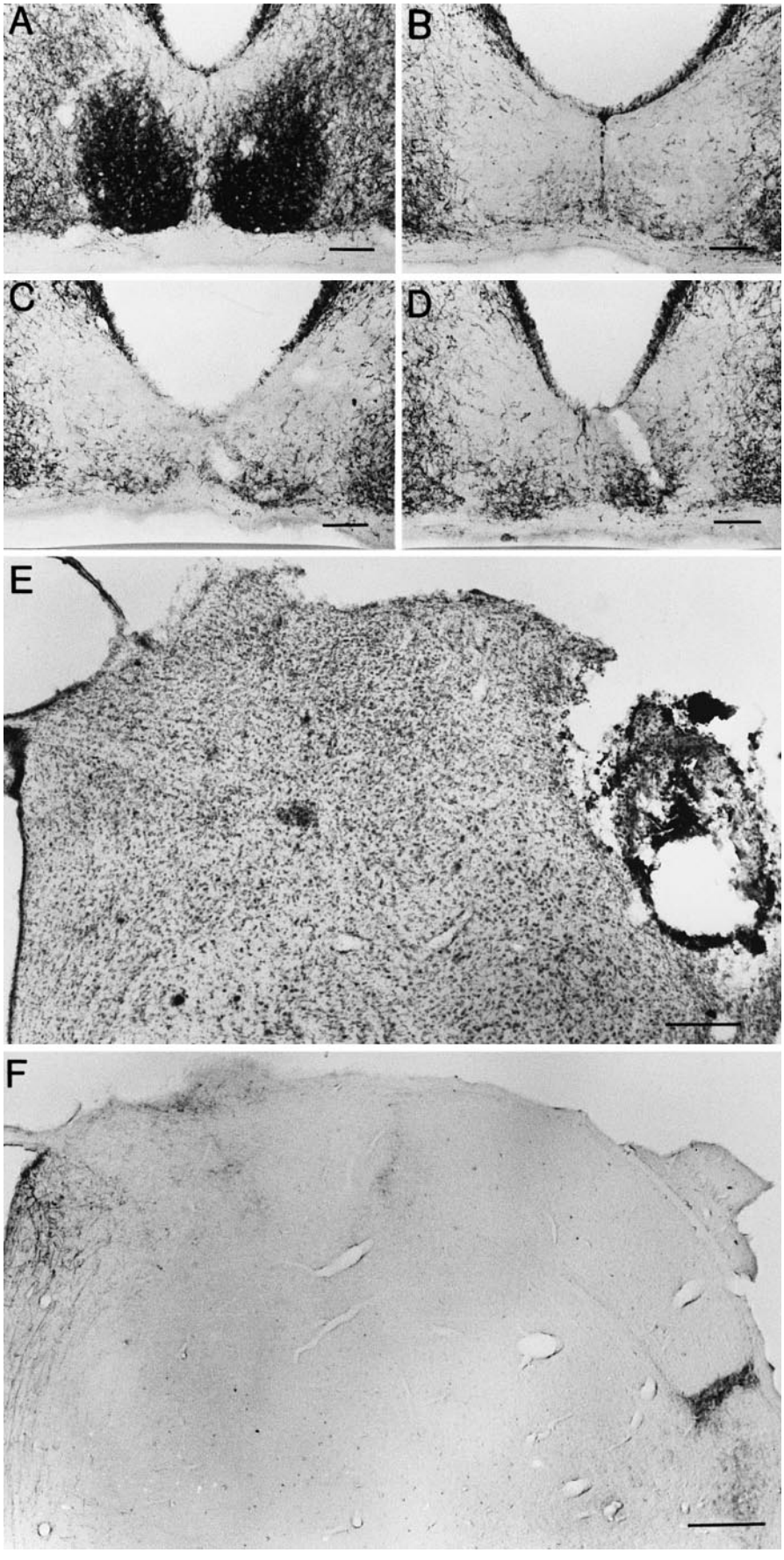

Fig. 1A–F *Top four panels* show suprachiasmatic nucleus (SCN): **A** dense neuropeptide Y (NPY) immunoreactivity of hamster with sham lesions (no. 7075); **B** almost total depletion of NPY in the SCN of hamster with intergeniculate leaflet (IGL) lesions (no. 7083); **C,D** extensive depletion of NPY in SCN of hamsters with IGL lesions (nos. 7078 and 7095). (**A–D**, scale bars = 50 μm) *Lower two panels* show IGL area: **E** counterstained lesion site of hamster no. 7083; **F** sham-lesioned hamster (no. 7075) with NPY immunoreactivity indicating the location of the IGL(**E–F**, *scale bars* = 100 μm)

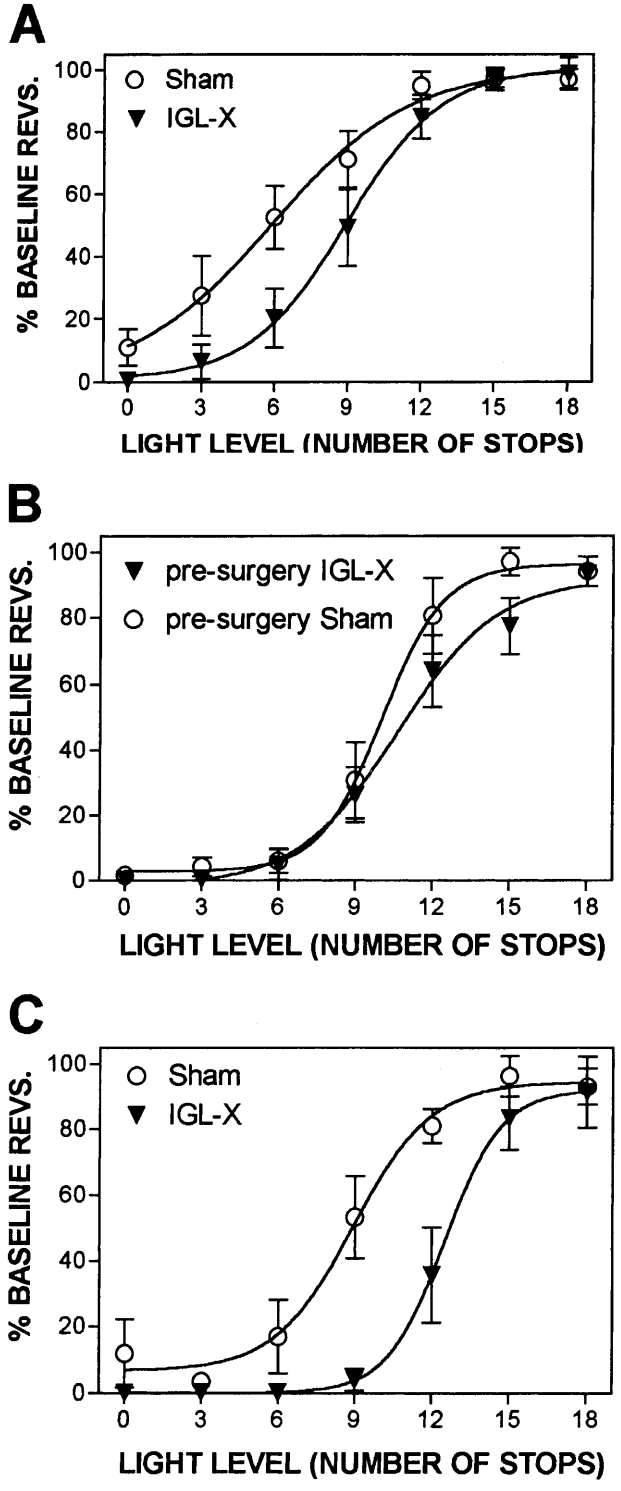

Fig. 2A–C Comparison of masking scores (mean ± SE) of IGL-lesioned and sham-operated hamsters. Masking scores are given as percentages of baseline running. Illumination was varied by adding neutral-density filters (for details see text). **A** Experiment 1. **B** Experiment 2 before surgery. **C** Experiment 2 post-surgery

geniculate nuclei, as well as the adjacent external medullary lamina of the thalamus (Fig. 1E). In some animals the lesions extended laterally and caused minor damage to the part of the hippocampus overlying the IGL. Further evidence of damage to the IGL came from study of the SCN to which NPY-containing fibres normally project. Immunostained sections of the SCN were scored by an observer, blind to the animal's group, in one of four categories for depletion of NPY: 1, no depletion evident; 2, clear depletion; 3, extensive depletion; 4, almost total depletion. All sham-operated animals fell in the no-depletion category. All lesioned animals in both experiments showed some degree of depletion (Fig. 1B–D). In experiment 1, 8 out of 14 animals with IGL lesions were scored as almost totally depleted. In experiment 2 extreme depletion was less common, with 4 out of 15 animals categorised as almost totally depleted. The remaining animals in both experiments were all either clearly depleted or extensively depleted in NPY.

Discussion

Lesions of the IGL, verified by depletion of NPY in the SCN and by conventional histology (Fig. 1), and resulting in the expected decrease in activity (Fig. 4), did not reduce the inhibition of locomotion by light in hamsters. Thus, the IGL cannot be a site of great importance for masking; there was not even an impairment of the response in the lesioned hamsters. This conclusion should be qualified in two ways. First, there could conceivably be a redundant mechanism for masking (Sisk and Stephan 1982), with the IGL playing a role in the intact animal but not being essential. Second, perhaps the IGL is important in masking at a circadian time (CT) other than that tested here. These possibilities do not seem very likely because the masking response in our tests was not compromised at all.

Surprisingly, masking was significantly enhanced in hamsters with IGL lesions. Whether this effect arises from damage to the IGL itself, or to adjacent structures, is a subject of future investigations. We can, however, dismiss some trivial explanations of the enhanced masking response. First, differences in activity levels between the lesioned groups could possibly affect the quantification of the activity suppression, and IGL lesions have been shown to lower activity levels (Johnson et al. 1989; Janik and Mrosovsky 1994, Kuroda et al. 1997). Although there was a reduction in the mean 24-h wheel counts for hamsters with IGL lesions (Fig. 4), wheel running, when compared to sham-operated controls, was not significantly reduced during the hour for masking tests (ZT 14–15). Therefore, differences in masking responses between the groups do not merely result from differences in activity levels. Second, Legg (1975) noted that lesions of the ventral geniculate nucleus, possibly as a result of destruction of the retinal input to the pretectum, compromised the pupillary light reflex. It is therefore possible that permanent pupillary dilation would result in animals with IGL lesions receiving more light than sham-operated controls. This is unlikely to have been the case with our experiments because tests

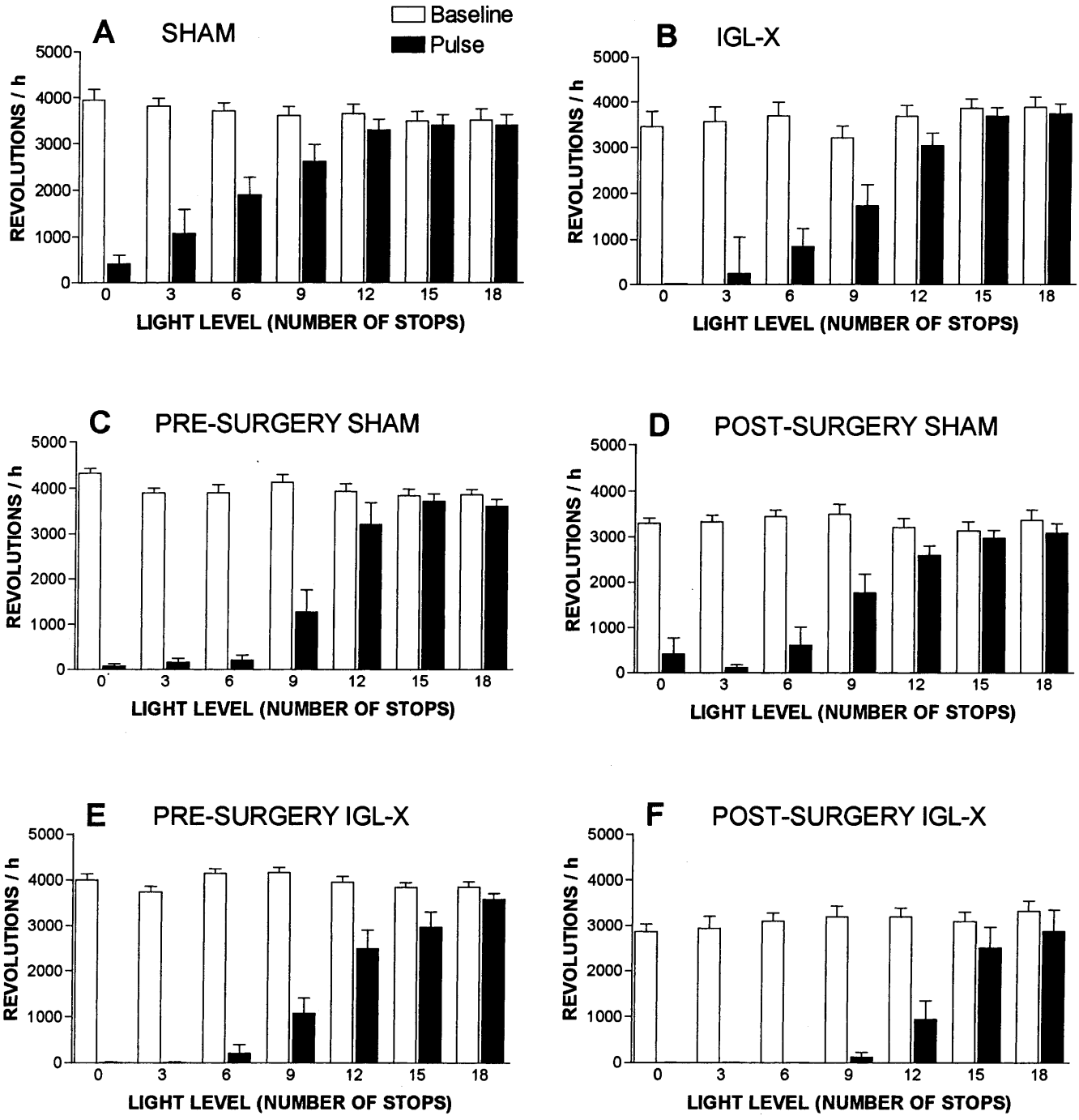

Fig. 3A–F Number of wheel revolutions (mean ± SE) in the masking threshold tests. Baseline days and pulse days are shown as a function of illumination during the pulse (for details see text). **A** Sham-lesion group, experiment 1. **B** IGL-lesion group, experiment 1. Wheel counts during the pulse were significantly lower in the IGL-lesion group compared to the sham-operated controls (two-way ANOVA, $P < 0.05$). **C–F** Experiment 2: **C** pre-surgery sham-lesion group; **D** post-surgery sham-lesion group; **E** pre-surgery IGL-lesion group; **F** post-surgery IGL-lesion group. Wheel counts during the pulse were not significantly different between sham- and IGL-lesion groups before surgery (two-way ANOVA, $P > 0.05$), but they differed between the groups after surgery (two-way ANOVA, $P < 0.0001$)

made just before the end of experiment 2 showed pupillary constriction in response to light to be present.

Another way to obtain insight into the enhanced masking response is to ask if other responses to light are enhanced. Considering the speculation that masking and phase shifting of circadian rhythms may be mediated by common photoreceptors (Mrosovsky 1994), it is relevant to note that enhanced phase shifting to a light pulse at about CT 14 has been reported by Pickard et al. (1987), although Harrington and Rusak (1986) found no such effects. However, the latter negative result may be explained by the use of light pulses that were too bright to allow for increases in the phase shifts after IGL lesioning

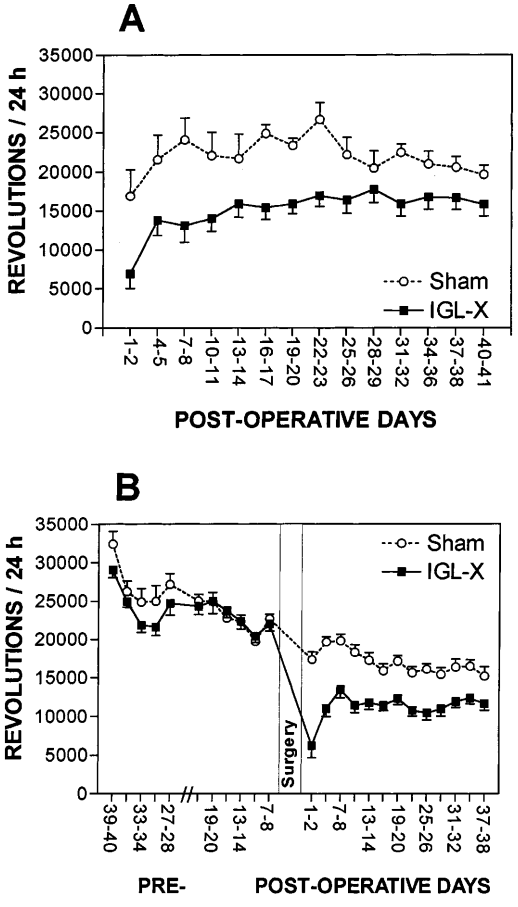

Fig. 4A,B Effects of IGL lesions and sham operations on daily wheel running (mean ± SE) of hamsters. **A** Experiment 1. **B** Experiment 2. Means were calculated for 2-day blocks; days are numbered with reference to the last day of surgery

(Harrington and Rusak 1986). As phase shifting, like masking, requires only detection of overall levels in illumination, IGL lesions could possibly result in some enhanced detection of irradiance, thereby enhancing both phase shifting and masking.

The increased negative phase angle of entrainment after IGL lesioning found in this study (Fig. 5) could

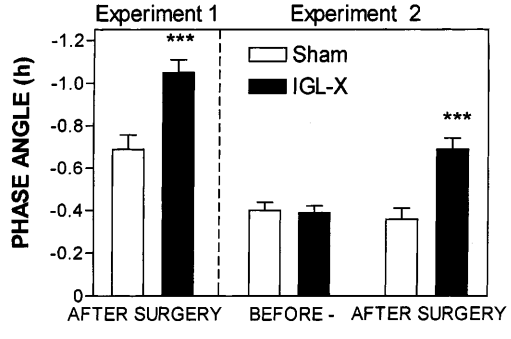

Fig. 5 Phase angles of entrainment to the light-dark (LD) 14:10-h cycle in IGL-lesioned and sham-operated hamsters. *Negative values* indicate that activity onset occurred after dark onset. Phase angles were determined as means of activity onsets of 7-day periods immediately before surgery (experiment 2) or of days 15–21 after surgery (experiments 1 and 2). $***P < 0.001$

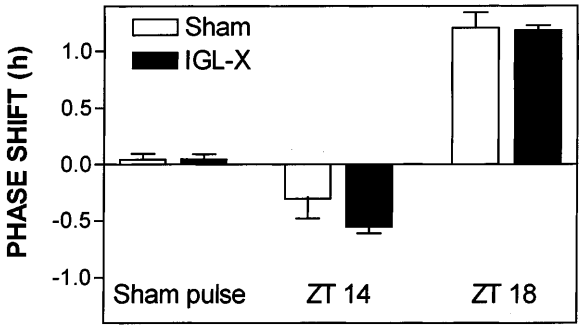

Fig. 6 Phase shifting to light pulses (1 h, 60 lx) given at ZT 14 and ZT 18 in IGL-lesioned and sham-operated hamsters in experiment 2. In addition, the results for one sham pulse (the light passage was blocked by cardboard) at ZT 14 are given. No differences between the experimental groups at either ZT 14 (*t*-test, $P = 0.11$) or ZT 18 were found (*t*-test, $P = 0.86$)

indicate such an overall effect on irradiance detection. If light is perceived as brighter this may lead to greater delay shifts in the late part of the day when the delay portion of the photic PRC coincides with light. The changed phase angles after IGL lesioning could therefore be explained by a heightened sensitivity of the circadian system to light. Two other studies reported phase angle changes after lesions of the IGL (Janik and Mrosovsky 1994, Maywood et al. 1997). Other investigators did not find significant changes in the entrainment of hamsters to LD cycles after IGL lesioning (Pickard et al. 1987; Harrington and Rusak 1988).

Several points suggest, however, that IGL lesions may not result in a general enhancement in irradiance detection. First, when hamsters with IGL lesions were tested for their preference in a dark over a light compartment, they spent significantly more time in the light side than the sham-operated controls (experiment 1). Hamsters with IGL lesions would be expected to spend more time in the dark side if light levels were perceived as brighter. Second, although some authors have reported increased phase shifting at CT 14 after IGL lesions, at CT 18 phase shifts have been found to decrease (Harrington and Rusak 1986; Pickard et al. 1987). Third, in the present work, phase shifting between the IGL-lesioned and sham-operated animals was not significantly different either at ZT 14 or ZT 18, although a trend for greater phase shifts in hamsters with IGL lesions was present (Fig. 6). The phase delays obtained (< 0.5 h) were smaller than the maximal shifts possible at CT 14 in the Syrian hamster (Takahashi et al. 1984; Mrosovsky 1991); therefore, phase shifts could have increased further after IGL lesioning.

Taken together, these points suggest that IGL lesions could have modified the masking response rather than the detection of light. The IGL could thus be a part of the circuitry regulating masking of locomotor activity by light. Some characteristics that might make the IGL suitable for such a task are its connections to and from the SCN, and its direct retinal afferents. IGL lesions decrease activity levels in some studies (Johnson et al. 1989; Janik

and Mrosovsky 1994; Kuroda et al. 1997; this study), but in one other study no such decrease in activity levels attributable to IGL lesions was reported (Maywood et al. 1997). Also, electrical stimulation of the IGL can cause increases in activity (Rusak et al. 1989). Considering that the IGL may adjust activity levels in the hamster, it seems possible that this function could be put to use for masking. An active intact IGL may promote activity; loss of this activity-promoting influence might lead to a greater suppression of activity by light.

In conclusion, although the IGL is not essential for masking of locomotor activity in hamsters, it may be part of the machinery which regulates masking. The role of the IGL in masking can be compared to that of the IGL for circadian phase shifting to light: both masking and phase shifting persist without the IGL, but alterations in these responses to light occur when the IGL is damaged.

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References

Albers HE, Lydic R, Moore-Ede MC (1982) Entrainment and masking of circadian drinking rhythms in primates: influence of light intensity. Physiol Behav 28: 205–211

Aschoff J (1960) Exogenous and endogenous components in circadian rhythms. Cold Spring Harbor Symp Quant Biol 25: 11–28

Cipolla-Neto J, Bartol I, Seraphim PM, Afeche SC, Scialfa JH, Peraçoli AM (1995) The effects of lesions of the thalamic intergeniculate leaflet on the pineal metabolism. Brain Res 691: 133–141

Edelstein K, Pfaus JG, Rusak B, Amir S (1995) Neonatal monosodium glutamate treatment prevents effects of constant light on circadian temperature rhythms of adult rats. Brain Res 675: 135–142

Groos GA, Meijer JH (1985) Effects of illumination on suprachiasmatic nucleus electrical discharge. Ann NY Acad Sci 453: 134–146

Harrington ME (1997) The ventral lateral geniculate nucleus and the intergeniculate leaflet: interrelated structures in the visual and circadian systems. Neurosci Biobehav Rev 21: 705–727

Harrington ME, Rusak B (1986) Lesions of the thalamic intergeniculate leaflet alter hamster circadian rhythms. J Biol Rhythms 1: 309–325

Harrington ME, Rusak B (1988) Ablation of the geniculo-hypothalamic tract alters circadian activity rhythms of hamsters housed under constant light. Physiol Behav 42: 183–189

Harrington ME, Rusak B (1989) Photic responses of geniculo-hypothalamic tract neurons in the Syrian hamster. Vis Neurosci 2: 367–375

Note added in proof Edelstein and Amir (1999) have also found that IGL lesions do not abolish masking responses to light; their procedures did not provide data bearing on the question of whether masking is enhanced or not.

Edelstein K, Amir S (1999) The role of the intergeniculate leaflet in entrainment of circadian rhythms to a skeleton photoperiod. J Neurosci 19: 372–380

Janik D, Mrosovsky N (1994) Intergeniculate leaflet lesions and behaviorally-induced shifts of circadian rhythms. Brain Res 651: 174–182

Johnson RF, Moore RY, Morin LP (1989) Lateral geniculate lesions alter circadian activity rhythms in the hamster. Brain Res Bull 22: 411–422

Kuroda H, Fukushima M, Nakai M, Katayama T, Murakami N (1997) Daily wheel running activity modifies the period of free-running rhythm in rats via intergeniculate leaflet. Physiol Behav 61: 633–637

Legg CR (1975) Effects of subcortical lesions on the pupillary light reflex in the rat. Neuropsychologia 13: 373–376

Maywood ES, Smith E, Hall SJ, Hastings MH (1997) A thalamic contribution to arousal-induced, non-photic entrainment of the circadian clock of the Syrian hamster. Eur J Neurosci 9: 1739–1747

Mikkelsen JD, O'Hare MMT (1991) An immunohistochemical and chromatographic analysis of the distribution and processing of proneuropeptide Y in the rat suprachiasmatic nucleus. Peptides 12: 177–185

Moore RY, Card JP (1994) Intergeniculate leaflet: an anatomically and functionally distinct subdivision of the lateral geniculate complex. J Comp Neurol 344: 403–430

Morin LP (1994) The circadian visual system. Brain Res Rev 67: 102–127

Morin LP, Blanchard JH (1997) Neuropeptide Y and enkephalin immunoreactivity in retinorecipient nuclei of the hamster pretectum and thalamus. Vis Neurosci 14: 765–777

Mrosovsky N (1991) Double-pulse experiments with nonphotic and photic phase-shifting stimuli. J Biol Rhythms 6: 167–179

Mrosovsky N (1994) In praise of masking: behavioural responses of retinally degenerate mice to dim light. Chronobiol Int 11: 343–348

Mrosovsky N, Hampton RR (1997) Spatial responses to light in mice with severe retinal degeneration. Neurosci Lett 222: 204–206

Mrosovsky N, Salmon PA, Vrang N (1998) Revolutionary science: an improved running wheel for hamsters. Chronobiol Int 15: 147–158

Mrosovsky N, Foster RG, Salmon PA (1999) Thresholds for masking responses to light in three strains of retinally degenerate mice. J Comp Physiol A 184: 423–428

Pickard GE (1985) Bifurcating axons of retinal ganglion cells terminate in the hypothalamic suprachiasmatic nucleus and the intergeniculate leaflet of the thalamus. Neurosci Lett 55: 211–217

Pickard GE, Ralph MR, Menaker M (1987) The intergeniculate leaflet partially mediates effects of light on circadian rhythms. J Biol Rhythms 2: 35–56

Redlin U, Mrosovsky N (1999) Masking by light in hamsters with SCN lesions. J Comp Physiol A 184: 439–448

Rusak B, Meijer JH, Harrington ME (1989) Hamster circadian rhythms are phase-shifted by electrical stimulation of the geniculo-hypothalamic tract. Brain Res 493: 283–291

Sisk CL, Stephan FK (1982) Central visual pathways and the distribution of sleep in 24-hr and 1-hr light-dark cycles. Physiol Behav 29: 231–239

Takahashi JS, DeCoursey PJ, Bauman L, Menaker M (1984) Spectral sensitivity of a novel photoreceptive system mediating entrainment of mammalian circadian rhythms. Nature (Lond) 308: 186–188

Vrang N, Larsen PJ, Møller M, Mikkelsen JD (1995) Topographical organization of the rat suprachiasmatic-paraventricular projection. J Comp Neurol 353: 585–603